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Modeling Sorption Isotherm of Instant Controlled Pressure Drop (ICPD) Treated Hot Air Dried (HAD) Banana Slices

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Abstract—*The Objective of this work was to study and model the sorption isotherms of dried banana slices which are dried by an innovative drying technique known as Instant Controlled Pressure Drop treated Hot Air Drying (ICPD treated- HAD). The ICPD is defined as a high-temperature/short-time (HTST) treatment that consists of subjecting a partially dried material to vapor pressure (P<1.0 MPa) at high temperature (below 180 ºC) for a short time (less than a minute). This HTST stage is followed by an abrupt pressure drop to a vacuum (3–5 kPa, in a time of ~10–60 milliseconds) inducing a mechanical effect such an abrupt pressure drop, provokes simultaneously auto vaporization of a part of water contained in the product and an instantaneous cooling of the product which stops their thermal degradation and gives a controlled expansion of the product. The sorption isotherms of dried banana slices were studied at 25°C using different salt solutions and various models available in the literature were fitted to model the sorption behavior of dried banana slices.*

Introduction

The preservation and stabilization of the main characteristics of foods (taste, crispness, *etc.*) during storage often requires control of their moisture content. Several preservation processes have been developed in order to extent the shelf-life of foodstuffs by lowering the availability of water to micro-organisms and inhibiting some chemical reactions. While moisture content is an important criterion to judge food quality [1], water activity (a_w), is an essential additional parameter to describe water availability and mobility in foods. Establishing the relationship between moisture content (X_e) and a_w which is known as the sorption isotherm, is important to understand the stability of foodstuffs [2]. Swell Drying (SD) is a novel drying techniques involving Instant Controlled Pressure Drop (ICPD) between two periods of conventional hot air drying [3]. The ICPD is defined as a high-temperature/short-time (HTST) treatment that consists of subjecting a partially dry material to vapor pressure (P<1.0 MPa) at high temperature (below 180 ºC) for a short time (less than a minute). This high temperature-short-time stage is followed by an abrupt pressure drop to a vacuum (3–5 kPa, time ~10–60 ms) inducing a mechanical effect such an abrupt pressure drop, provokes simultaneously auto vaporization of a part of water contained in the product and an instantaneous cooling of the product which stops their thermal degradation and gives a controlled expansion of the product.

The Moisture sorption isotherm is the relation between the equilibrium moisture content of a material (expressed as mass of water per unit mass of dry matter) and water activity, at a given temperature [4]. Since a_w is temperature dependent, it follows that temperature has a significant effect on sorption isotherms. So, when a food is subjected to an upward temperature shift, at any constant moisture content, a_w increases with increasing temperature [5]. Moisture sorption isotherms describe the relationship between a_w and the equilibrium moisture content of a food product [6]. Knowledge of water sorption isotherms is of great importance to various food processes, including drying, storage and packaging [7]. They are useful to calculate time and energy consumptions during drying, to predict ingredients behavior upon mixing, to assist packaging selection, to model moisture changes during storage and predict shelf life of food products [8]. The typical shape of an isotherm reflects the way in which the water binds the system [9]. For a fixed water content, the weaker the water interactions, the greater the water activity and the product becomes more unstable. Water activity depends on the composition, temperature and physical state of the compounds. These properties also give information about the sorption mechanisms and interactions between food components and water [4,5]. Moreover, moisture content and water activity of a food influences texture, storage stability and its susceptibility to microbial spoilage. Even though the relationship between moisture content and water activity has been studied for many dried fruits.

The moisture sorption isotherm may be measured by addition of water to a dry sample (adsorption) or by removal of water from a wet sample (desorption) The high number of sorption equations developed suggests the difficulty of having a unique mathematical model for describing the sorption data in the whole range of water activity for different food products. This is due to a number of reasons [10]

- The depression of water activity in foods is due to a combination of factors each of them being predominant in a given range of water activity. In general, the insoluble macromolecules dominate the sorption behavior at low aw and the soluble components exert their effects largely through their colligative properties over the high aw range.
- Moisture sorption isotherms of foods represent the integrated hygroscopic properties of numerous constituents whose sorption properties may change as a consequence of physical and/or chemical interactions induced by heating or other pre-treatments

The sorption isotherm describes the interaction between water and the food product. Equations for fitting these data are of special interest in many aspects of food preservation by dehydration. Numerous mathematical models for description of food moisture sorption behavior are available. Some of these models are based on theories on the sorption mechanisms; others are purely empirical or semi-empirical. The criteria generally used to select the most appropriate sorption model are the degree of fitting to experimental data and the physical meaning of the model. More than 75 correlations have been proposed for mathematical interpretation of the extensive experimental data (Van der Berg and Bruin, 1981). These authors developed more than 200 equations theoretically, semi-theoretically, or empirically. Moisture sorption isotherm can be based on monolayer model (BET model), on a multilayer and condensed film models (GAB, Lewicki I and Lewicki II models), on semi-empirical models (Ferro-Fontan, Henderson and Halsey models) and on empirical models (Smith, Oswin and Bizot models) According to the BET classification, food systems typically exhibit Type II or III isotherms. Starchy foods usually fit Type II behavior while foods rich in soluble components, such as sugars or salts, shows Type III behavior, with low moisture contents at low water activities and a sharp increase in moisture at high water activities [11]. The last one would be the case of spray-dried cherimoya pulp. But recently, the GAB model has been proposed by food engineers as the universal model to fit the sorption data for all foods [12]. [8] Reported that moisture sorption of foods can be described by more than one sorption model and GAB gives the best fit for more than 50% of the fruits, meats and vegetables analyzed.

In the preliminary experiments done by authors to produce Swell dried bananas it was found that the high pressure (Temperature) during ICPD treatment is resulting in the cooking of banana, to overcome this problem and to utilize the potential of ICPD treatment, in this study the ICPD treatment was used as a pre-treatment before the conventional hot air drying instead of using it as an intermediate treatment to improve the quality of dry bananas

Materials and Methods

Raw materials

Bananas (Musa ABB, locally this is called kachkal) in the matured nutritive stage were purchased from local agricultural farm, Tezpur, Assam. Dirtiness or dust particle attached to the peeling surface were removed by cleansing and washing under running tap water and wiped with tissue paper. The initial moisture content of samples was measured by conventional hot air oven drying device at 70°C for 24 hours as mentioned by(Khawas et al. 2015).The fresh and dry weights were measured with an electronic weighing balance (CPA225D, Sartorius AG, Germany) having 0.001 g accuracy. Chemicals used were of analytical grade and supplied my Merck, India and Himedia Laboratories and sigma chemicals, India.

ICPD (Instant Controlled Pressure Drop) experimental set up

The ICPD processing equipment consisted of four major units namely boiler, treatment chamber, vacuum tank fitted with vacuum pump, and instant vacuum release system, along with various other parts such as moisture trapper, pressure gauge, temperature gauge, control panel and pressure releasing valve to atmosphere etc the image of the equipment is shown in fig.

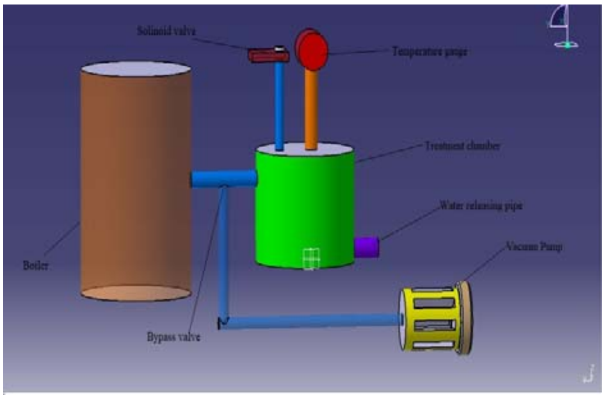

Figure 1: Schematic sketch of the ICPD reactor

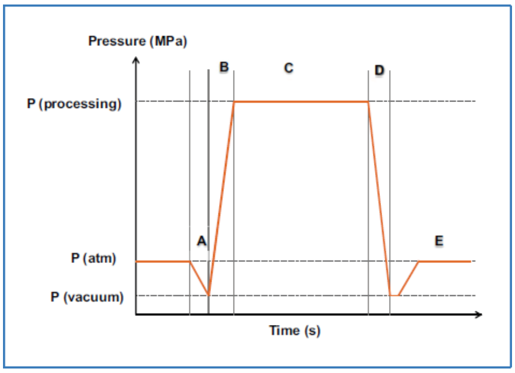

Figure 2: Pressure–time profile of ICPD processing cycle

Figure 3: Experimental set up of ICPD treatment

ICPD treatment and ICPD treated-hot air drying procedure

In the present study, the raw fresh banana was first cut into slice with dimensions of 8mm and then pretreated (blanched) by ICPD thus, hot air only intervened as a final treatment. The treatment design was achieved as illustrated in figure 4:

Raw Material	Assessment of initial characteristics: Moisture Content
Preparation	Cutting: 8mm slice
ICPD Treatment	ICPD experimental design: Treatment Pressure (P): 0.1MPa Treatment Time (T): 25 sec
Hot-air drying	Constant operative Drying condition: 70□; 1m/s
Dried banana slice	Assessment protocol

Figure 4: Scheme of treatment and assessment methods adopted for banana slice dried samples

Sorption isotherm methods

Equilibrium moisture contents of slice at several Aw were determined by the static gravimetric method at different temperatures. Six saturated salt solutions were prepared corresponding to a range of Aw from 0.082 to 0.973 as shown in Table 1.

Each solution was transferred into separated jars in such an amount to occupy a space of about 1.5 cm depth at the jar bottom. Triplicate samples of around 1 g of banana Fruit slice were weighed into small plastic receptacles and placed on tripods in the jars, which were then tightly closed and placed in a temperature-controlled chamber. The required equilibration time was 4–5 weeks, based on the change in samples weight expressed on a dry basis, which did not exceed 0.1% (0.001 kg/kg dry solids). The equilibrium moisture content was determined in a vacuum oven, at 60˚C for 48 h [13] and maximum deviations of about 5% were observed between the triplicates.

Table No.1 Saturated salt solution and their water activity

Sl. No	Name of Saturated salt solution	Water activity (25°C)
1	Sodium hydroxide ($NaOH$)	0.082 ± 0.021
2	Magnesium chloride ($MgCl_2$)	0.328 ± 0.002
3	Magnesium nitrate ($Mg(NO_3)_2$	0.529 ± 0.002
4	Sodium chloride ($NaCl$)	0.753 ± 0.001
5	Potassium chloride (KCl)	0.843 ± 0.003
6	Potassium sulfate (K_2SO_4)	0.973 ± 0.005

Isotherm Models

Five sorption isotherm equations – Brunauer-Emmett-Teller (BET) EquationOswin, Lewicki (two parameters), Lewicki (three parameters), Ferro- Fontan, Peleg and Guggenheim-Anderson-de Boer (GAB) – were tested to fit banana slice sorption isotherm data (Table 3). Model parameters were estimated by fitting the mathematical model to experimental data, using nonlinear regression. The adequacy of fitted functions was evaluated by the determination coefficient (R^2) and the magnitude of the square of standard error (SSE) and RMSE.

Table No.2 Sorption isotherm equations

Model	Expression	Reference
BET	$X = \frac{X_m CV}{(1-a_w)[1+(C-1)a_w]}$	BET (1938)
Oswin (1946)	$X = A.\left[\frac{a_w}{1-a_w}\right]^B$	Oswin (1946)
Lewicki (two-parameters)	$X = A.\left(\frac{1}{a_w}-1\right)^{B-1}$	(Lewicki and Wolf 1995
Lewicki (three-parameters)	$X = \frac{F}{(1-a_w)^G} - \frac{F}{1+a_w^H}$	Lewicki 1998
GAB	$\frac{(C-1).K.a_{w.}X_m}{1+(C-1).K.a_w} + \frac{K.a_w.X_m}{1-K.a_w}$	Van den Berg 1991

Results and discussion

Sorption isotherm

Equilibrium moisture contents versus a_w for ICPD treated-HAD banana slices at 25°C are shown in Table 4.5. The moisture content at each a_w represents the mean value of three replications. The standard deviations between triplicates were within a maximum limit of 4% from the average X_{eq}value, except for values corresponding to the lowest a_w, where the standard deviations attained up to 9% from the average X_{eq} value.

Table No. 3: Experimental equilibrium moisture contents (dry basis) for onion slices at 25°C

Water activity (a_w)	Equilibrium moisture content (%db)
0.082	15
0.328	28
0.529	39
0.753	65
0.843	76
0.973	84

Figure 5 shows sorption isotherms for banana slices at 25°C In the case of banana, this behavior was not so pronounced, maybe due to physical and/or chemical damages that occurred during the drying process of slices, because the shape and position of the isotherms are influenced by the sample composition, physical structure (crystalline or amorphous), applied pre-treatments or processing.

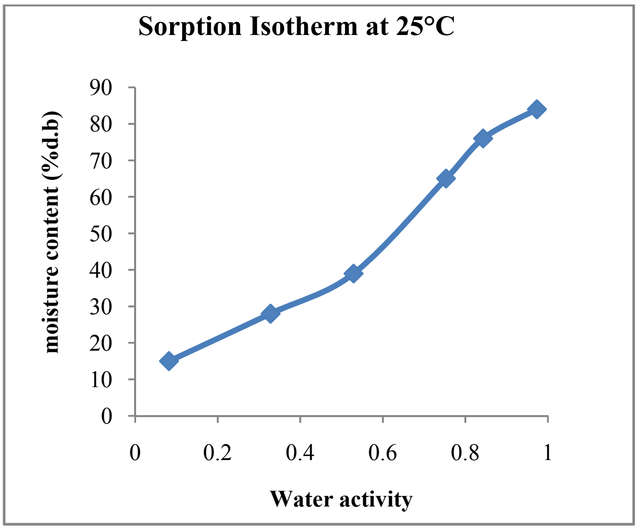

Figure 5: Sorption isotherm of ICPD treated-HAD dried banana slices

Model fitting

The results of nonlinear regression analysis in order to fit mathematical models to the experimental data are shown in Table 4 for banana slices. Despite the fact all the tested models had presented satisfactory adjustments to experimental data, the GAB equation is recommended to describe the banana isotherms, because it has been extensively used for foodstuffs, mainly for fruits and vegetables [4,8] as well as being simple and supplying parameters with physical meaning

Table No. 4: Estimated parameters for ICPD dried banana slices at 25°C

Model	Parameter	Estimated values
Oswin	A	38.01
	B	0.2212
	R^2	0.80
	SSE	975.9
	RMSE	13.93
Lewicki-2		38.01
		0.7788
		0.80
		775.9
		13.93
		1.29
GAB	C	0.1085
	K	0.4583
	Xm	0.58
	R2	0.97
	SSE	9.317
	RMSE	1.762
Lewicki-3	A	152.3
	B	0.01636
	C	1.377
	R2	0.95
	SSE	176.5
	RMSE	0.92
BET	C	0.0003034
	Xm	2.82

	R2	0.97
	SSE	117.3
	RMSE	5.416

Summary and Conclusion

In the present study modeling of sorption isothemrs of ICPD treated-HAD banana slices revealed that the sorption behavior of banana slices can be represented by both BET and GAB models with R2 Value of 0.97 and this models can be used to select the packaging and storage conditions of ICPD treated-HAD banana slices.

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