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Research Article

Mathematical Modeling of Infra-red Drying of Mango-Sweetpotato Leathers

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Abstract: Infra-red drying has in recent times been of use due to the potential for obtaining quality dried foodstuffs. To reduce losses associated with mangoes and sweet potatoes, infra-red dryer was employed in drying mango-sweetpotato leather. Cured sweetpotatoes were dextrinized in an oven and the edible portion removed and homogenized to obtain slurry. The slurry was added to mango puree in various proportions and dried in an infra-red dyer for 45, 50 and 55 ^oC for 1, 1.5 and 2 h with different tray loads of 100, 150, 200 g to study the drying characteristics using the infra-red dryer. The values obtained were fitted to four thin layer drying models. The effect of dextrinized sweetpotatoes on the drying characteristics of infra-red dried leathers has been investigated. Generally, all the drying processes occurred in the falling rate period. The Henderson and Pabis model best described the thin layer drying characteristics of infra-red dried mango-sweetpotato leathers. The high k_o values of 4.032×10^6, 4.20×10^6 and 4.342×10^6 (h^{-1}) show low resistance to moisture loss. Based on k_o and E_a values, the suitable temperature for drying mango-sweetpotato leathers is 50 ^oC.
Keywords: infra-red dryer, drying characteristics, dextrinization, mathematical models, mango sweetpotato

INTRODUCTION

Sweetpotatoes and mangoes are not stable in storage due to high moisture content. Mangoes (*Magnifera indica*) have shelf life of 3 to 4 weeks in good condition at low temperature of 10-12 ^oC (FAO, 2009). Some constraints of post harvest products of fruits are related to the perishable nature of the fruit [1] and their condition and market life are highly affected by temperature, humidity and the composition of the atmosphere. Also, for many indigenous tropical starch crops as sweetpotatoes, the lack of competitive market access has become the major obstacle to their contribution to agricultural development. Alternative use for mangoes and sweet potatoes is therefore necessary for a growing economy like Ghana's.

Drying is the major food processing operation to increase the shelf life of agricultural produce [2] such as mangoes and sweetpotatoes. Drying of food products does not only affect the water content on the product, but also alters other physical, biological, and chemical properties such as enzymatic activity, microbial spoilage, crispiness, viscosity, hardness, aroma, flavour and palatability of foods [3]. When fruit pulps are dried on a flat surface in a dryer or under direct sunlight, fruit leathers are produced [4].The purpose of drying fruit pulps is to produce a stable and easily handled product which will yield maximum quantity for the least volume, improve shelf life, reduce packaging costs, lower shipping weights, enhance appearance, and maintain nutritional value [4]. According to Natalia *et al.*[4]. sucrose or glucose syrup is added to increase sweetness and solids content. Sweetpotatoes was used to serve this purpose in this work.

Over the years, drying of fruit leathers is accomplished by oven, solar and electric cabinet dyers. These conventional processes are known to cause partial destruction of quality attributes of food products, especially heat-labile nutrients, and sensory attributes. A new drying technology, infra-red drying, has therefore been used in this study. This technology is known as a potential method for obtaining high quality dried foodstuffs such as fruits, vegetables, and grains [6-7]. It has higher energy efficiency, shorter drying time, and a better final product quality when compared with convective drying methods[8].

In drying, mathematical modeling and simulation of drying curves under different conditions is important to obtain a better control of this unit operation and an overall improvement of the quality of the final product [19]. Mathematical models are often used to study the variables involved in the process, predict drying kinetics of the product and to optimize the operating parameters and conditions [9].

A considerable amount of data has been reported in literature regarding the thin layer drying modeling of various agricultural products (fruits and vegetables) but no information is available on infra-red drying of fruit leathers. Hence the objective of this study was to determine the drying characteristics of infra-red dried mango-sweetpotato leathers and find the mathematical model that best describes the drying behaviour.

Table 1. Thin layer drying curve models

Model name	Model	References
Newton	$MR = \exp(-kt)$	(Henderson, 1974)
Page	$MR = \exp(-kt^n)$	[20].
Wang and Singh	$MR = 1+at+bt^2$	Wang and Singh [21].
Henderson and Pabis	$MR = a\exp(-kt)$	[22].

MR is the moisture ration; a k, t n, b, t are constants

MATERIALS AND METHODS

Materials

Sweetpotatoes (Faraa variety) were obtained from the Kumasi Central Market. Freshly harvested mangoes (Keitt variety) were obtained from the mango plantation of the Faculty of Agriculture, Kwame Nkrumah University of Science and Technology.

Sample preparation

The sweetpotatoes were wrapped in black polythene bags and exposed to full sunshine for five days to increase amylolyic activity. The sweetpotatoes were then baked in an oven for 2 h, 2.5 h and 3 h at 150-220 ºC to convert the starch to dextrins. The edible portion was scooped with a knife after cooling to 30 ºC. Approximately 200 g of scooped sweetpotato was homogenized in a laboratory blender (Philips Co. Ltd. model HR2021) with 20ml distilled water to obtain slurry with good consistency at high speed for 2 min. The slurry obtained was added to mango pulp for drying following the experimental design in Table 2.

Description of the infra-red dryer

A laboratory type catalytic infra-red (CIR) emitter, the Bruest Flameless Gas Infrared Catalytic Heater (Catalytic Industrial Group, model SR-12) with starter volt of 120 and fuel input of 5000 BTU was used in this research. In this study, natural gas was used as energy source after the IR emitter was powered with electricity for 15 min. The wavelength and total emitted energy was controlled by varying the gas supply to adjust the temperature of infrared emitter/heater. Temperature of drying was determined using a thermocouple.

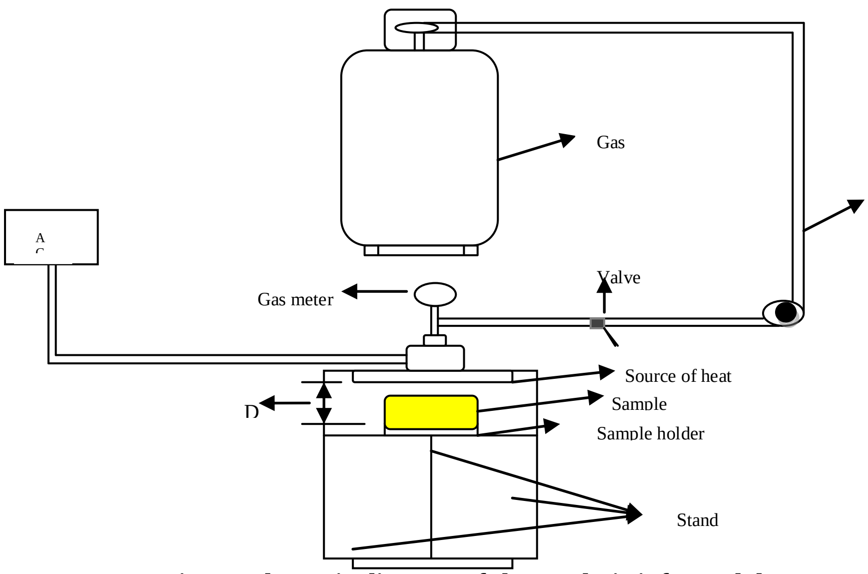

Fig-1: Schematic diagram of the catalytic infra-red dryer

AC: alternating current; D: distance between source of heat and sample

Development of mango- sweetpotato leather

The mango puree and the sweetpotato mash were mixed to obtain a homogeneous mixture of 10, 20 and 30% dextrinized sweetpotatoes. The mixture was poured into aluminum trays of dimension 7 mm×7 mm which had previously been washed, dried and coated with glycerol. Drying was done in triplicates and the change of sample mass due to moisture loss was recorded at every 15min interval for the first one hour, and every thirty min during the remainder of the drying test. Drying was continued until there was no change in mass of sample. After each test, the sample was oven dried at 103±2 ºC to determine the final moisture content. From the experimental data, drying curves were developed.

Drying process

The initial and final moisture contents of the leather were determined using the Official Methods of Analysis [10]. The moisture loss from the sample at a definite time was determined using the equation:

$$Mi = \frac{Wo\,(1-Mo)}{Wt} \times 100$$

where,

M_i= Moisture content at the i-th time, (%)
M_o = initial moisture content, decimal.
W_o = initial weight of the sample (g)
W_t =weight of sample at i-th time (g)

Mathematical modeling of thin layer drying curves

The moisture ratio (MR) of leathers during drying experiments was calculated using the equation,

$$MR = \frac{(Mt-Mo)}{(Mo-Me)}$$

where,

M_t= the moisture content at any time (% db)
M_e = the equilibrium moisture content (% db)
M_o= the initial moisture content (% db)

The values of M_e are relatively small compared to those of M_t or M_o, hence the error involved in the simplification is negligible [11]. Hence MR = M_t/M_o. In order to determine the drying model, drying curves were fitted to four thin layer drying models (Table 1). The best of fit was determined using three parameters: higher values for coefficient of determination (R^2), and the lowest value for reduced sum square errors (SSE) and root mean square error (RMSE).

$$R^2 = 1-\left[\frac{\sum_{i-1}^{N}(\text{MR per .i}-\text{MR exp .i})2}{\sum_{i-1}^{N}(\text{MRper } -\text{MRexp .i})2}\right]$$

$$SSE=\frac{\sum_{i-1}^{n}(\text{MRexp .i}-\text{MRpre .i})2}{N}$$

$$RMSE=\left[\frac{1}{N}\sum_{i-1}^{n}(\text{Mexp}-\text{Mpred})\right]^{1/2}$$

where,

MRpred is the predicted moisture ratio
MRexp is the experimental moisture ratio
N is the number of observations and
M is the number of constants

Activation energy

The correlation between the drying conditions and the determined values of the drying rate constant (k) was expressed using an Arrhenius type equation [12]. In order to obtain the magnitudes of the coefficients of the equation, the values of In k were plotted against 1/T. The activation energy was then calculated from the slope of the straight line (E/R), while the intercept was equal to In k_o.

$$k_o=A\exp^{(-E_a/RT)}$$

Experimental design and statistical analysis

A completely randomized design was used to determine the effect of dextrinized sweetpotato puree on the drying characteristics of fruit leathers. The ranges in Table 2 were determined from preliminary studies and analysis of results was done using Microsoft Excel and Minitab Software.

Table-2: Summary of experimental design

Factor	Levels
Temperature (**ºC)**	45, 50 and 55
Dextrinized sweetpotato (**%)**	10, 20 and 30
Tray load (g)	100, 150, 200

RESULTS AND DISCUSSION

Drying characteristics of infra-red dried mango-sweetpotato leather

The measurement of the material moisture content, as a function of time, under different drying temperatures resulted in drying curves. The drying curve of fruit leathers in Fig. 2 shows the moisture content decreased with increased drying time. It has been shown that during the drying process, water evaporation is achieved when internal mass transfer occurs with liquid diffusion, vapour diffusion, and capillary forces in the interior region of the product [13].

Fig. 2 also shows the effectiveness of increasing the drying temperature in accelerating the dehydration of sample. From the graph, the temperature of drying had significant effect on the drying time. The results obtained in terms of temperature effect on moisture loss agree with thin layer drying of garlic slices by Madamba et al.[12] and bell pepper by Taheri-Garavand et al.,[14]. At a constant tray load of 100 g, it can be observed that the time needed to reach equilibrium moisture content was reduced with increase in temperature.

Unbound water is removed during the constant rate period of drying when the nature of the food does not have a great effect on the drying process. According to Okos et al.,[3] and Slade L *et al* [24] bound water refers to water that exhibits a lower vapour pressure, lower mobility, and greatly reduced freezing point than pure water. Bound water molecules have different kinetic and thermodynamic properties than ordinary water molecules. In drying, only the physically held water is removed. From Fig. 3 the slow and slightly uneven nature of the curve for 45 °C could be attributed to low mobility of water due to lower energy of water molecules when compared to samples dried at 50 °C and 55 °C.

However, the shape of the drying curve in the falling rate stage depends solely on the mechanism of internal water transfer [15]. Significant difference existed between temperatures 55 °C, 50 °C and 45 °C but not 50 and 55 °C at $P<0.05$. The temperature 50 °C was therefore chosen for drying leathers for subsequent analyses. This temperature when used by processors will ensure complete drying of leathers around 2 h 10 min with final moisture content of about 14 % (db).

Drying behaviour of mango puree with 10-30% dextrinized sweetpotato at 50°C

From Fig. 3, increased incorporation of dextrinized sweetpotato slightly reduced the rate of moisture loss although the initial moisture content was approximately the same (80 % wet basis). The rate of drying in leathers with 10% sweetpotato was highest and 30% was least. This implies that internal granular organization, amylose content and molecular weight which affect gelatinization could also have influenced the drying process[25]. Notwithstanding, no significant difference was observed $p<0.05$. Generally, all the drying processes occurred in the falling rate period as have been reported for different crops [14, 16].

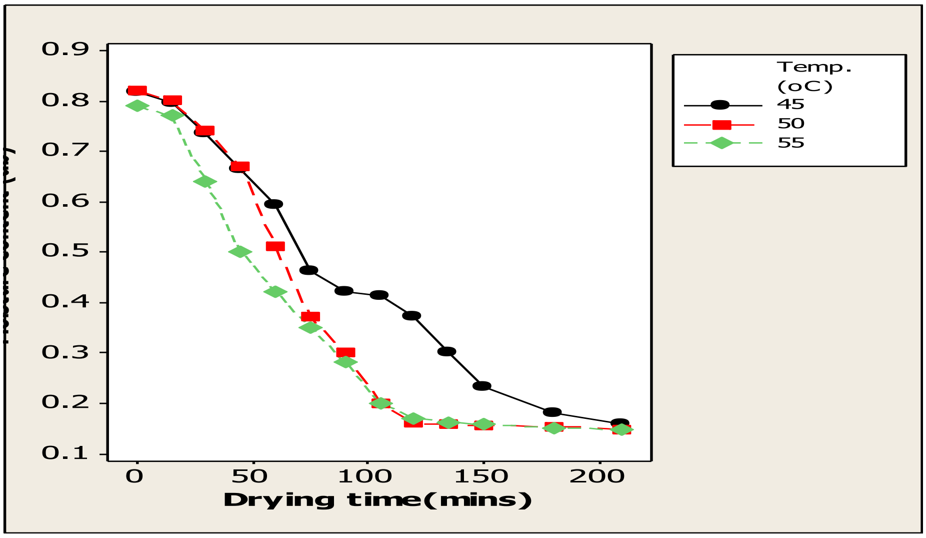

Fig- 2: Effect of drying temperature on drying rate of mango-sweetpotato leather

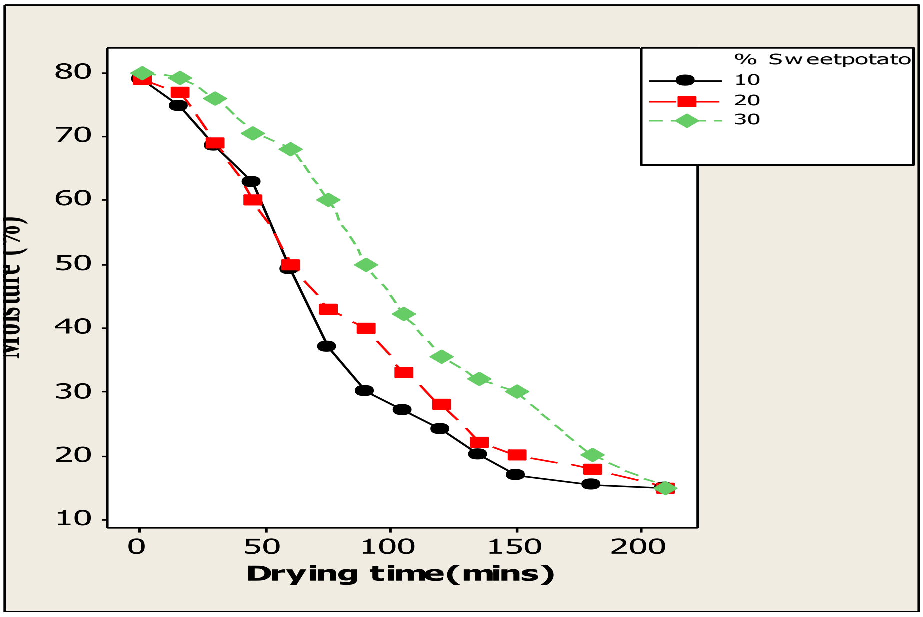

Fig-3: Effect of dextrinized sweetpotato on drying rate of leathers

Fitting the model

The moisture ratio calculated from the drying data at different temperatures and tray loads was fitted to four thin layer models Table 3. The statistical regression analysis of data obtained from the moisture ratios showed the model constants or coefficients k, n, a, and b. The best model was selected based on the highest R^2 and lowest χ^2 and RMSE values. From Table 3, the R^2 values were high and ranged from 0.769-0.924 for all the models except for Wang and Singh model which had lower values (0.21291-0.34503). The R^2 value serves as a measure of the closeness of the relation to linearity while RMSE and χ^2 represent the deviation between the predicted and the experimental values [17].

The Newton and Page models slightly fit the drying characteristics of the leathers for 55°C and 50 °C respectively with R^2 values of 0.988 and 0.9108; χ^2, 2 0.03532 and 0.01643 and RMSE of 0.10095 and 0.25946. Coefficients of determination (R^2) higher than 98% indicate a good adjustment of the model [12]. According to Drapper and Smith [18] and Panchariya *et al*.[17]. the RMSE value is inversely proportional to the capacity of the model when describing the allegiance of the phenomenon. However the Newton and the Page models could not predict the drying characteristics at low temperatures. Considering this criteria, the Henderson and Pabis model was found to be adequate with highest R^2 values for all the drying temperatures and least χ^2 and RMSE.

The Henderson and Pabis model was developed based on the approximation that diffusion controls the drying process[23]. The coefficient a, from the Henderson and Pabis model depends of the shape of the sample. The obtained a-values for all the three temperatures were observed to be not significantly different (p>0.05). The results correspond to the present study's assumption that at each temperature, the size and shape distribution of the samples were uniform. The drying constant k characterizes the rate of moisture removal from the material per unit time. The summary of the best fit model has been outlined in Table 3.

Table-3: Drying models and their coefficients, R^2, chi-square (χ^2) and root mean square error (RMSE) values for leathers with 30% sweetpotato dried at different temperatures.

odel	Temperature	Coefficients	R^2	SSE (χ^2)	RMSE
Newton	45	k=0.0695	0.7817	0.04235	0.50333
	50	k=0.0958	0.7695	0.04511	0.44217
	55	k=0.3265	0.9242	0.03532	0.25946
Henderson and Pabis	45	k=0.0958 a=1.0924	0.9686	0.03727	0.19569
	50	k=0.085 a=1.1379	0.9922	0.02504	0.16873
	55	k=0.1758 a=1.1923	0.9883	0.02135	0.19103
Page	45	k=0.9448 n=3.0603	0.8958	0.02002	0.16361
	50	k=2.961 n=2.2882	0.9108	0.01643	0.10095
	55	k=0.8539 n=2.8899	0.8058	0.02310	0.21372
Wang and Singh	45	a= -0.005 b= 2.45E-06	0.0128	0.24788	1.6438
	50	a= -0.0049 b=-2.08E-05	0.1828	0.21291	1.0946
	55	a= 0.007 b= -7.03E-06	0.0247	0.34503	1.7870

Critical observation between the predicted and experimental drying curves in Fig. 5 show that only a slight deviation between the two values with no significant difference (p<0.5). This gives a clear confirmation of the fact that the Henderson and Pabis model adequately depicted the drying characteristics of the drying process.

Frequency factors and activation energies

The slope/frequency factor, k_o is related to effective diffusivity [12].when drying takes place only in the falling rate and liquid diffusion controls the process[23]. It can be deduced that the frequency factor demonstrated linear behaviour in terms of the drying temperature, thus showing dependence on Arrhenius. The calculated frequency factors were 4.032×10^6, 4.20 $\times 10^6$ and 4.342×10^6 (h^{-1}) for temperatures 45 °C, 50 °C and 55 °C. 26. Sharma GP *et al* [26] stated that effective diffusivities depend on the drying air temperature besides variety and composition of the material. According to Madamba *et al*.,[12]. heat sorption which is a measure of moisture mobility within the food is another factor that affects effective diffusivity/frequency factor. The values obtained are high and could be attributed to the nature of the material (fruit pulp) under investigation. The higher k_o values imply lower resistance to diffusion of moisture. The activation energies for 45 °C, 50 °C and 55 °C were respectively found to be 52.829 KJ/mol, 52.831 KJ/mol and 52.837 KJ/mol. No significant difference was observed at p<0.05. The k_o and the activation energies are relevant in estimating the time for reduction of product moisture content under different drying conditions and also for designing thin layer dryers.

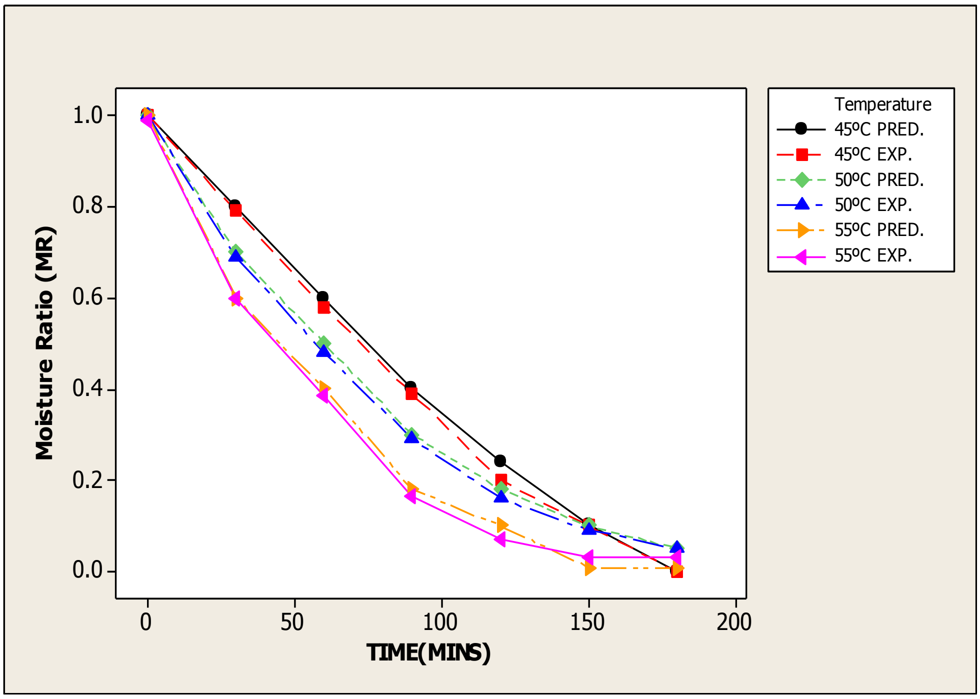

Fig-5: Experimental and predicted moisture ratio by the Henderson and Pabis model versus drying time for leather with 30% dextrinized sweetpotato

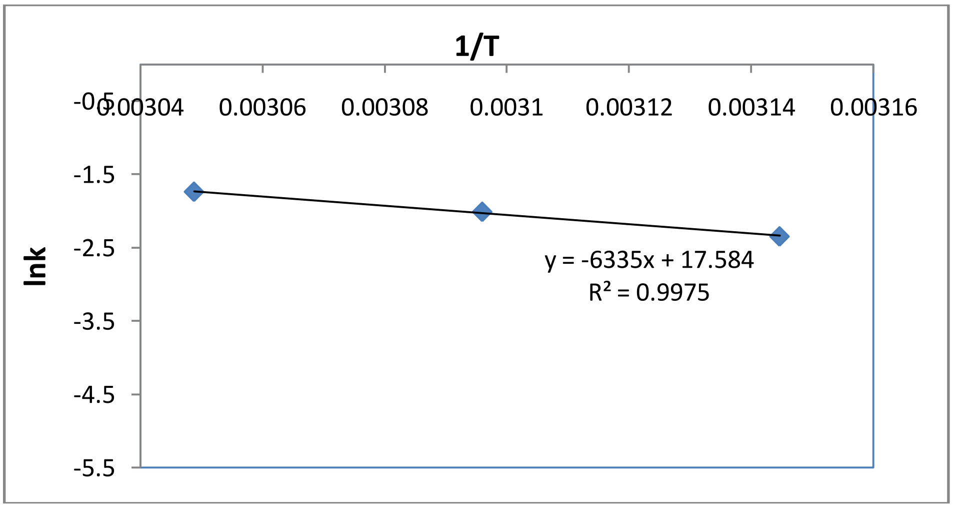

Fig- 6: Dependence of drying rate constant on temperature

CONCLUSIONS

The Henderson and Pabis model was found to appropriately depict the drying characteristics of mango-sweetpotato leathers at a temperature range of 45 ^oC, 50 ^oC and 55 ^oC. The high k_o values of 4.032×10^6, 4.20×10^6 and 4.342×10^6 (h^{-1}) show low resistance to moisture loss. Based on k_o and E_a values, the suitable temperature for drying mango-sweetpotato leathers is 50 ^oC

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