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Effect of Convective Drying on Texture, Rehydration, Microstructure and Drying Behavior of Yam (*Dioscorea pentaphylla*) Slices

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Drying is a critical primary processing technique in enhancing and maintaining the quality and storability of *Dioscorea pentaphylla*. The present work investigated the effect of forced convective drying at three drying temperatures (50, 60, and 70°C). Ten drying and four-color kinetics models were used to fit the drying data to study the drying behavior and the effect of temperature and time on color change. Moisture diffusivity increased with hot air temperature (4.88526×10^{-10}–8.8069×10^{-10} m^2/s). For *Dioscorea pentaphylla* slices, 27.04 (kJ/mol) of activation energy was found. Hii and others model gives the superior fitting for all the drying temperatures followed by logarithmic and Avhad and Marchetti model. Color kinetics was evaluated using L, a, and b values at a specified time during whole drying process. Temperature and time influenced the Lightness (L), yellowness (b), a value, chroma, hue, and browning index (BI). Dried slices from 70°C showed more color change, whereas those from 50°C had a medium-light brown. The modified color model is best fitted with high R^2 and lower chi-square. Potassium metabisulfite ($K_2S_2O_5$) pre-treatment and boiling significantly affected the drying time and final color of slices. The study reveals that drying at 50°C exhibits better color retention and could be effectively used to dry *Dioscorea pentaphylla*. Dried *Dioscorea pentaphylla* can be utilized in both food and pharmaceutical industries for several applications for formulations food products and health supplements.

Keywords: Activation energy, Drying and color kinetics, Industrial production, Modeling, Moisture diffusivity

Introduction

Globally, the burden of malnutrition and undernutrition is increasing as a result of the rapid population growth.[1] With a growing world population and dwindling natural resources, it is very important to diversify farming and find new sources of food to meet increasing demand of global population.[2] *Dioscorea pentaphylla* (Five Leaf Yam) is a good source of essential dietary minerals and bioactive constituents such as phenolics, flavonoids, saponins, diosgenin; containing mainly starch (75–85%) with a small amount of protein, lipids.[3,4] It is reported that *Dioscorea pentaphylla* exhibit analgesic, anti-oxidant, antimutagenic, anti-inflammatory, antibacterial, antigenotoxic potential.[4–6] The major hurdle in wider utilization of this yam is due to its poor storability, and higher microbial activity due to higher water activity and higher enzymatic browning, which affect the shelf life of yam tuber.[7] Thus, processing of tuber mainly pretreatment and drying are important step to reduce these issues and widen the applicability of dried yam in preparation of flour and value-added products, starch extraction, and extraction of dioscorin and disogenin medicinal compounds.

Drying is the most commonly used method in fruit and vegetable preservation by reducing the water activity, microbial growth, and moisture-related kinetic degradation.[8] Drying not only extends the shelf life of products, but also aids in the reduction of shipping, packing, and storage costs.[9] Sun drying is the often-utilized drying practice in rural and tribal areas of Asia and Africa.[10] However, it has several disadvantages and limitations in maintaining product quality. Therefore, much attention has been given to the drying process as it changes the physicochemical properties. The most widely used drying process in the food industry is hot air drying.[9,11] Hot air driers are simple in design and achieve better operation control over various drying conditions and maintain higher drying rate with better product quality. In drying process optimization is a challenging task and kinetics modeling is vital to understand product drying behavior under various drying conditions and selection of ideal drying conditions for superior quality products.[12] Modeling is critical for

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comprehending heat and mass transfer as well as minimizing experimental error to improve the better drying process for storage and processing of dried products.[11,13] Drying and color kinetics behavior of *Dioscorea hispida* has studied by Sahoo *et al*.[11] Though every species of Dioscorea will show different behavior with drying kinetics. This change in kinetics behavior is due to the chemical composition of species. Similarly, in Discoera species enzymes catalyze their reaction differently and vary with variety, cultivar, pH, anti-browning agents, and temperature.[4,5] Therefore, drying study of each species is important to understand the kinetics behavior and optimization of end quality of products.

To our knowledge, no prior research has been undertaken to investigate the drying behavior combining with the boiling pretreatment on color kinetics, texture, microstructure, and rehydration properties of *Discoera pentaphylla*. Considering these shortcomings, the current study is conducted to (a) investigate the effect of pretreatment and drying techniques on drying and color kinetics; and (b) to explore the effect of pretreatment and drying methods on color, texture, microstructure, and rehydration qualities; (c) to fit and study the mathematical models for drying kinetics and color kinetics models.

Material and Methods

Sample Preparations and Pretreatment

Dioscorea pentaphylla tubers were harvested with the assistance of native people (Angul, Odisha, India). *Dioscorea pentaphylla* tubers were peeled, washed and sliced into 4–5 mm thickness using a sharp knife. Slices of 300 gm were immersed in a solution of potassium metabisulphite (0.5 percent w/v) ($K_2S_2O_5$), an anti-browning agent and then boiled (100°C) for 30 minutes. Boiled samples were surface dried with a muslin cloth. The hot air oven method (AOAC, 930.15; 2005)[14] was used to determine the moisture content of yam slices.

Drying of *Dioscorea Pentaphylla* Slices

Drying experiments were undertaken in a lab-scale forced convective dryer (Fig. 1). The drying tray is attached over load cell (Siemens wl260 sp-s c3 model with 0.015% accuracy) and weight change was displayed and recorded from the designed auto weighing equipment. The time interval was set in the control panel to record the weight loss of the sample. The drying studies were conducted at three temperature levels (50, 60, and 70°C). A double-coated heat-sealed polythene pouch was used to keep the dried product dry and cool for additional investigations. Experiments were done in triplicate in this study.

Moisture Content and Drying Rate

The following expression in Eq. (1) determined the Moisture Ratio (MR) of sample drying during the experiment.

$$M_R = \frac{M_t - M_e}{M_0 - Me} \quad \ldots(1)$$

where, M_0, M_t, and M_e are the initial, time-varying, and equilibrium condition moisture contents of samples (g water/g dry matter).

The drying rate (*DR*) of *Dioscorea pentaphylla* slices at a specific time was computed using Eq. (2):

$$\mathrm{DR} = \frac{M_t - M_{t+\Delta t}}{t_2 - t_1} \quad \ldots(2)$$

where, $M_{t\,+\,\Delta t}$ represent the sample moisture at t + Δt drying time (g water/g dry matter/min).

Drying Kinetics and Mathematical Modeling

Drying models have been used in the design, construction, process optimization, and determination of drying behavior. In thin layer modeling, various mathematical models have been developed and classified as theoretical, semi-theoretical, and

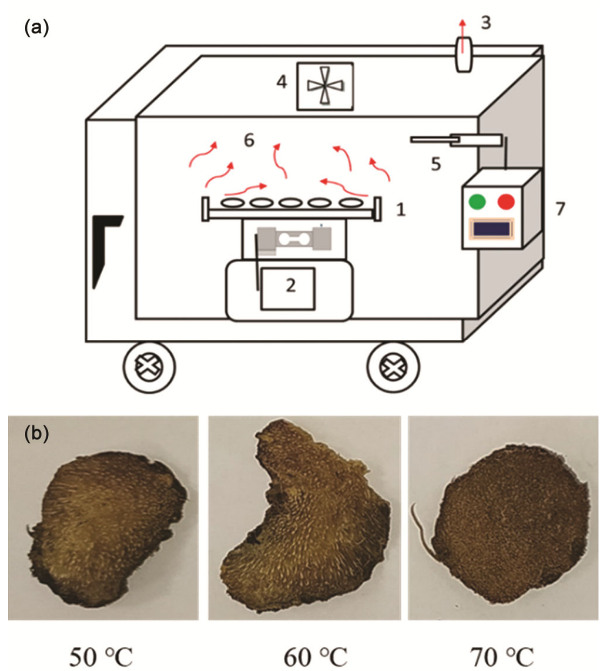

Fig. 1 — Schematic outline of lab scale hot air dryer (1-sample tray, 2-auto weighing system, 3-air outlet, 4-fan, 5-temperature sensor, 6-hot air, 7-Digital display) (b) Color changes of yam slices at different drying temperatures

Table 1 — List and prominence of the mathematical models used in the study [8,11–13]

S.N	Model name	Model
1.	Lewis model	$MR = \exp(-kt)$
2.	Page model	$MR = \exp(-kt^n)$
3.	Modified Page model	$MR = \exp[-(kt)^n]$
4.	Henderson and Pabis model	$MR = a \exp(-kt)$
5.	Logarithmic model (asymptotic Model)	$MR = a \exp(-kt) + c$
6.	Two-term model	$MR = a \exp(-k_0 t) + b \exp(-k_1 t)$
7.	Approximate diffusion model	$MR = a \exp(-kt) + (1-a) \exp(-kbt)$
8.	Midilli-Kucuk model	$MR = a \exp(-kt) + bt$
9.	Avhad and Marchetti model	$MR = a\exp(-kt^n)$
10	Hii and others model.	$MR = a \exp(-k_1 t^n) + b \exp(-k_2 t^n)$

empirical models.[15] The theoretical model such as distributed models and Lumped parameter models considered several assumptions, which led to many errors. On the other hand, in semi theoretical, external resistance is considered, which affects the drying characteristics of the product and provides flexibility by using experimental data for parameter considerations like product geometry, conductivity, and diffusivity.[12] Therefore, these models are simple, quick, efficient and more accurate in predicting the process.[16] Among several semi theoretical models, 10 commonly used models were selected and listed in Table 1.

Effective Diffusivity and Activation Energy

Effective moisture diffusivity is a transportation property that changes with type of dryer, drying conditions, and the properties of the materials. Fick's equations of diffusion can be used assuming an even moisture distribution in the sample, central symmetric mass transfer, and minimal shrinkage and external resistance. For an extended drying period, Fick's equation can be simplified[12] and stated in Eq. (3).

$$MR = \frac{8}{\pi^2}\, exp\left(\frac{-\pi^2 D_{eff}}{4L^2} t\right) \quad ...(3)$$

where, D_{eff} represents the moisture diffusivity (m^2/s), L represents the half-thickness of slices (m), and t represents the drying time (s).

Eq. (4) is simplified by calculating the natural logarithms of both sides.

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

The slope (K) is determined by regressing ln(MR) against drying time. Gradients (K) can be used to calculate effective diffusivity (D_{eff}).

$$K = \frac{\pi^2 D_{eff}}{4L^2} \quad ...(5)$$

Diffusivity of foods depends on temperature, as the Arrhenius equation demonstrates. Therefore, the activation energy was estimated by plotting ln (D_{eff}) vs. 1/T, which resulted a slope of ($-Ea/R$)[11]. The activation energy (Ea) can be estimated using the following formula expression (Eq. 6).

$$D = D_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right) \quad ...(6)$$

where, D_0, E_a, R and T denote the Pre-exponential factor (m^2/s), activation energy (kJ/mol), universal gas constant (8.314 kJ/mol K) and air temperature in drying (°C), accordingly.

Texture Measurement

Textural hardness and crispiness of dried food products are important quality attributes for consumer preference. Textural properties of dried slices of *Dioscorea pentaphylla* were analyzed using Texture Analyzer (Model: TA. HDplusC, Stable Microscopes, England, UK) equipped with a P/0.25 spherical probe. A trigger force of 10 g and a test speed of 2 mm/s were used.[11] Hardness, crispiness, work done, and the number of peaks was determined from force displacement curve using connect lite software. Twenty samples were used in each experiment for each treatment in triplicates.

Morphology of Dried Yam Slices

The effect of the drying method on dried *Dioscorea pentaphylla* at the micro-level can be studied using a Scanning Electron Microscope (SEM). Structural properties at the micro-level can be used to select the best processing methods in *Dioscorea pentaphylla* drying. SEM micrograph of dried *Dioscorea pentaphylla* was obtained using FEI Scanning Electron Microscope (Model: Zeiss EVO 50, German). The images were captured at 20 KV excitation voltages at 70x to 500x magnifications. The obtained images were analyzed using ImageJ software.

Rehydration Ratio

The rehydration capacity of dried *Dioscorea pentaphylla* slices was estimated using method described by Xiao *et al*.[17] with little modifications. Dry *Dioscorea pentaphylla* slices were rehydrated in a water bath maintained at 40°C. Distilled water (100 ml) is added into a 150 ml container and placed in a water bath. A sample of 5 gm was weighed and placed in a water bath for 60 minutes, then placed on a filter paper to remove surface moisture and weighed again. The below-given equation was used to compute the rehydration ratio.

$$\text{Rehydration ratio} = \frac{R_0}{D_0} \quad \text{...(7)}$$

where, R_0 and D_0 represent rehydrated and dehydrated (dried) sample weight.

Color Measurement

A colorimeter (CIE Lab) (Model: CR20, Konica Minolta, Inc., Japan) was used to record the visual appearance and color change of *Dioscorea pentaphylla* slices before and after dipping in solution and throughout drying time at specified time interval.[11] In the CIE Lab system, the L value indicates the color brightness, a value indicates the red or green color, and b value indicates the yellow or blue color in the samples. The total color difference (ΔE), chroma (C), hue angle (α), and browning index (BI), were determined from L, a, and b values using Eq. 8–11.[(18,19)] Hue angle ranges from 0–360° and represents color change from red to green while chroma indicates color intensity.[20]

$$\Delta E = \sqrt{(L_0 - L_t)^2 + (a_0 - a_t)^2 + (b_0 - b_t)^2} \quad \text{...(8)}$$

$$C = (a_t - b_t)^2 \quad \text{...(9)}$$

$$\alpha = tan^{-}\left(\frac{b_t}{a_t}\right) \quad \text{...(10)}$$

$$BI = \frac{100\,(X - 0.31)}{0.17} \quad \text{...(11)}$$

$$\text{where, } x = \frac{a_t + 1.75L_t}{5.646L_t + a - b_t}$$

where, "$_0$" and "t" indicates the color readings of treated slices and at particular drying time interval, respectively.

Color Kinetics

Drying requires kinetic modeling to produce a kinetic rate dependent on process variables and predicts color change behavior. Color kinetics models describe the degradation or formation of color in the sample. The following equation (Eq. 12) can explain the quality factor's concentration rate (C).

$$\frac{dC}{dt} = -kC^n \quad \text{...(12)}$$

C indicates the quality concentration attribute at time t, and n is the rate of reaction order.

By integrating Eq. (12), zero-order, first-order, modified kinetics, and fractional conversion kinetics models can be deduced and expressed in Eq. (13–16).[(11,18,20)] The color data obtained from hot air drying fitted in Eq. (13–16) using non-linear regression analysis.

$$C = C_0 \pm kt \quad \text{...(13)}$$

$$C = C_0 \exp(\pm kt) \quad \text{...(14)}$$

$$\frac{C}{C_0} = At^2 + Bt + 1 \quad \text{...(15)}$$

$$\frac{C - C_f}{C_0 - C_f} = \exp(\pm kt) \quad \text{...(16)}$$

C_0, C_f, and C represent the initial, final, and specified time color values of samples and ± sets the color formation and degradation in the sample.

Statistical Analysis

All experiments were performed in triplicates. The data on texture and rehydration are reported as mean ± SD. To examine the data at a P-value of 0.05 ($P \leq 0.05$), a post hoc Tukey test was used (IBM SPSS, version 26, Armonk, NY, USA). ORIGINLAB software (2021b) was used to fit models and examine drying data statistically.

Results and Discussion

Moisture Content and Drying Rate

The moisture ratio was calculated using the weight change of samples recorded in auto weighing system during the drying experiments. Typical Moisture Ratio (MR) curves of yam slices at 50–70°C temperatures are elucidated in Fig. 2a. Sample moisture content was decreased with drying time until it reaches equilibrium moisture content. At initial stage of drying in all temperatures, faster reduction was observed. This could be linked to the diffusion and availability of surface water. Further, a comparatively higher rate of MR reduction at a higher temperature of 70°C could be due to an increased evaporation rate. Drying time of 16, 11, and 9 h were

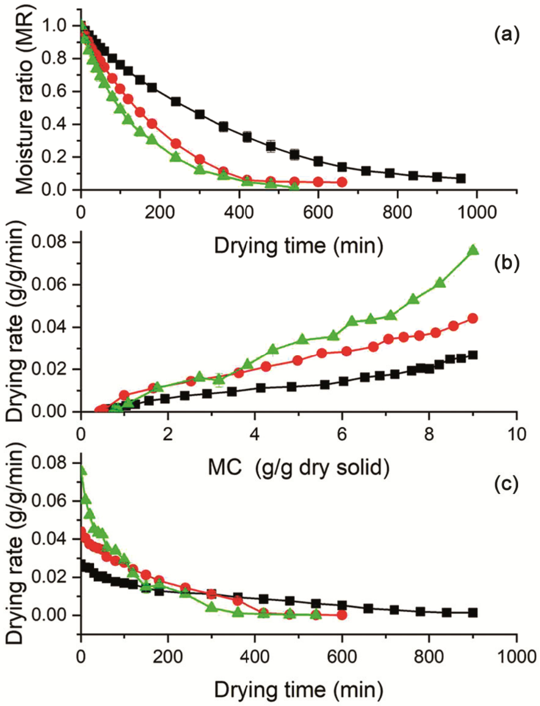

Fig. 2 — Drying of yam slices at 50°C (■), 60°C (●) and 70°C (▲): (a) Moisture ratio (MR) vs. drying time (b) Drying rate vs. drying time, and (c) Drying rate curves of yam slices

observed at 50, 60 and 70°C drying temperature to reach equilibrium moisture content, respectively. Similar trends for drying time were observed in hot air dried *Dioscorea hispda*[11] (11–16 h), and *Dioscorea rotundata and alata*[7] (19–32 hr). At 70°C, the kinetics of heat and mass transport were observed to be faster than at the other two temperatures. Samples drying at 50°C required 50–52% more drying time to attain a moisture ratio below 0.2 compared with 70°C. Similar trends were reported for elephant foot yam and *Dioscorea hispda* yam.[11,21,22]

Drying Rate (DR) was calculated using the moisture content of the sample at a particular time and presented in Fig. 2b and c. The drying rate was continuously decreased with increased drying duration and decreased moisture content. From Fig. 2b, it is clearly visible that, there is no constant drying period in the drying curve, hence drying process was observed to follow the falling rate. As the drying proceeds, increased internal resistance for moisture diffusion results in reduced DR. Similar, falling rate period were observed in yam drying.[11,23] The drying process taking place in two distinct falling periods as shown in Fig. 2b. In the initial falling phase, the DR was higher and relies on the internal and external mass transfer rates. This could be related to the rapid removal of free moisture along the yam slices' surface.[12,15] DR was decreased drastically due to lower sample moisture content in second falling phase. This increased resistance could be attributed due to the reduced porosity caused by progressive shrinkage and cell collapse of samples.[7,24] At 50, 60, and 70°C, the average DR was 0.013, 0.017, and 0.020 (g/g/min), respectively. At 70°C higher heat and mass transfer causes the core moisture to travel from wet areas to the surface, where it is evaporated. This results in a faster drying rate. While in other two temperatures, hot air over the wet surface is unable to supply enough heat for quicker moisture removal. Similar observations were noted in the hot air drying of yam slices.[11,17,22]

In all the drying temperatures, the potassium metabisulfite pretreatment and boiling had significant effect on moisture removal rate due to higher moisture uptake and gelatinization of starch. Moreover, addition of drying time enhances the starch gelatinization process. Further, progressive shrinkage and reduced porosity restrict the water movement.[11,25] The higher resistance for movement of a water molecule from the core wet region to the surface was observed in the sample of 50°C dried samples. As a result, samples dried at 50°C had a longer drying time and a slower drying rate. This is due to the hot airflow over the wet surface of the material, unable to supply enough heat for moisture removal. The findings complement previous work on yam slices.[11]

Effective Diffusivity and Activation Energy

Effective moisture diffusivity is a complex phenomenon involving several factors like liquid and vapor diffusion, material characteristics, and pretreatment. The logarithmic curve of moisture content vs. drying time for hot air drying is shown in Fig. 3b. The effective moisture diffusivity was calculated using the slope of the plot. In hot air drying, effective moisture diffusivity increased with increasing drying temperature and ranges from 4.88×10^{-10} – 8.80×10^{-10} m^2/s. The results are in good agreement with prior research on fruits and vegetables. The moisture diffusivity of food products generally ranged between 10^{-11}–10^{-9} m^2/s.[11] Diffusivity values for hot air-dried sweet potato from 3.66×10^{-10} to 2.11×10^{-9} m^2/s, *Dioscorea alata L.* from 4.77×10^{-10} – 8.90×10^{-10} m^2/s, and *Dioscorea alata L.* 5.5454×10^{-10} – 1.0804×10^{-9} m^2/s.[22,26,27] Higher diffusivity at high temperature (70°C) occurs

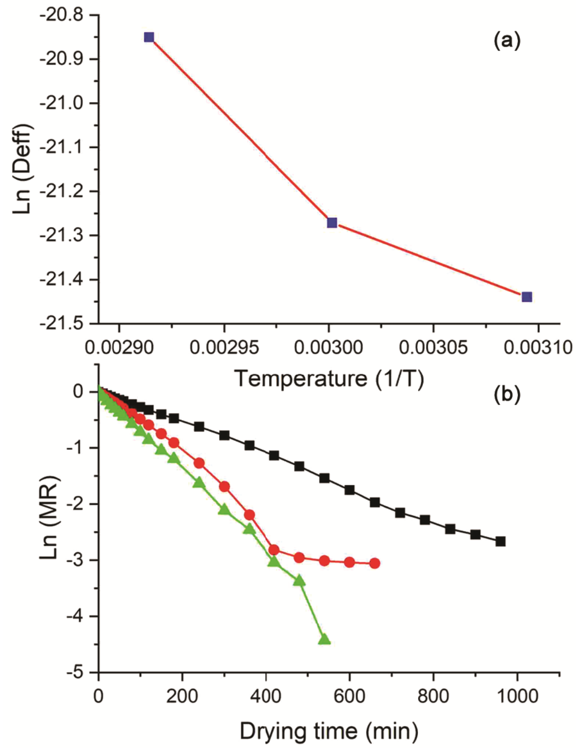

Fig. 3 — (a) Arrhenius plot between ln (Deff) versus 1/T for yam slices (b) ln (MR) Vs time for 50°C (■), 60°C (●) and 70°C (▲)

as a result of overcoming some resistance caused by shrinkage, reduced porosity, and cell collapse. Therefore, drying time is reduced at 70°C as compared with the other two temperatures. In the process of drying or heating, boiling helps water diffusion by removing entrapped air from cell and tissue samples by softening it.[28] Boiling has a detrimental effect on tubers with a high starch content due to gelatinization of starch, forming a resistance film layer.[29] Initially, moisture diffusivity is higher due to available free and surface moisture, and thereby, it decreases slowly and then sharply with low moisture content. Similar behaviors have been observed in the drying of taro and yam.[7,11,30]

The activation energy of a product determines its temperature sensitivity and the amount of energy required to remove the product's moisture content. By plotting ln (D_{eff}) vs. 1/T (K), the activation energy was estimated (Fig. 3a). The linear relationship was found for ln (D_{eff}) vs. 1/T (ln (Deff) = −3252.48427/T ± 4.81714) with a correlation coefficient of 0.93397 indicated a good fit for given temperatures. The activation energy of yam slices was 27.04 (kJ/mol). This observed activation energy value is supported by the previously reported values for *Dioscorea alata* varies from 25.25–46.46 (kJ/ mol)[7], *Dioscorea rotundata* from 41.75–72.47 (kJ/mol)[7], elephant foot yam from 25.18–32.46 (kJ/mol)[21], and in close range with 23.53 kJ/mol for *Dioscorea hispida*.[11] The activation energy for agricultural materials was observed to vary between 12 and 110 kJ/mol depending on the sample size, material characteristics, variety, operation conditions, and pretreatment.[12,15]

Modeling of Yam Drying

The drying process of *Dioscorea pentaphylla* slices is described by comparing actual data to anticipated data from the model applied under the stated drying conditions and presented in Table 2.

The table shows that all the applied mathematical models well explain the drying behavior of *Dioscorea pentaphylla* slices when exposed to hot air temperatures. However, the model with the best fit was selected using statistical values of χ^2, RSS, R^2, and RMSE mentioned in Table 2. The statistical values of χ^2, RSS, R^2, and RMSE varies from −0.0000826732 0.00131, 0.000764–0.02093, 0.99111– 0.99969, and 0.00767 0.03617, respectively for all the models. However, among all the fitted models for hot air drying of yam slices, Hii and others showed the highest R^2 and lowest χ^2, RSS, and RMSE values, and provided the best model. The coefficient of variation at 50–70°C was found to be 0.99969, 0.99955, and 0.99955 for Hii and others model. Therefore, drying behavior of the *Dioscorea pentaphylla* slices could be better explained by using the Hii and others model. This model has been successfully used for predicting the drying behavior of various fruit and vegetable.[15] Followed by the Hii and others model, logarithmic and Avhad and Marchetti model were close-fitted with experimental data. The goodness of fit of these models were comparable with the Hii and others model. However, other models also hold a good prediction rate for experimental data.

The drying constant is an important parameter that can be correlated with the drying process by moisture removal rate constant.[11] The constants for the selected 10 models are presented in Table 3. It was observed that the drying constant (k) increases with hot air temperature. Other constant obtained from model such as k_0, a, b, c, N, and n, varies with hot air temperatures. However, increasing or decreasing trend was not observed for theses parameters for hot air temperatures. A similar remark was conveyed in elephant foot yam and *D hispida* drying.[11,21,22]

Table 2 — Results obtained from the statistical analysis of the ten selected model at 50–70°C temperatures

Model	Temperature (°C)	X^2	RSS	R^2	RSME
Lewis	50	0.000144	0.00347	0.99874	0.01202
	60	0.000464	0.00835	0.99613	0.02154
	70	0.000568	0.00965	0.99437	0.02383
Page	50	0.000116	0.00268	0.99903	0.01079
	60	0.00018	0.00306	0.99858	0.01342
	70	0.000265	0.00424	0.99753	0.01628
Modified page	50	0.000144	0.00347	0.99874	0.01202
	60	0.000464	0.00835	0.99613	0.02154
	70	0.000568	0.00965	0.99437	0.02383
Henderson and Pabis	50	0.00015	0.00345	0.99875	0.01225
	60	0.000404	0.00688	0.99681	0.02011
	70	0.00046	0.00736	0.99571	0.02145
Avhad and Marchetti	50	0.000088975	0.00196	0.99929	0.00943
	60	0.000201338	0.00342	0.99855	0.01419
	70	0.000279549	0.00419	0.99755	0.01672
Midillikucuk	50	0.000373036	0.00783	0.99715	0.01931
	60	0.00131	0.02093	0.99111	0.03617
	70	0.0000947375	0.00133	0.99923	0.00973
Two term	50	0.000138811	0.00305	0.99889	0.01178
	60	0.000458341	0.00688	0.99681	0.02141
	70	0.000393016	0.0059	0.99656	0.01982
Logarithm	50	−0.0000826732	0.00182	0.99934	0.00909
	60	0.000352311	0.00599	0.99846	0.01877
	70	0.000113306	0.0017	0.99901	0.01064
Diffusion Approach	50	0.000151	0.00347	0.99874	0.01229
	60	0.000186	0.00316	0.99866	0.01364
	70	0.000643	0.00965	0.99437	0.02537
Hii and others model	50	0.0000931745	0.00196	0.99969	0.00965
	60	0.000213921	0.00342	0.99955	0.01463
	70	0.0000587818	0.000764	0.99955	0.00767

Validation of Model

The fitting of the experimental data and predicted data of the Hii and others model is described in Fig. 4. From these graphs, it is revealed that the predicted data are banded to and closely around the straight line, which shows the suitability of these models for the prediction of drying behavior of *Dioscorea pentaphylla* slices in all drying temperatures. Various fruits and vegetables have been accurately predicted by the drying behavior predictions of this model.[12] Drying time and temperature-dependent evolution of the drying process for final product characteristics can be well suited to explain the behavior of *Dioscorea hispida* drying.

Color Change of *Dioscorea pentaphylla* Slices

Color is an essential attribute for consumer acceptance and marketability of dried products Browning and shrinkage in the final dried product have a negative impact on acceptance. The color change of final dried products in *Dioscorea pentaphylla* mainly affected by enzymatic browning, non-enzymatic browning, pigment degradation and ascorbic acid oxidation.[11] In drying, color change is directly related to applied temperature and product moisture content and affected the non-enzymatic browning and pigment degradation in the products. Thus, color readings (L, a, and b) were recorded at a specified time intervals during the whole drying process.

The color of fresh-cut *Dioscorea pentaphylla* slices shows white and yellowness in the sample. These tubers contain the highest levels of polyphenol oxidase activity and within a few seconds of peeling and cutting, yam slices turn into dark brown color.[3,5] Therefore, Potassium Metabisulfite soaking and boiling is an important pretreatment was applied to reduce the enzymatic activity in the yam slices. After pretreatment sample shows the appearance of the little darker, greener, and lower yellowish color on the slices. Average color values of L, a and b were reduced by 66.2– 53.35, 6.5–3.2, and 34.1–18.1, respectively. This could be attributed due to the

Table 3 — Model constant obtained by non-linear regression model fitting of the experimental data

Model	Constant	Temperature (°C)		
		50	60	70
Lewis	k	0.00276	0.00523	0.00697
Page	k	0.00231	0.00319	0.01096
	n	1.02982	1.09643	0.90549
Modified page	k	0.0525	0.07231	0.08347
	n	0.0525	0.07231	0.08347
Henderson and Pabis model	a	1.00159	1.01912	0.97317
	k	0.00276	0.00538	0.00667
Avhad and Marchetti	a	0.98455	0.98632	1.00517
	k	0.00184	0.00274	0.01151
	n	1.06535	1.12157	0.89677
Midillikucuk	a	0.96411	0.94777	0.99048
	k	−0.00256	−0.00468	−0.000095
	n	−0.00034	−0.00115	0.00768
	b	1.15995	1.07224	0.98858
Two term	a	1.01448	0.09427	0.04772
	k_0	−0.02199	0.92487	0.95143
	b	0.00276	0.00538	0.05966
	k_1	−0.01269	−0.00538	−0.00654
Logarithm	a	1.03457	1.03703	0.93833
	k	0.00251	0.00505	0.00769
	c	−0.04073	−0.02496	0.05165
Diffusion Approach	a	1.00212	1.1804	1
	b	1	1	1.03
	k	0.00275	0.00793	0.00697
Hii and others model	a	0.000423378	0.49245	0.49222
	b	0.99411	0.49245	0.49222
	k_1	−0.0122	0.00262	0.00183
	k_2	0.00881	0.00262	0.00183
	n	0.95333	1.13043	1.0658

enzymatic activity and component leaching from the sample gives lower reflectance in the sample. Similar trends of color change in L, a and b values were observed for Dioscorea species such as *D. hispida* slices and *D. rotundata*.[11,31] This suggested that pretreatment had a significant color change in yam slices. Drying temperature and pretreatment implicitly affected the color change of final dried products. Color values of L and b decreased with increasing drying time and temperature at all three temperatures and presented in Fig. 5a and c. For a values first increase then decrease at 50 and 60°C, while increase in a value at 70°C drying temperature were observed and presented in Fig. 5b.

The lightness of the sample is represented by the L value, which is a browning indicator.[19] The sample lightness was reduced at all drying temperatures as the moisture content was gradually removed from the sample with increasing temperature and drying time. The lightness of sample at 50, 60 and 70°C drying temperature was reduced from 54.55 to 20, 54.70 to 17.56, and 54.45 to 14.6, respectively (Fig. 5a). More

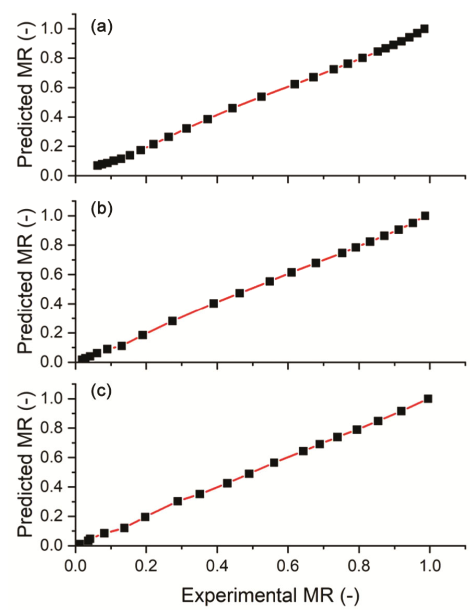

Fig. 4 — Predicted moisture ratio by Hii and others model versus experimental moisture ratio of the yam slices at the drying temperatures of (a) 50°C (b) 60°C and (c) 70°C (■) predicted moisture ratio and (▬) regression line

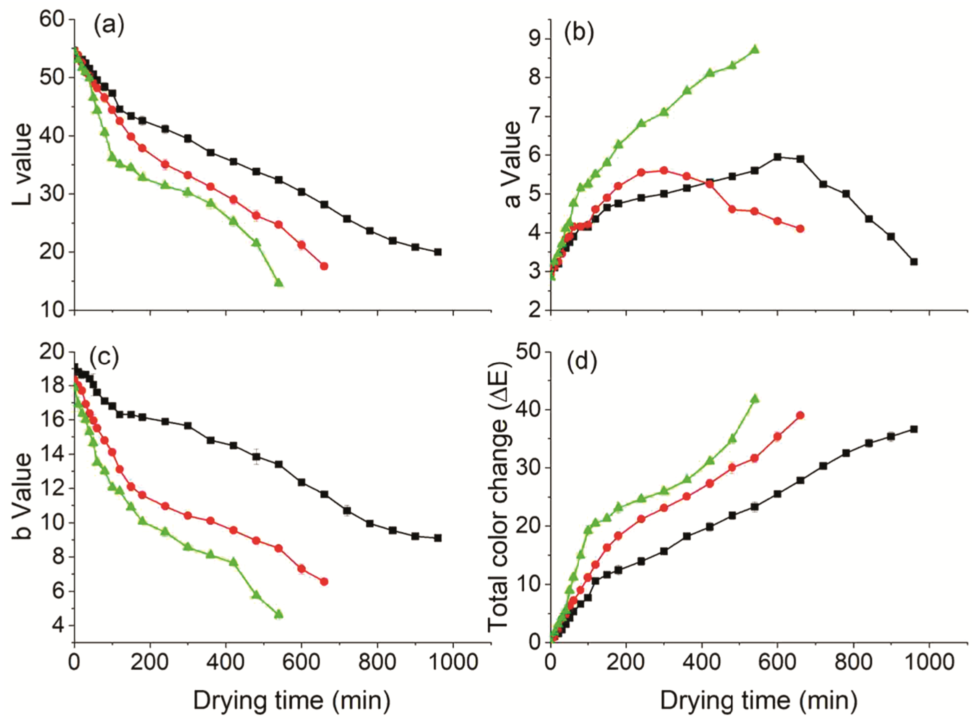

Fig. 5 — Kinetics of change in the color characteristics: (a) L value, (b) a value, (c) a value and (d) total color (ΔE) of yam slices as a function of drying time at 50°C (■), 60°C (●) and 70°C (▲)

darkness was observed in sample dried at 70°C and 73–88 % higher lightness in sample dried at 50°C as compared with the other two temperatures. This could be due to non-enzymatic browning and variations in starch gelatinization clarity characteristics in the product.[32] A similar pattern of decreases in lightness values was observed in hot air drying of chinese yam[33], elephant foot yam[21], *D. rotundata*[25], and *D. hispida*[11].

Similarly, the change in a value at 50, 60 and 70°C drying temperature were 2.95–3.25, 2.90–4.10, and 2.85–8.7, respectively (Fig. 5b). The increase in a value at 50 and 60°C drying temperature was observed when the moisture content of the sample was in the range of 0.005–0.011 g/g dry solid, respectively and there after decrease in color values were observed. A gradual increase in a value was observed during the initial drying period. After removal of major moisture from the product, the color values were decreased due to lower reflectance. While sample dried at 70°C shows increase in a value from 2.85 to 8.7. This increase in a value at 70°C attributed due to higher temperature leads to increased rate of millard reactions in the sample. Similar trends were observed in Chinese Yam[33], elephant foot yam[21], apple[34] and banana.[35]

The change in b value at 50, 60 and 70°C drying temperature were from 19.10 to 9.10, 18.35 to 6.55, and 17.9 to 4.6, respectively (Fig. 5c). The yellowness of samples decreased in all drying temperatures. A higher reduction was observed in 70°C followed by 60°C and 50°C. The presence of yellowness is due to the carotenoid in the sample.[36] The decrease in b value might indicate the degradation of carotenoid in the sample which leads to darker brown color in the sample.[17] The intensity of darker brown color was increased from 50 to 70°C (Fig. 1b). Similar trend of decrease in b value was reported in *Dioscorea rotundata*[27], dates[20], pumpkin[37], sweet potato[23] and banana.[35]

The value presents higher variation as compared with L and b values, indicating the uneven browning on yam slices. This might be due to the uneven distribution of polyphenol compounds and nonenzymatic browning in the samples. Browning degree of samples shows increasing order of 50°C < 60°C < 70°C in the drying conditions (Fig. 1b). This variation in the browning of samples occurs due to polyphenol oxidation, nonenzymatic browning, and caramelization.[34] At the initial drying, the polyphenol oxidase activity initiated and resulted into decreased in L and b values and an increase in a value.[34,38] Color values (L, a and b) were more affected by drying at higher drying temperature (70°C). The total color change (ΔE) represents the overall extent of the color variation among raw and dried samples and presented in Fig. 5d. The total color change was increased with hot air temperature (50–70°C) and varied between 36.63 and 41.71. The lower color change was observed for 50°C compared with the other two hot air-drying temperatures. Thermal degradation and non-enzymatic browning contribute to the darkening of the slices after drying.[20] For each drying temperature, the chroma, hue, and browning index are displayed in Fig. 6 a-c.

The term chroma refers to the saturation or purity of a color and is related to its intensity. The product's chroma dropped with each of the temperatures, following b values. The chroma values ranged from 7.73–9.85; however, the chroma value was higher at 70°C and lower at 60°C.[18] Chroma value varies significantly for fresh and dried products and among three different temperatures. Increased chroma values indicate a darker shade of black brown in the sample.[20] In terms of visual appearance, the hue angle (α°) is the most prominent color appearance, and a single numerical value expresses it. Hue value was

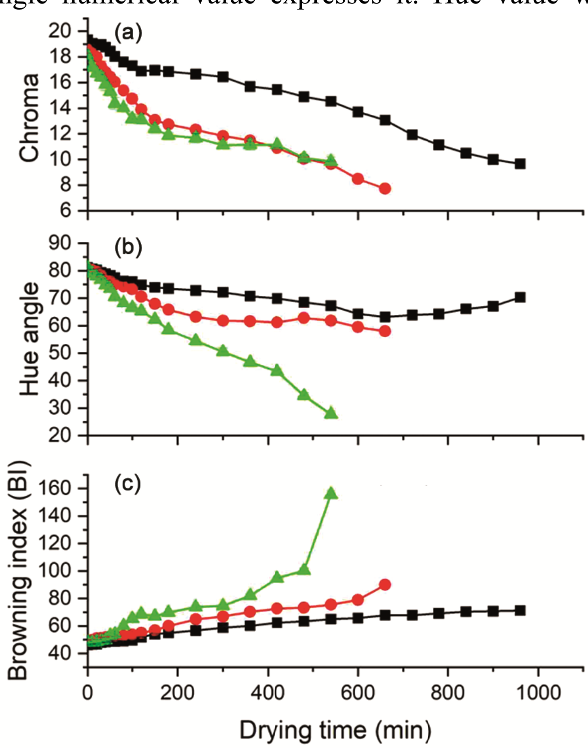

Fig. 6 — Kinetics of change of the (a) Hue (b) Browning index and (c) Chroma value of yam slices as a function of drying time at 50°C (■), 60°C (●) and 70°C (▲)

reduced from 81.22 to 70.34, 81.02 to 57.96, and 80.95 to 27.74 for 50, 60, and 70°C drying temperature, respectively, showing a variation in color tone to a red appearance on the dried yam surface. Many researchers have made comparable findings.[37,39,40] The browning index was used to determine the purity of the brown look in dried slices.[40] The range of the browning index lies between 71.21–155.72 and has intensified significantly with increased temperature and drying time. Drying at 70°C shows higher browning in the final products (Fig. 1b). The current study is in line with some earlier color kinetics studies.[19,39,41]

Color Kinetics of *Dioscorea pentaphylla* Drying

Four-color kinetics model were used to understand the color kinetics behavior of *Dioscorea pentaphylla* slices during the drying process. The fitted experimental data was analyzed using nonlinear regression analysis. The optimal color kinetics model was chosen using statistical parameters such as R^2, χ^2, and RMSE, and is provided in Table 4. From this table, it evident that the R^2 value for zero, first, fraction and modified color model varied from 0.193–0.983, 0.171–0.988, 0.627–0.996, and 0.888–0.996, respectively.

For L values, the R^2 values varied from 0.887–0.995 for all temperatures. Fraction model can give best fitting of L values for samples dried at 50, 60 and 70°C. The highest R^2 value for fraction model (50, 60 and 70°C) were 0.98944, 0.99505, and 0.94971, respectively. Similarly, chi square values varied from 1.37878–7.86758. For a values, modified color model gives best fitting for experimental data and gives highest the R^2 (0.94217–0.991) and lower chi square values (0.05115-0.06614). Followed by, modified model, fraction model shows well-fitting to the experimental data. Zero and first order model shows poor fitting of experimental data due to the increase and decrease in a value of sample during the drying process. For b values, Faction model can give best fitting of b values for samples dried at 50 and 60°C. While modified color model can give best fitting for 70°C. The highest R^2 value for fraction color model (60 and 70°C), and modified model (50°C) were 0.9813, 0. 0.98259, and 0.97707, respectively. All the model shows best fitting to the experimental b values.

Total color change was well explained by fraction color model followed by modified color model. The R^2 values in fraction model at 50, 60 and 70°C drying temperature were 0.99082, 0.98916, and 0.95531,

Table 4 —Non-linear regression analysis results of colour parameters from four selected model at 50–70°C temperatures

Drying temperature (°C)	Parameter	Model 1 (Zero order)			Model 2 (First order)			Model 3 (Fraction model)			Model 4 (Modified color model)		
		$\chi2$	R^2	RSME	$\chi2$	R^2	RSME	$\chi2$	R^2	RSME	$\chi2$	R^2	RSME
50	L	2.679	0.979	1.637	1.319	0.989	1.149	1.379	0.989	1.174	1.549	0.988	1.245
	a	0.682	0.193	0.826	0.701	0.171	0.837	0.330	0.627	0.574	0.051	0.942	0.226
	b	0.194	0.981	0.441	0.253	0.976	0.503	0.411	0.960	0.641	0.203	0.981	0.451
	ΔE	3.042	0.980	1.744	16.418	0.891	4.052	1.444	0.991	1.202	1.606	0.990	1.267
	Chroma	0.203	0.979	0.451	0.322	0.967	0.568	0.365	0.963	0.604	0.186	0.982	0.431
	Hue angle	7.451	0.789	2.730	9.271	0.858	3.045	2.782	0.924	1.668	1.756	0.952	1.325
	BI	3.227	0.962	1.796	5.110	0.940	2.261	0.299	0.996	0.547	0.331	0.996	0.576
60	L	5.129	0.964	2.265	1.756	0.988	1.325	1.485	0.995	1.219	2.108	0.986	1.452
	a	0.538	0.226	0.734	0.555	0.203	0.745	0.176	0.761	0.420	0.064	0.913	0.253
	b	1.457	0.901	1.207	0.754	0.949	0.869	0.272	0.983	0.522	0.582	0.963	0.763
	ΔE	6.682	0.957	2.585	22.506	0.856	4.744	1.797	0.989	1.340	2.690	0.984	1.640
	Chroma	0.975	0.918	0.987	0.586	0.951	0.766	0.114	0.985	0.338	0.503	0.960	0.710
	Hue angle	10.985	0.832	3.314	9.271	0.858	3.045	1.253	0.982	1.119	2.781	0.960	1.668
	BI	3.374	0.977	1.837	3.843	0.974	1.960	6.628	0.955	2.574	3.566	0.977	1.888
70	L	16.529	0.887	4.066	10.424	0.929	3.229	7.868	0.950	2.805	11.218	0.928	3.349
	a	0.259	0.929	0.509	0.464	0.872	0.681	0.038	0.990	0.194	0.066	0.991	0.257
	b	1.454	0.912	1.206	0.647	0.961	0.804	0.406	0.977	0.637	0.691	0.961	0.832
	ΔE	17.806	0.889	4.220	33.213	0.793	5.763	7.635	0.955	2.763	11.437	0.933	3.382
	Chroma	1.426	0.798	1.194	1.092	0.845	1.045	0.114	0.985	0.338	0.503	0.960	0.710
	Hue angle	4.444	0.983	2.108	3.810	0.986	1.952	3.623	0.987	1.903	3.793	0.987	1.948
	BI	120.338	0.839	10.970	3.843	0.974	1.960	152.927	0.796	12.366	89.442	0.888	9.457

respectively. Chroma and Hue were well described by fraction model for sample dried at 50 and 60°C and modified color model for sample dried at 50°C. While browning index was poorly fitted with Fraction, modified color and first order model for 50 and 60 and 70°C, respectively. The value of $\chi2$ for BI is high due to the sample data does not fit the expected values very well. After 200 minutes of drying, more change in BI values was observed; therefore, model is not fitted well with BI of experimental data.

Among these models, modified color followed by fraction model best fitted with color parameters with high R^2 and lower chi square. Zero order and first order are mainly popular in colour kinetics but in this study these two models are not well fitted with experimental data. The results are in agreements with previous studies on color kinetics.[18,20,40] Model constant values signifies the color change pattern at different temperature levels and exhibited in Table 5. The drying constant is an important parameter that is linked to the sample moisture removal rate. From Table 5, it is noted that the drying constant (k) varies and increases with hot air temperatures. An analogous study has been recorded in yam drying.[11]

Rehydration Capacity

For dried products, rehydration is an important quality indicator. The rehydration ratio for different hot air temperatures was presented in Table 6. The rehydration for hot air drying at 50, 60 and 70°C were 2.68, 3.01 and 3.11, respectively. Rehydration ratio increases with drying temperatures. However, there was no significant difference between sample dried at 60°C and 70°C. The rehydration properties of samples are connected with the structural properties of samples. The higher rehydration ratio depicted that uptake of moisture through capillary was high and strongly correlated with porosity and cavities of the microstructure of the sample. Higher temperature had a more void and porous structure thus showing high rehydration ability. Moreover, the chips dried with 50°C show collapsed cells with lower and uneven pore structures, thus showing lower rehydration ability. Similarly, type of trend was observed in FIR and heat pump dried Chinese yam[33] and hot air-dried *Dioscorea hispida* slices.[1]

Textural Properties

Textural properties of foods are important quality attributes as these traits influence consumer preference.[42] The drying methods significantly affected the hardness and crispiness of the *Dioscorea*

Table 5 — Model constant obtained by non-linear regression analysis results of colour parameters of the experimental data

Drying temperature (°C)		Model 1 (Zero order)		Model 2 (First order)		Model 3 (Fraction model)			Model 4 (modified color model)		
		C_0	K_0	C_0	K_0	C_0	C_f	K_0	C_0	A	B
50	L	51.646	0.036	53.057	0.001	53.120	1.757	0.001	52.834	0.000	−0.001
	a	4.013	−0.001	4.075	0.000	2.857	5.014	0.011	3.154	0.000	0.003
	b	18.487	0.010	18.741	0.001	18.941	7.106	0.001	18.486	0.000	−0.001
	ΔE	3.205	0.037	7.415	0.002	1.610	58.455	−0.001	1.880	0.000	0.027
	Chroma	18.904	0.009	19.105	0.001	19.148	2.952	0.001	18.732	0.000	0.000
	Hue angle	78.032	0.016	77.455	0.001	81.019	65.116	0.004	80.626	0.000	−0.001
	BI	48.121	0.028	48.872	0.000	45.751	75.602	−0.002	46.280	0.000	0.001
60	L	51.172	0.053	53.120	0.002	53.883	10.812	0.002	53.176	0.000	−0.002
	a	3.955	−0.002	4.008	0.000	2.754	4.945	0.016	3.173	0.000	0.004
	b	16.500	0.017	17.213	0.002	18.277	7.181	0.005	17.577	0.000	−0.002
	ΔE	4.039	0.055	8.219	0.003	0.845	43.905	−0.003	1.737	0.000	0.051
	Chroma	17.002	0.015	17.503	0.001	17.994	10.466	0.009	17.801	0.000	−0.002
	Hue angle	76.867	0.033	77.455	0.001	81.873	59.242	0.006	80.138	0.000	-0.001
	BI	49.432	0.054	50.394	0.001	47.414	94.238	−0.002	49.520	0.000	0.001
70	L	49.146	0.064	51.584	0.002	54.398	18.670	0.005	52.025	0.000	−0.002
	a	3.791	0.010	4.127	0.002	3.238	9.302	−0.004	3.270	0.000	0.006
	b	15.665	0.022	16.594	0.002	17.357	4.984	0.005	16.719	0.000	−0.002
	ΔE	5.946	0.067	9.803	0.003	0.295	37.550	−0.005	2.820	0.000	0.043
	Chroma	15.888	0.013	16.248	0.001	17.994	10.466	0.009	17.801	0.000	−0.002
	Hue angle	77.845	0.091	80.005	0.002	79.216	−35.070	0.001	78.951	0.000	−0.001
	BI	45.390	0.141	50.394	0.001	43.119	174.176	−0.001	52.484	0.000	0.000

pentaphylla slices (Table 6). In hot air-dried sample, hardness was decreased with hot air temperature and varies from 32.37 to 50.31 N. However, there was not significant difference found between 50 and 60°C-dried samples. Similar type of decreases in hardness (127.39–97.85 N from 40–70°C drying temperature) was observed in hot air-dried elephant foot yam.[21] Similarly, crispiness of sample decreased with hot air temperature and varied from 47.07−94.08 N/mm. For crispiness, there was significant difference between all temperatures. The number of peaks during texture analysis for sample dried at 50, 60 and 70°C were 5.3, 4.6, and 2.6, respectively while reaching to zero point. Compare with 50 and 60°C, hardness, crispiness and number of peaks were significantly reduced for sample dried at 70°C, which indicates crispier pentaphylla slice. A similar type of trends was observed in ultrasound assisted far infrared dried potato slices[43]. Work done is the amount of energy necessary to break the strength of a sample's internal bonds. The work done was decreased with increased temperature varied between 0.037−0.043 (J). No significant difference was found for work done. The samples dried at 50°C had a higher energy and work output. A similar textural trend was observed in hot air-dried elephant yam[21], pumpkin and green pepper.[16]

Effect of Drying Temperature on the Microstructure

During drying, material experiences stress due to temperature and moisture gradient causing alteration in cell structure. Therefore, it is important to understand the structural changes that occurred during the drying process. The effect of drying temperature was explained by SEM micrographs of dried yam slices presented in Fig. 7. The images represented the cell structure of polygonal and polyhedron shape and different size starch granules.

From the Fig. 7, it is clearly evident that sample dried at 70°C had larger voids with connected cell structure as compared with other 2 temperatures. Samples dried at 50°C had flattened cell with lower num and uneven pore structure. The compact structure was observed in sample dried at 50°C due to contraction along with removal of water, but such compactness in structure obstructs the outward diffusion of internal moisture. This collapse of cell structure in hot air dried was due to higher drying time and prolonged thermal destruction caused shrinkage in the samples. The void size is increased with hot air-drying temperatures. The larger voids in the samples helps in higher effective diffusivity, evaporation rate, and faster drying. A similar type of trends was observed in sweet potato[23], and kiwi fruits by Zeng *et al.*[44]

Table 6 — Textural and rehydration characteristics of hot air-dried pentaphylla slices

Treatment	Hardness (N)	Crispiness (N/mm)	Number of peaks	Work done (J)	Rehydration ratio
50°C	50.31 ± 17.11^b	94.08 ± 15.27^c	5.3 ± 2.2^a	$0.0\ 43 \pm 0.018^a$	2.68 ± 0.19^a
60°C	47.60 ± 15.94^b	73.50 ± 19.37^b	4.6 ± 2.6^b	0.041 ± 0.019^a	3.01 ± 0.07^b
70°C	32.37 ± 6.78^a	47.07 ± 8.82^a	2.6 ± 1.8^b	0.037 ± 0.009^a	3.11 ± 0.09^{ab}

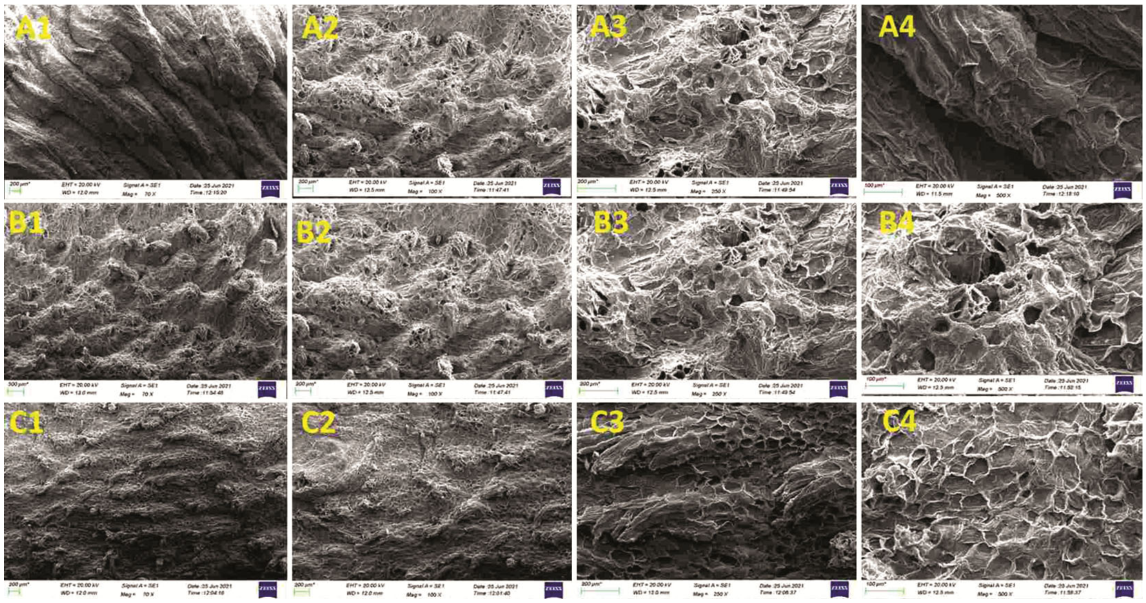

Fig. 7 — SEM (70x, 100x, 250x and 500x magnification) of Dioscorea pentaphylla slice by hot air drying at 50°C (A1, A2, A3 and A4), 60°C (B1, B2, B3 and B4), and 70°C (C1, C2, C3 and C4)

Conclusions

This research work revealed that the study of the drying behavior is important for optimizing the drying rate, drying time and other quality parameters of *Dioscorea pentaphylla* slices. It was observed that the boiling and potassium metabisulfite ($K_2S_2O_5$) had significant effect on moisture diffusion and color changes. All models revealed strong correlations for statistical parameters and a good match to experimental data. However, the Hii and other models showed a high value of R^2 and low value of χ^2, RMSE, and RSS values. The drying behavior of yam slices during convective drying may thus be predicted using this Hii model and other models. Similarly, for the prediction of color changes during convective drying, Fraction kinetics model can be used as it proved to best fit among all the color models. Hot air temperatures and time affected the texture, microstructure, and rehydration. Both the hardness and crispiness decreased with time, while the rehydration ratio increased. This work presented a brief idea for production of dried yam slices for long-term storage and food value application using convective dryer. However, in depth studies regarding effect of drying time and temperature on the nutritional properties, phytonutrients and other techno-functional properties of dried yam slices or flour can be studied in the future to get a detailed insight of *Dioscorea pentaphylla* to produce high-quality dried slices for long-term preservation and high-end applications in the food and pharmaceutical sectors.

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