The Pharma Innovation Journal 2022; 11(3): 709-716

www.ThePharmaJournal.com
The Pharma Innovation

ISSN (E): 2277- 7695
ISSN (P): 2349-8242
NAAS Rating: 5.23
TPI 2022; 11(3): 709-716

www.thepharmajournal.com
Received: 08-01-2022
Accepted: 18-02-2022

Minati Mohapatra
1. Department of Agricultural and Food Engineering, Indian Institute of Technology, Kharagpur, West Bengal, India
2. College of Agricultural Engineering and Technology, Orissa University of Agriculture and Technology, Bhubaneswar, Odisha, India

Ashok Kumar
1. Department of Agricultural and Food Engineering, Indian Institute of Technology, Kharagpur, West Bengal, India
2. College of Food Technology, Central Agricultural University, Imphal, Manipur, India

Corresponding Author:
Ashok Kumar
1. Department of Agricultural and Food Engineering, Indian Institute of Technology, Kharagpur, West Bengal, India
2. College of Food Technology, Central Agricultural University, Imphal, Manipur, India

Moisture sorption behaviour of pre-conditioned rice for puffing

Minati Mohapatra and Ashok Kumar

Abstract
Salt and heat treatment to parboiled rice (pre-conditioning) to bring low moisture level (10% wb) is a pre-requisite for its puffing. Rapid moisture adsorption deteriorates puffing quality, and knowledge on Moisture Sorption Isotherm (MSI) characteristics becomes essential for appropriate packaging design. MSI of raw, parboiled and pre-conditioned rice with different salt levels (0.0, 2.5, 3.5 and 5.0% w/w) were determined at 20, 30, 40 and 50ºC following isopiestic vapor transfer method. Equilibrium moisture content (EMC) of pre-conditioned rice were lower than raw and parboiled rice, but followed a crossover phenomenon beyond water activity range of 0.55 – 0.75. All exhibited type II BET isotherms. Modified GAB model is best fit model tested. Microstructure of pre-conditioned rice revealed continuous and compact surface that influences sorption. The net isosteric heat of sorption showed exponential relation with moisture content from 5.0- 30.0% db and lower for salt conditioned rice than control samples.

Keywords: Moisture sorption isotherms, sorption behavior, rice, puffed rice

Introduction
Production method of puffed rice, a popular ready to eat (RTE) breakfast cereal worldwide, varies widely from traditional hot-sand bed roasting (Chinnaswamy & Bhattacharya, 1983) [9] to puffing in oil (Robert *et al*., 1951; Villareal & Juliano, 1987) [21, 29], gun puffing (Villareal & Juliano, 1987) [29] and hot air puffing (Chandrasekhar & Chattopadhayay, 1991) [8]. Recently, study on puffing of rice using domestic microwave oven has been reported (Jayasmita, 2008; Maisont & Narkrugsa, 2010; Mohapatra & Das, 2011) [15, 18, 20]. They advocated that microwave puffing of rice could be an ecofriendly and alternative commercial feasible process to make hygienic product on demand. Pre-conditioning of rice is a vital step in these rice puffing processes to obtain high expansion and smooth surface puffed rice (Chandrasekhar & Chattopadhyay, 1991) [8] that might be attributed to some micro structural changes in the rice kernel during salt curing process (Bhanudas, 2009) [6]. Pre-conditioning of rice involves overnight soaking of milled pressure-parboiled rice with dilute salt (NaCl) solution (final concentration of salt: rice adjusted to 2.5 to 5.0 g per 100 g rice; initial moisture level around 30-35% wb). It is followed by tempering for 8 - 9 hours, and finally slow and uniform drying till the desired moisture content around 9-10% (wb) is attained (Jayasmita, 2008) [15]. In traditional sand roasting and air puffing processes, freshly prepared pre-conditioned rice is utilized within short period to avoid decreasing in percent of rice puffed and volume expansion ratio of the puffed grains. Decay in puffing characteristics of stored pre-conditioned rice was studied by Jayasmita (2008) [15] and Mohapatra (2010) [19]. They observed direct correlation between this decay kinetics and moisture adsorption of the pre-conditioned rice. Thus, knowledge of moisture sorption characteristics of the pre-conditioned rice could be a useful tool to understand shift in equilibrium moisture content under different storage environments. Further, sorption characteristics of the pre-conditioned rice and the best-fitted sorption models could be applied in designing a suitable packaging system (Das, 2005) [11] to control moisture migration and preserve puffing quality. Puffing of pre-packaged pre-conditioned rice using domestic microwave oven could be explored - similar to that of commercially available microwavable popcorn in retail packages. Bianco *et al*. (1997) [7] reported differences in sorption characteristics of three varieties of rice were quite apparent at lower temperature (15 ºC) but it converged at higher temperatures (25, 35 ºC). Sun (1999) [26] took data on Equilibrium moisture content/ Equilibrium relative humidity of rice from eighteen published literature and analyzed that Strohman-Yoerger equation is the best equation for describing these values. Basunia and Abe (2001) [4] studied moisture sorption characteristics of medium-

grain rough rice (cv. Japonica) in the temperature range of 11.8 - 51.0 °C and ERH values from 37.1 to 89.7%. They observed that, among four three-parameter sorption models (modified Henderson, modifed Chung-Pfost, modifed Oswin and modifed Halsey equations), modified Chung-Pfost equation was most appropriate for representing the EMC/ERH desorption isotherms of rough rice. Iguaz and Virseda (2007) [13] reported experimental sorption data of medium-grain rough rice (cv. Lido) at high temperatures (40 to 80 ºC). Among the five sorption models tested, modified GAB equation was best fit in the water activity ranged from 0.1 to 0.90, suggesting it an appropriate model for the description of the desorption moisture isotherms of rough rice at drying temperatures. In recent review on hygroscopic equilibrium of rice, Choi *et al*. (2010) [10] reported that modified Henderson and modified Chung-Pfost equations were most frequently recommended for predicting the sorption behavior of rice. They also reported that for any given temperature and relative humidity, the EMC of milled and brown rice were consistently the greatest, generally followed by rough rice, bran, and hull. Witek *et al*. (2010) [30] observed lower pressure for heat treated rice kernels (280-300 °C) compared to that of raw rice in the water activity (a_w) range of 0.1 – 0.8, followed by a reverse trend at higher a_w values. Sootjarit *et al*. (2011) [24] have developed empirical sorption model for prediction of EMCs of pre-germinated rough rice and pre-germinated brown rice at 30 °C, 50 °C, 60 °C, and 80 °C. Haque *et al*. (2007) [12] reported that net-isosteric heats of desorption and adsorption for hybrid rough rice kernels was higher followed by brown rice and milled rice kernels. However, no information on moisture sorption characteristics of salt infused heat cured rice (termed as pre-conditioned rice) is available in the literature. This paper aimed to study the moisture sorption characteristics and modeling of pre-conditioned rice following the models generally applied for rice studies i.e. modified GAB, modified Chung -Pfost, modified Oswin, modified Henderson and modified Halsey equations (Aviara *et al*., 2006; Basunia and Abe, 2001, Iguaz and Virseda, 2007) [3,4,13], at different salt concentrations and storage temperatures. Micro-structural changes in the pre-conditioned rice kernel have been compared with untreated parboiled rice (control) for better understanding on the sorption behavior.

Materials and Methods

Preparation of the sample

A long rice variety (*Hira,* length: breadth ratio 2.64), mostly used for making puffed rice, was chosen. The paddy was collected from the local market of village Bondeuli, West Midnapur district of West Bengal state in India (22.167°N, 87.250°E) during May 2009. In this sorption study, three category of rice samples were taken, *viz*., salt treated pre-conditioned rice containing 0.0 (as control), 2.5, 3.5, 5.0% (w/w) common salt, parboiled rice and raw rice. The initial moisture content of raw, parboiled, preconditioned rice samples were 10.54±0.32, 9.85±0.18 and 9.15±0.74% (w.b.) respectively. Raw rice was obtained by dehusking the paddy in a laboratory dehusker (Satake, Japan, model – THU35A) and polishing (5%) using laboratory polisher (Satake, Japan, Model – TM05). Parboiled rice suitable for puffed rice (Process A) and pre-conditioned rice (Process B-continued after process A) were prepared following the steps as given in Fig. 1. Care was taken to avoid any localized or over heating the rice grain during pre-conditioning process. Control sample without salt was prepared similarly.

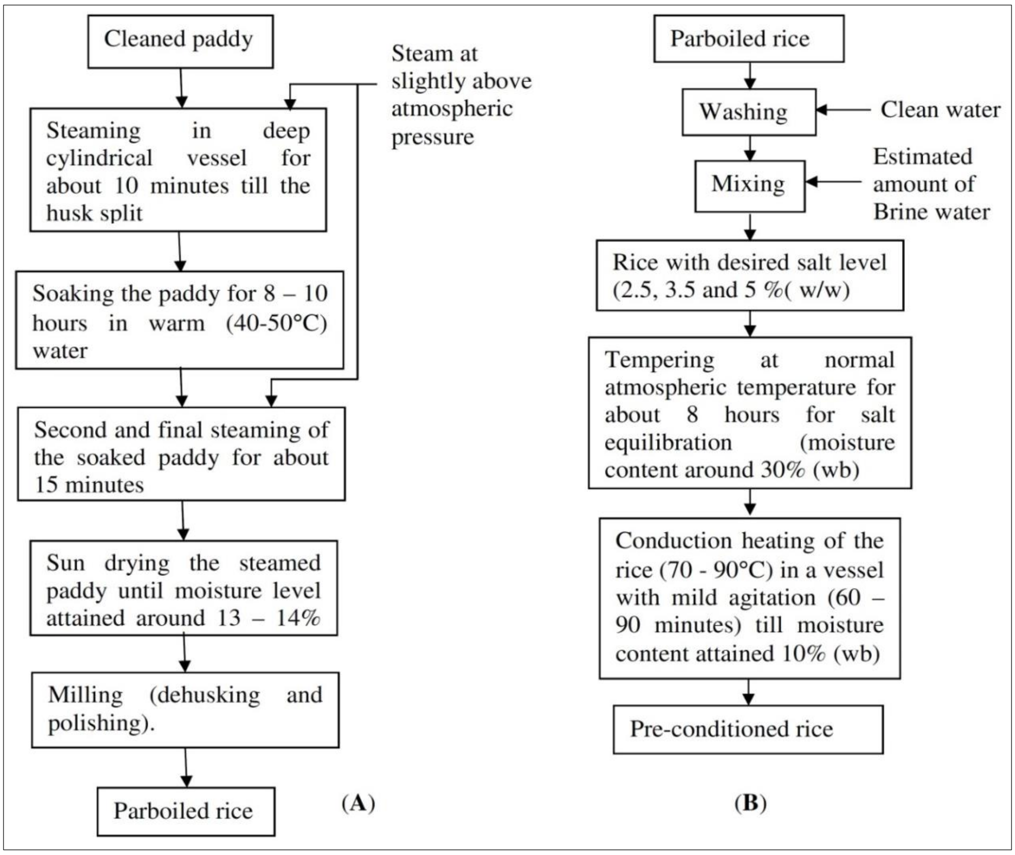


Fig 1: Process flow chart of preparation of parboiled (A) and pre-conditioned rice (A and B) for puffing

Isopiestic transfer method for moisture sorption

The moisture adsorption isotherms of pre-condition rice were determined at 20, 30, 40 and 50°C by static gravimetric technique based on isopiestic transfer. Saturated solutions of various salts (NaOH, CH_3CO_2K, $MgCl_2$, K_2CO_3, $MgNO_3$, $NaNO_3$, NaCl, KCl and K_2SO_4 – reagents laboratory grade, Loba Chemicals, India) were taken in respective vacuum desiccators to generate control humidity environment ranging between 9.32– 97.59% (9 levels). The change in equilibrium relative humidity of the salt solutions due to change in temperature were estimated (Labuza, *et al*., 1985) [17]. The rice samples (in triplicate) were taken in glass-stopper weighing bottles (5 ml) weighed (± 0.001g accuracy) and then placed inside the desiccators with stoppers removed. This procedure was done for all the nine desiccators. Vacuum (around 200 mm Hg) was created inside the desiccators to accelerate the adsorption process (Suthar & Das, 1997) [27]. All these desiccators were placed inside an incubator maintained at set temperature ±1°C. A trial experiments on this adsorption process showed that rice took about 28 days to reach equilibration (constant weight). Thus, all the desiccators were allowed to equilibrate up to 28 days and the final weights were noted. The moisture content of each equilibrated sample was determined by the vacuum oven drying method (AOAC, 1990) [2] and expressed in mean value ± standard deviation. The whole procedure was repeated for different temperatures. To control fungal growth in samples stored at high relative humidity, they were exposed to UV treatments in a laminar flow for 5 minutes to sterilize.

Moisture Sorption Isotherm (MSI) Models

As reported by previous workers (Aviara *et al*. 2006; Basunia & Abe, 2001; Choi *et al*., 2010; Iguaz & Virseda, 2007) [3, 4, 10, 13], five MSI models (Table 1) were chosen for this study to examine its goodness of fit with the experimental data following standard statistical analyses as described in section below.

Table 1: Moisture sorption isotherm models used to fit the experimental data on raw, parboiled rice and pre-conditioned rice containing various amount of salt.

Model	Mathematical expression	Equation Number	Reference
Modified GAB	$M_e = \dfrac{AB\left(\dfrac{C}{T}\right)a_w}{(1-Ba_w)\left[1-Ba_w+\left(\dfrac{C}{T}\right)Ba_w\right]}$	(1)	Iguaz and Virseda (2007) [13]
Modified Chung-Pfost	$M_e = -\dfrac{1}{C}\ln\left[-\left(\dfrac{T+B}{A}\right)\ln a_w\right]$	(2)	Basunia and Abe (2001) [4]
Modified Oswin	$M_e = (A+BT)\left(\dfrac{a_w}{1-a_w}\right)^{\frac{1}{c}}$	(3)	Aviara *et al*. (2006) [3]
Modified Henderson	$M_e = \left[-\dfrac{\ln(1-a_w)}{A(T+B)}\right]^{\frac{1}{c}}$	(4)	Aviara *et al*. (2006) [3]
Modified Halsey	$M_e = \left[-\dfrac{\exp(A+BT)}{\ln a_w}\right]^{\frac{1}{c}}$	(5)	Basunia and Abe (2001) [4]

Me - equilibrium moisture content (% db); aw is the water activity; A, B, C are characteristics model parameters; T is temperature in ºC

Net Isosteric Heat of Sorption

The energy involved in moisture sorption in food or biological materials over and above the latent heat of vaporization of pure water is net isosteric heat of sorption or excess heat of sorption (q_{st} in kJ mol^{-1}) (Rizvi, 2005) [22]. It is derived from Clasius–Clapeyron equation (Eqs. 6 and 7). This net isosteric heat of sorption for any particular moisture level is obtained from the slope ($-q_{st}/R$) of the straight line obtained from the plot '$\ln a_w$' versus '1/T'.

Where, R is universal gas constant (8.314 kJ mol^{-1} K^{-1}); T is temperature in K, and Z is integral constant. The values of q_{st} are exponential function of moisture content of the product. Iguaz & Virseda (2007) [13] have used correlations between q_{st} and equilibrium moisture content (M_e); the exponential model (Eq. 8) and the model followed by Kechau & Maalej, (1999) [16] (Eq. 9). These two models were tested in the present study for the samples of raw, parboiled and pre-conditioned rice with 0, 2.5, 3.5 and 5.0% salt.

$$\ln a_w = -\frac{q_{st}}{RT} + Z \quad (6)$$

$$\ln\frac{a_{w2}}{a_{w1}} = -\frac{q_{st}}{R}\left(\frac{1}{T_2}-\frac{1}{T_1}\right) \quad (7)$$

$$q_{st} = q_0 . \exp\left(-\frac{M_e}{M_r}\right) \quad (8)$$

$$q_{st} = \frac{a.M^b{}_e}{c+M^d{}_e} \quad (9)$$

Where, q_0 = constant, kJ mol^{-1}; M_r, a, b, c and d are characteristics constants in respective equations.

Statistical analysis
The model parameters for each sorption equations (Table 1) were evaluated following non-linear regression analysis using a statistical software package (SigmaStat 3.5 package; Systat Software Inc. 2008). The goodness of fit of these models were estimated on the basis of root mean square error (RMSE), mean relative percent deviation modulus (P) and co-efficient of determination (R^2).

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(M_{\exp i} - M_{\text{pre}i})^2\right]^{\frac{1}{2}} \quad (10)$$

$$P = \frac{100}{N}\sum_{i=1}^{N}\frac{(M_{\exp i} - M_{\text{pre}i})}{M_{\exp i}} \quad (11)$$

$$R^2 = 1 - \frac{SSE}{SST} \quad (12)$$

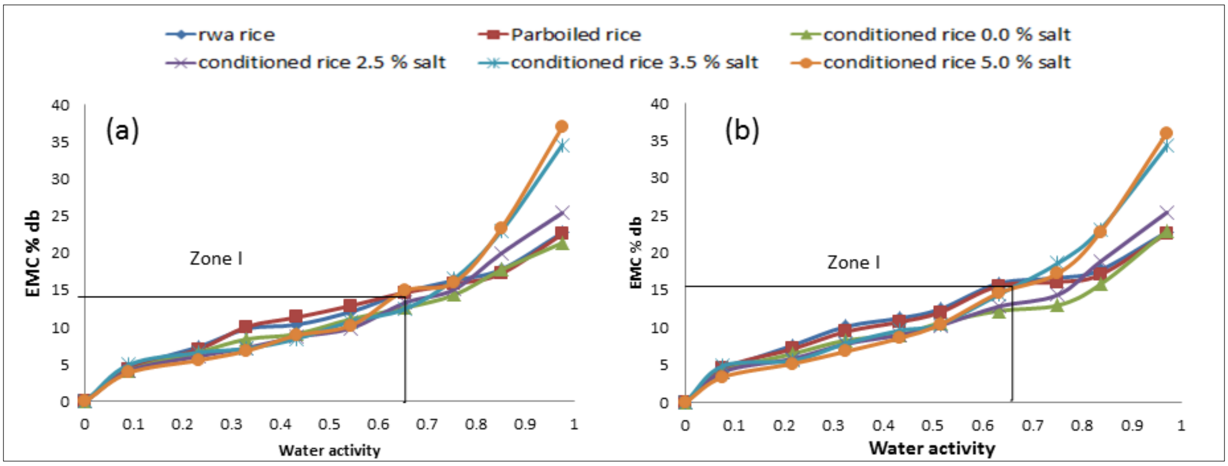
Where, $SST = \sqrt{\frac{\sum_{i=1}^{N}(\overline{M} - M_i)^2}{N-1}}$;

$$SSE = \sum_{i=1}^{n}\left(M_{\exp i} - M_{pre i}\right)^2$$

Where $M_{\exp}$ and M_{pre} are the experimental and predicted equilibrium moisture contents (%db), respectively; $\overline{M}$ is the average equilibrium moisture content (%db); N is the number of observations; *SSE* and *SST* are sum of squares explained by the regression model and total sum of squares, respectively. The model was considered acceptable if P value was less than 10% (Samapundo *et al*., 2006) [23] and minimum RMSE value (Basunia & Abe, 2001) [4]. Parameters of net isosteric heat of sorptions (q_{st}) in Eqs. 8 and 9 were tested for goodness of fit on the basis of R^2 and RMSE values stated above.

Results and Discussion

Moisture sorption characteristics of raw, parboiled and pre- conditioned rice: Figure 2 shows the moisture sorption characteristics of rice samples at different temperatures, *viz*., raw rice, parboiled rice and pre-conditioned rice with different salt levels. These behaviors manifested in the form of sigmoid shaped curve thus reflecting Type II (according the BET classification) isotherm characteristics (Rizvi, 2005) [22]. The moisture sorption behavior of raw rice, parboiled rice and control were found to be different from those with the salt treated rice samples. At any particular level of water activity up to 0.65-0.75 and temperature between 20 °C and 30 °C (Zone I) (Figs. 2a and 2b), the equilibrium moisture content (EMC) of raw rice was found to be highest followed by parboiled, parboiled-conditioned without salt and pre-condition rice with salt. Similar phenomenon has been observed at temperature between 40 and 50 °C, but that is apparent at water activity value above 0.55 (Zone II) (Figs. 2c and 2d). After zones I and II at respective sorption temperature range, EMC values of pre-conditioned rice with salt became higher compared to raw, parboiled and no-salt pre-condition rice samples. This phenomenon of lower EMC values (compared to raw rice) of heat-treated rice samples (parboiled and pre-condition rice samples) at lower range of water activity, and followed by higher EMC values at higher range of a_w is quite similar to EMC values for heat-treated rice as reported by Witek *et al.* (2010) [30]. After heat treatment, most of the starch in raw rice transformed from crystalline to amorphous form, and there was loss of structural order between nano and micro-scale. These lead to lower moisture sorption and enhanced kinetics of hydration in the heat-treated rice. Further, EMC of salt-infused pre-conditioned rice showed a correlation with its salt content. In zones I and II, corresponding EMC values was found to be inversely proportional to salt content in pre-conditioned rice. Pre-conditioned rice with highest salt content (5%) showed lowest EMC value. This value was highest for lowest salt content pre-conditioned rice (2.5%). Beyond these two respective zones, a reverse trend was observed. EMC values of pre-conditioned rice were directly proportional to the salt content: highest for high salt pre-conditioned rice followed by decreasing EMC values for low salt pre-conditioned rice. Quite similar cross-over phenomenon have been reported for sugar-rich product at high a_w and higher temperature. (Alhamdan & Hassan, 1999; Jagannadha Rao *et al*., 2006; Verma & Narain, 1990) [1, 14, 28]. This might be attributed to transition of crystalline salt at low equilibrium relative humidity (a_w) to partial solubilization of salt with adsorbed water; thus capable of holding more moisture at higher level of water activity (increased hygroscopicity).



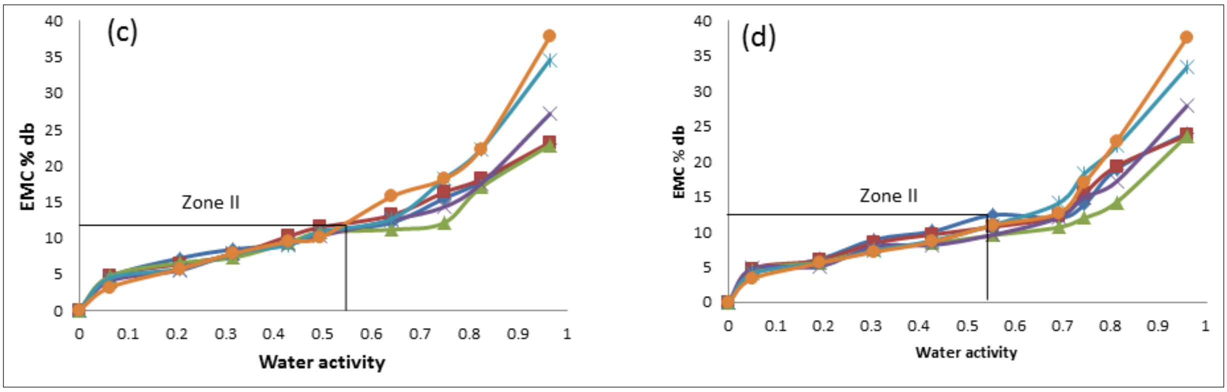


Fig 2: Moisture sorption isotherms of raw, parboiled and pre-conditioned rice samples at (a) 20 ºC, (b) 30 ºC (c) 40 ºC and (d) 50 ºC

Fitting of sorption models to experimental data

Sorption behaviours of all these samples were fitted to different models (Table 1) following nonlinear regression. Table 2 shows the detail analysis for goodness of fit to these models. It was observed that, GAB equation could be taken as best fit model to these experimental data for all rice samples based on acceptable ranges of coefficient of determination ($R^2 \geq 0.99$), Root Mean Square Error ($0.61 \leq RMSE \leq 0.89$) and percent deviation modulus ($5.89 \leq \%P \leq 7.33$). Modified Henderson model and modified Chung-Pfost model were found next best to fit well the pre-conditioned rice samples containing 0.0 to 5.0% salt content. Modified Henderson model was best-fit model next to modified GAB model for pre-conditioned rice without salt.

Figure 3 shows moisture sorption isotherms of rice samples fitted to modified GAB equation. The experimental data were close to these prediction lines for pre-conditioned rice samples than that of either raw or parboiled rice. Further, it is revealed from these figures that, when the environmental relative humidity was adjusted beyond 50% (water activity 0.5), increase in temperature from 20 to 50 ºC, equilibrium moisture content did not vary significantly, and sorption characteristics become indistinguishable. This phenomenon was more prominent with pre-conditioned rice samples (contained salt or no salt). These might be attributed to modification of adsorption sites at the core and surface of the grain during the heat curing process.

Table 2: Estimated parameters of different models using sorption data of rice samples

Rice sample	Model	Model parameters A	B	C	R2	RMSE	% P
Raw rice	MHEE	5.79x 10-5	33.188	2.11	0.97	1.12	7.84
	MOSE	11.54	-0.035	0.18	0.86	1.69	13.07
	MHAE	9.42	-0.009	3.96	0.86	1.80	19.59
	MCPE	764.07	42.60	0.24	0.95	1.07	10.77
	MGAB	7.96	0.68	749.32	0.99	0.89	7.33
Parboiled rice	MHEE	3.45 x 10 -5	89.79	2.10	0.98	1.13	6.85
	MOSE	11.41	-0.01	4.62	0.91	1.64	14.86
	MHAE	9.40	-0.004	4.04	0.85	2.12	19.87
	MCPE	989.94	69.21	0.24	0.94	1.27	9.60
	MGAB	8.53	0.66	501.46	0.99	0.77	6.37
Pre-Conditioned rice without salt	MHEE	3.99 x 10 -5	59.76	2.28	0.99	1.09	5.07
	MOSE	10.31	-0.02	4.17	0.96	1.05	8.82
	MHAE	8.03	-0.007	3.64	0.92	1.46	13.53
	MCPE	984.62	93.78	0.25	0.98	0.74	5.46
	MGAB	6.25	0.74	975.56	0.99	0.84	5.89
With 2.5% salt	MHEE	2.60 x 10-5	377.21	1.81	0.98	0.89	6.24
	MOSE	10.47	0.00	4.01	0.96	1.46	15.30
	MHAE	6.91	0.001	3.20	0.93	1.81	17.50
	MCPE	669.12	97.36	0.19	0.97	0.85	6.47
	MGAB	6.21	0.78	735.29	0.99	0.71	6.14
With 3.5% salt	MHEE	3.45x 10-5	89.79	2.10	0.98	0.99	9.15
	MOSE	13.65	-0.02	4.16	0.93	2.82	25.56
	MHAE	6.56	-0.005	2.82	0.93	2.07	21.03
	MCPE	466.50	91.36	0.14	0.98	0.92	9.82
	MGAB	6.64	0.83	749.32	0.998	0.61	6.45
With 5.0% salt	MHEE	5.79 x 10 -5	33.18	2.12	0.98	1.24	8.13
	MOSE	12.83	0.004	4.01	0.97	3.30	26.44
	MHAE	5.70	-0.001	2.58	0.94	2.36	24.89
	MCPE	398.61	99.94	0.13	0.98	1.26	13.25
	MGAB	6.51	0.85	388.86	0.998	0.79	6.54

(MHEE- Modified Henderson; MOSE – Modified Oswin; MHAE – Modified Halsey; MCPE- Modified Chung-Pfost; MGAB- Modified GAB equation.)

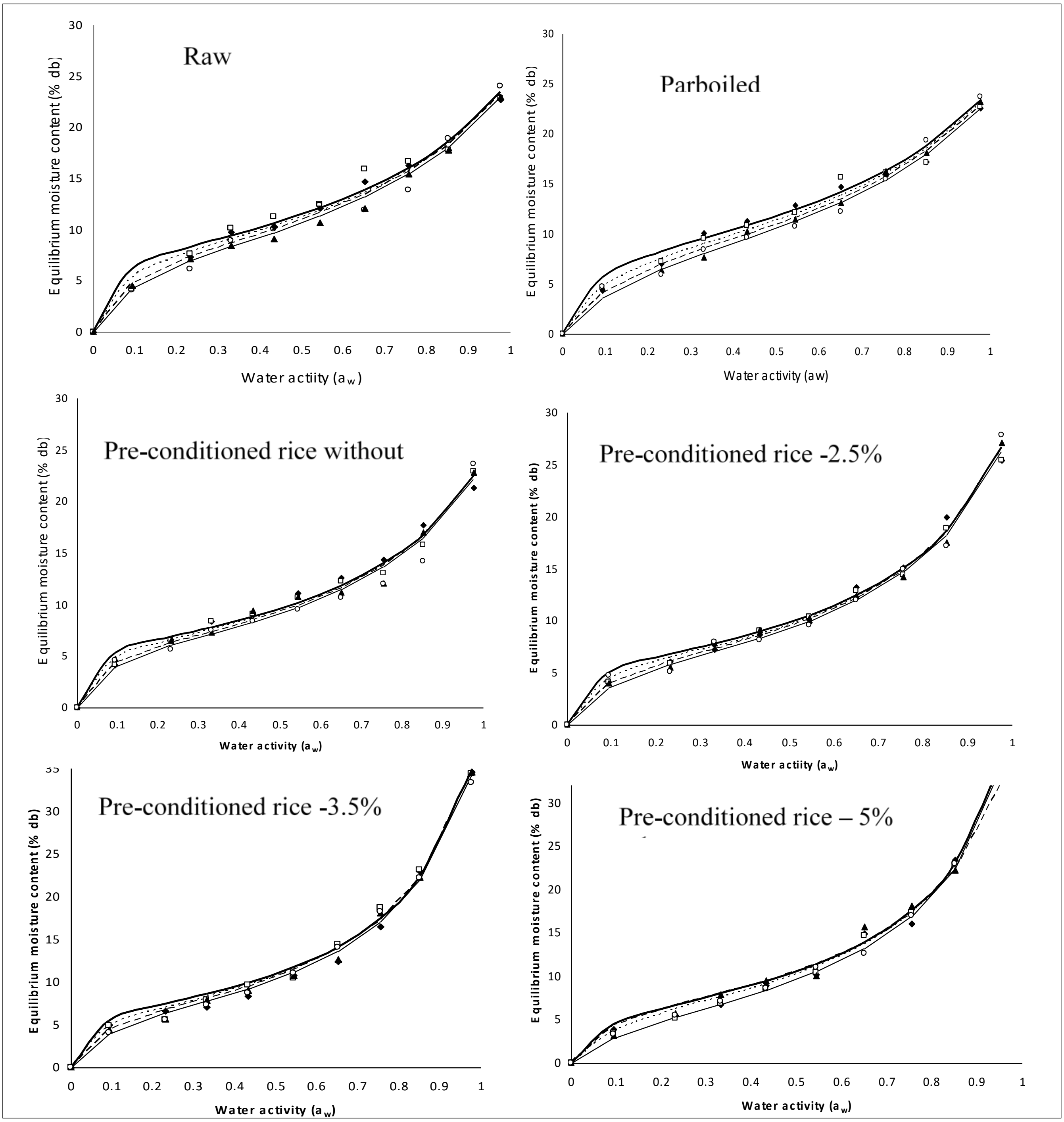


Fig 3: Moisture sorption isotherms of rice samples at 20 ºC (♦), 30 ºC (□), 40 ºC (▲) and 50 ºC (○) and the prediction lines obtained through modified GAB equation

Microstructure of parboiled and pre-conditioned rice samples are compared in Fig. 4. The modification in surface of the grain induced in the pre-conditioning process is quite apparent. Surface of parboiled rice appeared to be discontinuous than that of pre-conditioned rice (Figs. 4a and b). This discontinuity of the rice surface might be due to uneven stress development during cooling of parboiled kernel. Continuous surface structure of the pre-conditioned rice might have been generated through prolong heat treatment (about 90 minutes in 200-250 ℃ temperature and slow and uniform heating) of the high moisture kernel with possible transition from sol to gel (integrated network) structure (Bhanudas, J.S., 2009; Witek *et al*. 2010; Villareal and Juliano, 1987) [6, 29, 30]. Due to this, it creates an impervious layer for moisture migration from interior to surface of the kernel. Consequent up on this, it might have hindered the moisture sorption behavior of the pre-conditioned rice. Water was mostly held in the available gap (cracks or capillary) without much lowering of pressure (water activity) through active binding. However, the continuity in the core of both parboiled and pre-conditioned rice samples are comparable and no significant difference in water binding process is expected. Thus, controlling of environmental relative humidity is more desirable for better keeping quality of the pre-conditioned rice than controlling the storage temperature. A packaging material with high moisture barrier property could be best packaging material for maintaining low puffing moisture content in the pre-conditioned rice.

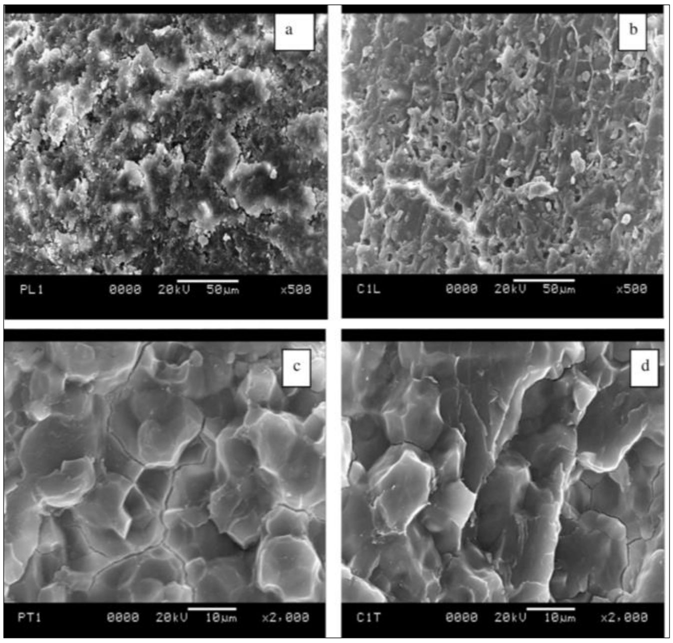


Fig 4: Comparison of microstructure of surface (a and b) and core (c and d) respectively for parboiled rice and pre-conditioned rice without salt

Net Isosteric heat of sorption

Net Isosteric heat of sorption of rice samples varying with moisture content is shown in Fig. 5. The net isosteric heat of sorption (q_{st}) of rice samples were obtained from semi-log plot of ln a_w versus 1/T stated in equations 6 and 7. It varied from 2.28-0.48, 4.127-0.54, 3.99-0.48, 1.239-0.179, 1.056-0.247 and 1.0143-0.0604 kJ mol^{-1} for raw, parboiled, 0.0, 2.5, 3.5 and 5.0% salt conditioned rice, respectively within the moisture range of 5.0-30.0% db. The net isosteric heat of sorption values followed a decreasing trend with increase of moisture content. These decreasing trends of Isosteric heat of sorption are quite similar to many cereal grains and seeds (Sopade & Ajisegiri 1994; Suthar & Das, 1997) [25, 27] and particularly for rice (Benado & Rizvi, 1989, Haque *et al*., 2007) [5, 12]. The effect of parboiling and pre-conditioning of rice shows lower values of net isosteric heat of sorption for salt conditioned rice samples (2.5, 3.5, 5.0% salt) as compared to raw, parboiled or pre-conditioned rice with 0% salt (control samples). Lower values of q_{st} for pre-conditioned rice samples with salts compared to either control, raw or parboiled rice further suggests irreversible loss of binding sites in the former. Among the salt treated pre-conditioned rice samples, it is higher for 2.5% salt samples than 3.5 or 5.0% salt. The presence of high salt content in pre-conditioned rice became more hygroscopic in nature and required less energy to bind water molecules in the absorption sites and therefore giving lower values of net isosteric heat of sorption for 3.5 and 5.0% compared to 2.5% salt. Table 3 shows the estimated values of the constants of equations 8 and 9 along with R^2 and RMSE values. The experimental data are correlated well with both the models (Kechau & Maalej (1999) [16] model and exponential model). However, on the basis of RSME values, it appears that exponential model fits well to all the rice samples.

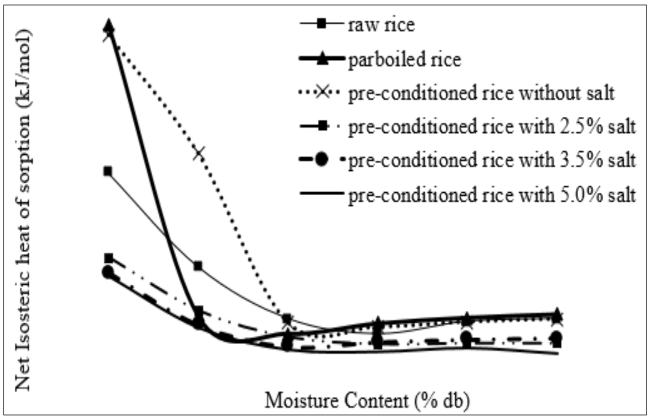


Fig 5: Net Isosteric heat of sorption of rice samples varying with moisture content

Table 3: Estimated values of parameters correlating net isosteric heat of sorption and equilibrium moisture contents of rice samples

$q_{st} = q_o \exp\left(-\frac{M_e}{M_r}\right)$	**Parameters**				**R^2**	**RMSE**
Sample:	q_o		M_r			
Raw rice	3.30		5.10		0.90	0.34
Parboiled	4.34		6.93		0.95	0.30
Conditioned rice without salt	5.32		7.99		0.80	0.87
Conditioned rice with 2.5%salt	2.03		12.34		0.58	0.31
Conditioned rice with 3.5% salt	0.84		14.92		0.60	0.23
Conditioned rice with 5.0% salt	0.78		12.20		0.54	0.20
$q_{st} = \frac{a.M_e^b}{c + M_e^d}$	Parameters				R^2	RMSE
	a	b	c	d		
Raw rice	6.84	0.53	1.42	1.63	0.94	0.74
Parboiled	9.23	1.03	1.54	1.98	0.97	0.71
Conditioned rice without salt	9.57	2.10	1.29	2.91	0.75	1.06
Conditioned rice with 2.5% salt	18.84	0.65	11.12	1.94	0.65	0.39
Conditioned rice with 3.5% salt	17.55	0.68	28.22	2.29	0.68	0.20
Conditioned rice with 5.0% salt	2.06	2.18	2.08	3.09	0.71	0.24

Conclusions

The moisture sorption isotherms of raw, parboiled and pre-conditioned rice followed Type II isotherms according to BET classification. Hydrothermal treatment (parboiling) and heat curing (pre-conditioning) of raw rice causes loss of binding sites with consequent decrease in equilibrium moisture content. At higher relative humidity environment, the pre-conditioned rice with salt becomes more hygroscopic than raw or parboiled rice. Modified GAB equation is found to be best-fit model for describing the sorption behaviour of raw, parboiled and pre-conditioned rice containing salt or no salt. The heats of sorption showed an exponential relationship with decreasing trend with the increase in moisture contents. Moisture adsorption of pre-conditioned rice could be controlled well with low relative humidity of storage environment and using low water permeability packaging material.

References

1. Alhamdan AM, Hassan BH. Water sorption isotherms of date pastes as influenced by date cultivar and storage temperature. Journal of Food Engineering. 1999;39:301-306.
2. AOAC. Official Methods of Analysis (15th Edition.) Washington, DC: Association of Official analytical Chemists Inc. 1990.
3. Aviara NA, Ajibola OO, Aregbesola OA, Adedeji MA. Moisture sorption isotherms of sorghum malt at 40 and 50 ºC. Journal of Stored Products Research. 2006;42:290-301.
4. Basunia MA, Abe T. Moisture desorption isotherms of medium-grain rough rice. Journal of Stored Products Research. 2001;37: 205-219.
5. Benado AL, Rizvi SSH. Thermodynamic properties of water on rice as calculated from reversible and irreversible isotherms. Journal of Food Science. 1989;50:101-105.
6. Bhanudas JS. Mechanized system for pre-conditioning of rice for puffing in microwave oven and its progressive microstructural changes, Unpublished M. Tech. Thesis, IIT, Kharagpur, WB, India. 2009, 38-41.
7. Bianco AM, Pollio ML, Resnik SL, Boente G, Larumbe A. Comparison of water sorption behaviour of three rice varieties under different temperatures. Journal of Food Engineering. 1997;33:395-403.
8. Chandrasekhar PR, Chattopadhyay PK. Rice puffing in relation to its varietal characteristics and processing conditions. Journal of Food Process Engineering. 1991;14(4):261-277.
9. Chinnaswamy R, Bhattacharya KR. Studies on expanded rice: Optimum processing conditions. Journal of Food Science. 1983;48:1604-1608.
10. Choi BM, Lanning SB, Siebenmorge TJ. A review of hygroscopic equilibrium studies applied to rice. Trans. ASABE. 2010;53(6):1859-1872.
11. Das H. Food Processing Operations Analysis. Asian Books Private Limited, New Delhi. 2005, 30-42.
12. Haque Md A, Shimizu N, Kimura T, Bala BK. Isosteric heats of asorption and desorption for different forms of hybrid rice. International Journal of Food Properties. 2007;10(1):25-37.
13. Iguaz A, Vírseda P. Moisture desorption isotherms of rough rice at high temperatures. Journal of Food Engineering. 2007;79:794-802.
14. Jagannadha Rao PVK, Das SK, Das Madhusweta. Moisture sorption isotherms of sugarcane, palmyra-palm and date-palm jaggery. In: Proceedings of American Society of Agricultural and Biological Engineers Annual International Meeting (paper no. 063007), Portland, Oregon, 2006 July.
15. Jayasmita. Development of a rice conditioner for making puffed rice using domestic microwave oven. Unpublished M.Tech. Thesis, Indian Institute of Technology, Kharagpur, WB, India. 2008, 38-42.
16. Kechau N, Maalej M. Desorption isotherms of imported banana. Drying Technology. 1999;7(6):1201-1202.
17. Labuza TP, Kaanane A, Chen JY. Effects of temperature on the moisture sorption isotherms and water activity shift of two dehydrated foods. Journal of Food Science. 1985;50:385-391.
18. Maisont S, Narkrugsa W. Effects of salt, moisture content and microwave power on puffing qualities of puffed rice, Kasetsart Journal - Natural Science. 2010;44(2):251-261.
19. Mohapatra M. Mechanized preconditioning of rice and its microwave puffing. Ph.D. Thesis, Indian Institute of Technology, Kharagpur, WB, India. 2010, 83-99.
20. Mohapatra M, Das SK. Effect of Process Parameters and optimization on microwave puffing performance of rice. Research Journal of Chemistry and Environment. 2011;15(2): 454-461.
21. Robert RL, Houston DF, Kester EB. Expanded rice product. A new use of parboiled rice. Food Technology. 1951;5:361-363.
22. Rizvi SSH. Thermodynamic properties of Food Dehydration, In: Engineering Properties of Foods, Eds. Rao, M. A., Rizvi, S. S. H. and Datta, A., 3rd Ed., CRC Press, USA. 2005, 249-326.
23. Samapundo S, Devlieghere F, Meuleneur B, Atukwase A, Lamboni Y, Debevere JM. Sorption isotherms and isosteric heat of sorption of whole yellow dent corn. Journal of Food Engineering. 2006;79:168-175.
24. Sootjarit S, Jittanit WS, Phompan P, Rerkdamri. Moisture sorption behavior and drying kinetics of pre-germinated rough rice and pre-germinated brown rice, Trans. of ASABE. 2011;54(1):255-263.
25. Sopade PA, Ajisegiri ES. Moisture sorption study of Nigerian Foods: Maize and Sorgham. Journal of Food Process Engineering. 1994;17:33-56.
26. Sun Da Wen. Comparison and selection of EMC/ERH isotherm equations for rice. Journal of Stored Products Research. 1999;35:249-264.
27. Suthar SH, Das SK. Moisture sorption isotherms for Karingda [*Citrullus lanatus* (Thumb) Mansf] seed, kernel and hull. Journal of Food Process Engineering. 1997;20:349-366.
28. Verma VK, Narain M. Moisture absorption isotherms of jaggery. Journal of Stored Products Research. 1990;26(2):61-66.
29. Villareal CP, Juliano BO. Varietal Differences in Quality Characteristics of Puffed Rices. Cereal Chemistry. 1987;64(4): 337-342.
30. Witek M, Weglarz WP, De Jong L, Van Dalen G, Blonk JCG, Heussen P, *et al*. The structural and hydration properties of heat-treated rice at multiple length scale. Food Chemistry. 2010;120:1031-1040.s