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Original Research Paper

Modelling of freeze-drying kinetics of osmosed jackfruit (*Artocarpus heterophyllus*) bulb slices

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ABSTRACT

Osmotic freeze-drying technique was employed to produce value added snacks from jackfruits for year-round availability to the consumers. To reduce the freeze-drying time, the osmotic pretreatment was done to jackfruit bulb slices, to bring down the moisture level. The drying kinetics of osmosed jackfruit bulb slices (OJBS) in a freeze dryer (FD) were investigated at plate temperatures ranging from 20-40°C with a fixed interval of 10°C. Drying of OJBS materialized in the falling rate period of a drying rate curve. The time taken was 22, 18 and 16 h, respectively to dry the OJBS from IMC of 200% (d.b.) to FMC of 8% (d.b.) at plate temperatures of 20, 30 and 40°C. The experimental drying data was analyzed employing eight different drying models, revealing that both the Logarithmic and Verma et al. models accurately predicted the moisture ratio (MR) of OJBS at varied plate temperature in a FD. The effective moisture diffusivity (EMD) values increased from 1.3×10^{-10} m^2s^{-1} to 2.3×10^{-10} m^2s^{-1} with increase in the plate temperature of FD from 20°C to 40°C. The activation energy (E_a) was calculated to be 20.81 $kJmol^{-1}$ and diffusion coefficient (D_o) to be 6.67×10^{-7} m^2s^{-1} for OJBS in a FD at plate temperatures of 20°C to 40°C.

Keywords: Activation energy, drying characteristics, effective moisture diffusivity, freeze drying, modelling

INTRODUCTION

Jackfruit (*Artocarpus heterophyllus* L.) is extensively cultivated in both tropical and subtropical zones in well drained and salinity free soil conditions. Jackfruit is largely grown in Brazil, Caribbean, East Africa, South Asia, South-East Asia, and many islands *viz*., Fiji, Papua New Guinea, Hawaiian, Caribbean, Palau, Pohnpei, Nauru, Tabiteuea in Kiribati and Samoa has jackfruit cultivation. Annual world production of jackfruit is 40 lakh tonnes (FAO, 2022) and Indian jackfruit production is 33 lakh tonnes (Arathi & Ushadevi, 2024). Jackfruit is consumed afresh or used in curry, chutney preparation and also consumed in ripen form. Ripe jackfruits are used in preparation of desserts, halwa, RTS drinks and other culinary purpose. Jackfruit seeds are edible and roasted/boiled seeds are consumed. In addition, jackfruit trunk and branches are used as firewood. Jackfruit as a whole provides food, fodder and fuel to the mankind. Thus, the diversified utilities and benefits of the jackfruits have made it special from all the fruits available and populously known as 'poor man fruit'. Deseeded bulbs have taste similar to that of pineapple (APAARI, 2012).

Almost three-fourth of jackfruit produced worldwide gets spoiled due to inadequate processing techniques/ equipment, proper preservation methods, storage facilities. Conventional utilization of jackfruit lies in the drying of its bulbs, seeds etc. Dried jackfruit bulbs are rich sources of minerals, nutrients and vitamins. Conventional drying methods for JBS noticeably affect the end product's quality, causing inevitable darkening. To maintain or enhance quality, freeze dryers (FD) were preferred over conventional approaches (Patil & Gawande, 2018; Pandidurai et al., 2022), which provides uniform dried product with superior parameters *viz.*, maximum colour retention and minimal or no shrinkage. The high adaptability of FD technology for preparation/preservation of high valued foods despite of its high energy requirements in freezing and consecutive drying has attracted many researchers and food processors in the recent times due to the quality of end product obtained (Menlik et al., 2010). Several studies were reported to describe drying attributes of different horticultural crops such as chillies (Kaleemullah & Kailappan, 2006), sweet pepper (Vengaiah & Pandey, 2007), button mushroom slices (Pei et al., 2014). This study investigates the freeze drying behaviour of jackfruit bulb slices (JBS) and suitability of model to depict the drying kinetics.

Analysis of the osmotic freeze-dried jackfruit bulb slices (OFDJBS) revealed significant reductions in moisture content (MC), resulting in prolonged shelf life. Moreover, the OFDJBS retained original colour, aroma, and flavour making them highly appealing to consumers. FD proved to be an effective method in preserving OJBS while retaining their quality attributes. This study highlights the potential of OFDJBS as a convenient, nutritious snack with an extended shelf life, offering consumers a healthy alternative to traditional dried fruits and vegetables.

MATERIALS AND METHODS

Raw material

Fresh jackfruits were procured from the local *mandi* and washed thoroughly to remove dust and dirt adhered to its surface. A long stainless steal knife was used to cut the jackfruits and yellow sheaths were manually scooped off without the oil application. This measure was taken to prevent oil adherence to the JBS, which hinders the osmosis process. Firm jackfruit sheaths were cut into 20×20×5 mm (Ranjith et al., 2023) square shaped JBS. The fresh JBS had an initial moisture content (IMC) of 200% (d.b.).

Osmotic pre-treatment

The JBS were immerged in 60° Brix sugar syrup at 56°C for 137 min, respectively (Mithun & Kaleemullah, 2019). 0.3% w/v, food grade citric acid (Selvakumar & Tiwari, 2018) and 1% w/v, food grade potassium metabisulfite (Mithun et al., 2019) were added to the sugar syrup. Osmotic pretreatment is generally done to bring the high MC of JBS to a favourable level so that the optimum moisture content can be attained by any of the drying technique, assisting in shortening the drying time.

FD process

FD process involves external freezing of foods and consecutive FD of the frozen foods in vacuum inorder to sublimate all the water present in the ice form to vapour. Triple point of water is the important concept that aids in the proper understanding of sublimation process wherein the solidified water vapourizes.

External freezing

The osmosed jackfruit bulb slices were frozen externally in a blast freezer (NS Bioscience, USA) at -20°C for 24 h (Shofian et al., 2011), respectively. This step aids in solidification of all the available moisture in the OJBS, upon bringing to sub-freezing temperatures.

Freeze drying (FD)

25 g of pre-frozen OJBS were placed immediately on the three stage shelves provided in drying chamber of the FD (Delvac, India) (Model: LYO0555) for drying. The drying chamber was maintained at vacuum of around 0.0010 mbar. Mean values of triplicate experimentations were reported.

Modelling

The MR (Eq. 1) of OJBS dried at 20-40°C in a FD were used for the study. Eight drying models tabulated in Table 1, were adopted and investigated, to find the best fit model. IBM SPSS (Statistical Package for Social Science) version 23 software, was employed to determine the parameters of all the models. The model suitability depends on chi-square (χ^2) (Eq. 2), coefficient of determination (R^2) and root mean square error (RMSE) (Eq. 3). The highest R^2 values, lowest χ^2 values and RMSE were favoured for their goodness of fit (Kalender & Topdemir, 2023).

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad \text{... (1)}$$

$$\chi^2 = \sum_{i=1}^{n} \frac{(MR_{exp,i} - MR_{pre,i})^2}{N-z} \quad \text{... (2)}$$

$$RMSE = \sqrt{\left[\frac{1}{N}\sum_{i=1}^{n}(MR_{exp,i} - MR_{pre,i})^2\right]} \quad \text{... (3)}$$

where,

M_i = Initial moisture content (IMC) (%, d.b.)
M_e = Equilibrium moisture content (EMC) (%, d.b.)
M_t = Moisture content at a particular time (%, d.b.)
$MR_{exp,i}$ = i^{th} experimentally observed MR
$MR_{pre,i}$ = i^{th} predicted MR
N = number of observations and
z = number of constants in models.

Effective moisture diffusivity (EMD) and activation energy (E_a)

Fick's law of diffusion for slab (Eq. 4) was adopted to ascertain the EMD at different temperatures (Demiray et al., 2017).

Table 1 : Mathematical models used for predicting drying curves

Model	Model equation	Reference
Newton	$MR = e^{-kt}$	Kalender & Topdemir (2023)
Page	$MR = e^{-at^{b}}$	Kalender & Topdemir (2023)
Henderson & Pabis	$MR = a \times e^{-kt}$	Kalender & Topdemir (2023)
Logarithmic	$MR = a \times e^{-kt} + c$	Kalender & Topdemir (2023)
Two-term	$MR = a \times e^{-k_1 t} + b \times e^{-k_2 t}$	Senadeera et al. (2020)
Two-term exponential	$MR = a \times e^{-kt} + (1-a) \times e^{-kat}$	Kalender & Topdemir (2023)
Verma et al.	$MR = a \times e^{-kt} + (1-a) \times e^{-bt}$	Kalender & Topdemir (2023)
Kaleemullah	$MR = e^{-(aT+b) \times t^{(cT+d)}}$	Kaleemullah & Kailappan (2006)

where,

MR = dimensionless moisture ratio
$k/ k_1/k_2$ = drying rate constants
a, b, c, d = dimensionless empirical constants
N = dimensionless empirical coefficient
t = time, h
T = temperature, °C
a, b and c= coefficient, $°C^{-1}\ t^{-(cT+d)}$ (Kaleemullah model)
d = dimensionless coefficient (Kaleemullah model)

$$MR = \frac{8}{\pi^2} \times e^{\left(-D_{eff} \times t \times \frac{\pi^2}{4 \times a^2}\right)} \quad \text{... (4)}$$

where,

D_{eff} = diffusivity, $m^2\ s^{-1}$
t = time, h
a = half the thickness of slab, m

The EMD *vs* Temperature relationship was established by Arrhenius equation (Kaleemullah and Kailappan, 2006) (Eq. 5). The linearized equation of Eq. 5 is represented as Eq. 6.

$$D_{eff} = D_0 \times e^{-\frac{E_a}{RT}} \quad \text{... (5)}$$

where,

D_{eff} = effective moisture diffusivity (EMD), $m^2\ s^{-1}$
D_0 = constant equivalent to the diffusivity at infinitely high temperature, $m^2\ s^{-1}$
E_a = activation energy , $kJ\ mol^{-1}$
R = universal gas constant [8.314×10^{-3} kJ (mol. K)$^{-1}$]
T = absolute temperature, K

$$\ln(D_{eff}) = \ln(D_0) - \left(\frac{E_a}{R}\right) \times \left(\frac{1}{T}\right) \quad \text{... (6)}$$

Colour

Colour is an important parameter evaluated by consumers who decide the freshness of JBS using the yellow chromaticity values. The colour of fresh, OJBS and FD-OJBS were measured using ColorFlex EZ spectrophotometer (HunterLab, USA).

RESULTS AND DISCUSSIONS

Osmotic pre-treatment

Osmosis process has reduced the MC of JBS from 200% (d.b.) to 100% (d.b.). Thus osmotic pre-treatment is a good dehydration process in freeze drying of the horticulture produce.

Drying behavior

The time required to dry OJBS in a FD from IMC of 100% (d.b.) to FMC of around 8% (d.b.) (Saxena et al., 2015) took 16, 18, 22 h at 40, 30, 20°C of plate temperature in drying chamber of FD, respectively. Plate temperature showed considerable influence on drying of OJBS. With increase in plate temperature in the drying chamber of FD with a vacuum pump setup, difference in water vapour pressure within the slices and the surrounding environment triggers, resulting in increased moisture migration, aiding in reduced drying time. Similar observations were reported for grapes (Adiletta et al., 2015). Drying of any food material depends upon its moisture content, solid content in food and diffusability of water through food. Moisture ratios versus drying time curves at temperature of 20-40°C were shown in Fig. 1.

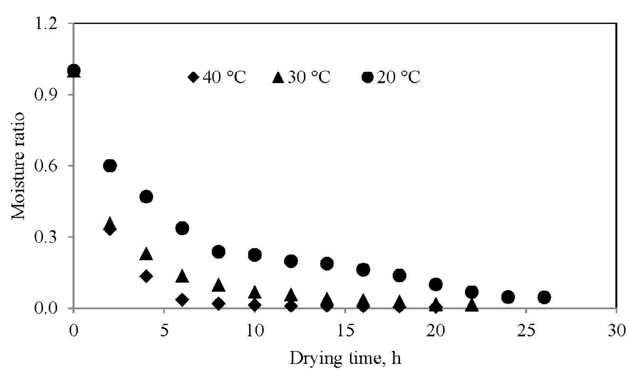

Fig. 1 : Effect of drying time on MR of OJBS in a FD at different plate temperatures

The MR of OJBS reduced exponentially with increased drying time. Continuous decrease in MR values indicates that, diffusion phenomena have governed the internal mass transfer. Higher plate temperatures attributed to decreased MR values, due to the increased heat supply rate to the slices and accelerated moisture migration. This is in agreement with the literature quoted for chinese yam cubes (Li et al., 2020), strawberry slices (Xu et al., 2021) and okra pods (Xu et al., 2021). It was also noted that moisture content declined with prolonged drying time, as also reported in persimmon slices (Senadeera et al., 2020).

A plot of drying rate (DR) and average moisture content (AMC) was represented in Fig. 2. The DR of OJBS was 42.17%, 42.81% and 37.92% d.b. h^{-1} within the first 30 min and 0.22%, 1.11%, 1.62%, d.b. h^{-1} in the last stage of drying time at 40, 30 and 20°C of plate temperature in FD, respectively. The DR was more for OJBS dried at high plate temperatures rather than at low plate temperatures. It can be inferred that the increased mass transfer rate attributed by increased plate temperature. The continuous fall in DR, attributed that the drying ensued to be falling rate mostly. No constant drying rate incidence was observed in DR curve of OJBS in FD.

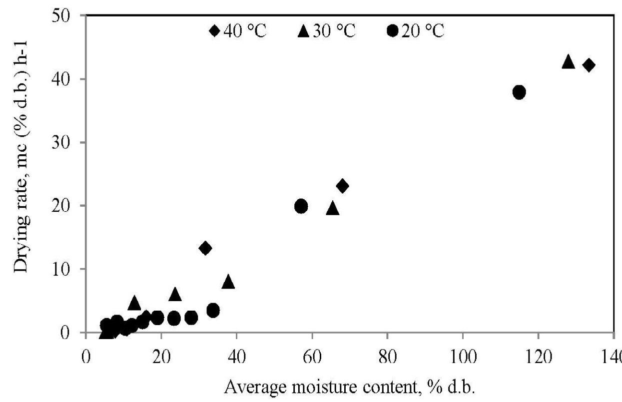

Fig. 2 : Effect of MC on DR of OJBS in a FD at different plate temperatures

Table 2 : Predicted values of parameters of different drying models used for drying of OJBS at 20-40 °C in FD

Model	Temperature	k_1	k_2	a	b	c	d	R^2
Newton	20	0.299	-	-	-	-	-	0.967
	30	0.319	-	-	-	-	-	0.973
	40	0.481	-	-	-	-	-	0.998
Henderson and Pabis	20	0.286	-	0.964	-	-	-	0.969
	30	0.312	-	0.98	-	-	-	0.973
	40	0.481	-	1	-	-	-	0.998
Logarithmic	20	0.36	-	0.935	-	0.054	-	0.986
	30	0.399	-	0.937	-	0.064	-	0.994
	40	0.503	-	0.988	-	0.014	-	0.999
Verma et al.	20	0.118	-	0.342	0.597	-	-	0.996
	30	0.068	-	0.165	0.464	-	-	0.995
	40	0.004	-	0.015	0.503	-	-	0.999
Two-term exponential	20	0.744	-	0.299	-	-	-	0.984
	30	0.685	-	0.339	-	-	-	0.984
	40	0.602	-	0.596	-	-	-	0.998
Two-term	20	0.286	0.286	100.482	-99.518	-	-	0.969
	30	0.312	0.312	-28.127	29.106	-	-	0.973
	40	0.481	0.481	12.853	-11.853	-	-	0.998
Page	20	-	-	0.494	0.661	-	-	0.993
	30	-	-	0.486	0.697	-	-	0.989
	40	-	-	0.497	0.969	-	-	0.998
Kaleemullah	20-40	-	-	-0.031	1.646	0.046	-0.575	0.992

These results coincide with the findings presented for amla candy (Patil & Gawande, 2018) and garlic (Guo et al., 2023). It was inferred that DR is proportional to the moisture contained in the food. With high moisture in food, there exhibits high DR and when moisture reaches equilibrium state, the DR also got declined. Comparable results are recorded for onion slices (Demiray et al., 2017). With increase in plate temperature, the DR increased whereas the drying time decreased. Comparable results are recorded for onion slices (Demiray et al., 2017) and rice grains (Sadaka, 2022).

Modelling

The average MRs of OJBS dried at different plate temperatures of 20-40°C in a FD were fitted in eight models namely Henderson and Pabis, Kaleemullah, Logarithmic, Newton, Page, Two-term, Two-term exponential and Verma et al. models and the predicted values of the parameters of the different drying models were listed in Table 2.

Empirical relationships between the drying model parameters and plate temperatures were tabulaed in Table 3. This relationship ensures its applicability to higher ranges of the plate temperatures apart from the plate temperature investigated in this study. The equations presented in Table 3, offer a means to derive the values of diverse parameters for the models at 20-40°C in a FD.

The estimated values of χ^2, RMSE, R^2 were tabulated in Table 4. Average grade and rank were given. Logarithmic and Verma et al. were models suited best among all the models. Patel et al. (2023) reported that Verma et al. model was highly suitable in predicting the drying characteristics of cotton seeds.

EMD and activation energy of OJBS

The plot of ln (D_{eff}) and 1/T (Fig. 3) depicts a linear line for the temperature range of 20-40°C, which apprises of Arrhenius dependence (Sadaka, 2022).

The EMD represents the overall mass transport property of moisture in the food material. The EMD of OJBS in a FD at different plate temperatures of 20°, 30° and 40°C is 1.3×10^{-10} $m^2 s^{-1}$, 1.6×10^{-10} $m^2 s^{-1}$, 2.3×10^{-10} $m^2 s^{-1}$, respectively. Similar pattern of results was quoted for chillies (i.e. 10^{-9}-10^{-11} $m^2.s^{-1}$) (Kaleemullah & Kailappan, 2006), mango slices (Goyal et al., 2006) and for berberis (Aghbashlo

Table 3 : Correlation between drying model parameters and FD plate temperatures

Model	Correlation between model parameters and plate temperature
Newton	$k = 0.0007t^2 - 0.0335t + 0.685$
Henderson & Pabis	$k = 0.0007t^2 - 0.0332t + 0.663$
	$a = 2E\text{-}05t^2 + 0.0006t + 0.944$
Logarithmic	$k = 0.0003t^2 - 0.0123t + 0.477$
	$a = 0.0002t^2 - 0.0121t + 1.078$
	$c = -0.0003t^2 + 0.016t - 0.146$
Verma et al.	$k = -7E\text{-}05t^2 - 0.0015t + 0.176$
	$a = 0.0001t^2 - 0.0244t + 0.777$
	$b = 0.0009t^2 - 0.0563t + 1.379$
Two-term exponential	$k = -0.0001t^2 + 0.0001t + 0.79$
	$a = 0.0011t^2 - 0.0503t + 0.87$
Two-term	$k_1 = 0.0007t^2 - 0.0332t + 0.663$
	$k_2 = 0.0007t^2 - 0.0332t + 0.663$
	$a = 0.8479t^2 - 55.258t + 866.47$
	$b = -0.8479t^2 + 55.258t - 865.51$
Page	$a = 1E\text{-}04t^2 - 0.0056t + 0.567$
	$b = 0.0012t^2 - 0.0554t + 1.297$

Table 4 : Estimated values of χ^2, RMSE, R^2, average grade and ranking of different models

Model	χ^2	RMSE	R^2	Average grade	Rank
Newton	0.0001935^4	0.013909^5	0.998^2	3.66	4
Henderson & Pabis	0.0002211^6	0.013909^5	0.998^2	4.33	5
Logarithmic	0.0001045^1	0.008855^1	0.999^1	1	1
Verma et al	0.0001053^2	0.008888^2	0.999^1	1.66	2
Two termexponential	0.0001890^3	0.012861^3	0.998^2	2.66	3
Two term	0.0003884^7	0.015579^6	0.998^2	5	6
Page	0.0002159^5	0.013745^4	0.998^2	3.66	4
Kaleemullah	0.0010706^8	0.025868^7	0.992^3	6	7

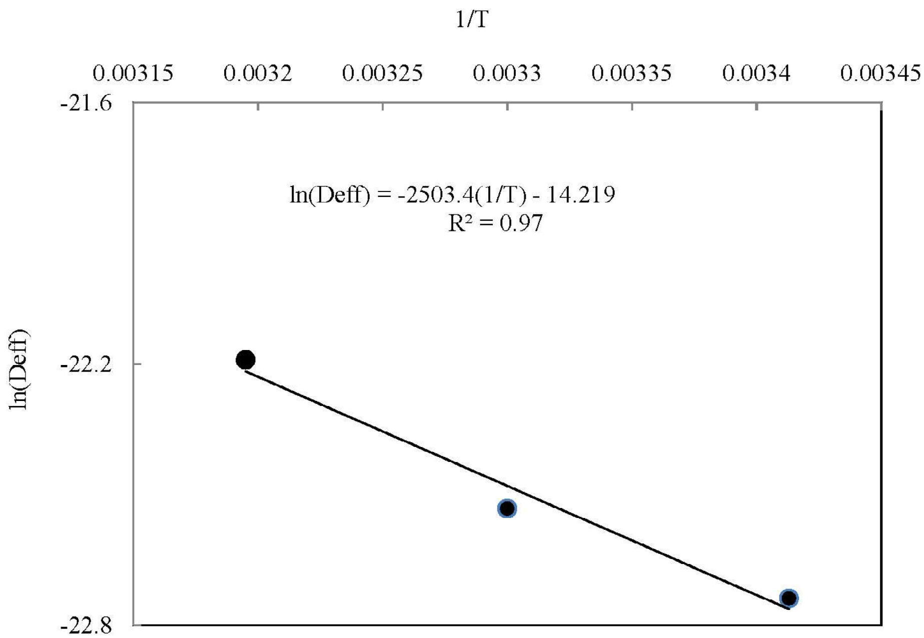

Fig. 3 : Arrhenius plot between EMD vs reciprocal of absolute temperature

et al., 2008). It is deduced that the EMD rises as the plate temperature increases in a FD, consistent with Kaleemullah & Kailappan (2006) findings for red chillies.

Activation energy (E_a) is 20.81 kJ mol^{-1} and diffusion coefficient (Do) is 6.67×10^{-7} m^{2}s^{-1} of OJBS in FD at 20-40°C. The activation energy values for OJBS in FD was in agreement with the Aghbashlo et al. (2008) for various agricultural products (12-110 kJ mol^{-1}). The activation energy (E_a) of OJBS in a FD was less than chillies (37.76 kJ mol^{-1}) (Kaleemullah & Kailappan, 2006). Any biological product's water diffusivity increases as the activation energy decreases, indicating greater water mobility within the product. Activation energy reflects the challenge water molecules face in overcoming the energy barriers during migration within the product. Conversely, higher activation energy values correspond to lower water diffusivity, signifying reduced water mobility within the product, and vice-versa (Jorge et al., 2019)

Colour

The b* (yellowness) of fresh, OJBS and FD-OJBS values were found to be 43.6±2.2, 44.8±4.0 and 47.8±1.9, respectively. Very slight differences in the yellowness values were observed. It can be inferred that the FD-OJBS retained the colour which is very close to the yellow chromaticity values of OJBS and fresh JBS. Comparable results were reported for freeze dried roselle extract (Duangmal et al., 2008) and kiwi (Domin et al., 2020). The freeze dried samples showed maximum colour retention and is comparable with that of fresh JBS.

CONCLUSION

The drying behaviour of OJBS in FD was investigated at three different plate temperatures in a drying chamber. The time required to dry OJBS from an IMC of 100% (d.b.) to the FMC of 8% (d.b.) was 16, 18, 22 h at 40, 30, 20°C of plate temperature in a FD. DR increased with plate temperature in a FD, reducing the drying time. Entire drying process of OJBS occurred in the falling rate period and not in constant rate period. The Logarithmic and Verma et al. models are found suitable to predict the moisture ratio of OFBS in a FD. EMD's increased with increase in plate temperature in a FD. Modelling FD kinetics of OJBS optimizes energy use, improves product quality, reduces drying time, and enables scalability, cost-effective production of high-quality nutritious snacks.

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