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Hydration behaviour of food grains and modelling their moisture pick up as per Peleg's equation: Part I. Cereals

Singh Vasudeva · Vishwanathan K. H. · Aswathanarayana K. N. · Indhudhara Swamy Y. M.

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Abstract Cereals and millets generally hydrate at a moderate rate and their hydration behaviour differs in native and in processed state. The study was on the hydration of paddy, milled rice, parboiled rice, wheat, millets and equilibrium moisture content (EMC) on soaking at room temperature. Paddy hydrated very slowly, hydration rate was slow in brown rice but fast in milled rice and highest in waxy rice. In most of the rice varieties, maximum absorption occurred at the end of 30 min. In wheat hydration rate was slow and its EMC was highest (43%). Maize grits of big size hydrated slowly compared to small grits. In coarse cereals EMC varied from 28 to 38%. Foxtail millet hydration was slow whereas that of finger millet was fast. The data were tested on the Peleg's equation, which gave a reasonable fit to experimental data. Peleg's constants k_1 and k_2 were calculated for the above grains and their hydration behaviour has been predicted. The model fitted very well to milled rice hydration data where the coefficient of variance ranged from 0.9982 to 0.9995. With exception in some millet the hydration data fitted well with the Peleg's equation. Generalized equations have been formulated for prediction of moisture content of cereals and millets.

Keywords Cereals · Millets · Equilibrium moisture content · Hydration behaviour · Peleg's equation

Vasudeva S.[1] · Vishwanathan K. H.[2] · Aswathanarayana K. N.[1] · Indhudhara Swamy Y. M.[1]
[1]Department of Grain Science and Technology;
[2]Department of Food Engineering, Central Food Technological Research Institute, (Council of Scientific and Industrial Research), Mysore - 570 020, India

Singh V. (✉)
E-mail: singhva2003@yahoo.co.in

Introduction

Hydration behaviour of raw, parboiled paddy, parboiled rice at room temperature (~28°C) indicated that equilibrium moisture content (EMC) was 0.5 to 2% more in steamed rice and 5 to 15% more in parboiled rice compared to EMC of raw rice which was because of gelatinized and retrograded starch in parboiled rice (Swamy et al. 1971). Dry heat parboiled rice registered high EMC and beaten rice showed much higher EMC compared to that of raw rice (Ali and Bhattacharya 1976). World rice varieties have been classified into 8 groups, based on insoluble amylose content as one of the important properties along with other physico-chemical properties like alkali score, stickiness, consistency, viscographic behaviour and EMC and similarly on the same parameters Indian rice varieties have also been classified (Bhattacharya et al. 1979a, 1980). Vasudeva Singh et al. (2000) have studied the thermal and physico-chemical properties of rice grain, flour and starch from indica, japonica (Nipponbare) and japonica waxy rice (Himenomochi) varieties. It was noticed among the physico-chemical properties studied, EMC showed an important differentiation, where indica milled rice had EMC of ~28%, japonica 30% and japonica waxy had 35% on wet basis. Swamy et al. (1978) have studied the changes in physico-chemical properties with ageing of rice varieties where again the EMC played a key role. Unnikrishnan and Bhattacharya (1987) have studied varietal variation after parboiling by mild and severe conditions based on EMC as one of the important parameters. Varietal difference in EMC as well as effect of kernel chalkiness on moisture absorption was studied and they inferred that chalky grains showed higher EMC (Bhattacharya et al. 1979b). Srinivas et al. (1984) observed that chalky grains registered higher EMC compared to non-chalky grains. Hydration was generally assumed to follow a first-order chemical reaction with a single rate constant (Ramesh 2001). Sashikala et al. (2005) reported that parboiled rice has high EMC compared to raw rice. Jagtap et al. (2008) showed that parboiled rice requires high energy for grinding and also registers high viscosity in its slurry form which is because of retrograded starch compared to raw rice where absorption of moisture was also high in parboiled rice. Generally, published literature is lacking about the study of simultaneous hydration behaviour of cereals, millets and modeling their sorption data.

Present study reports on absorption of moisture by rice in the form of paddy, brown rice, milled rice as well as some of millets in order to understand the characteristics of constants in the equation. Absorption of moisture by food materials have been analyzed by Fick's laws of diffusion with appropriate equations (Crank 1975). But these equations are complex and cumbersome. A simplified equation was proposed by Peleg (1988) to fit sorption data, and its application has been demonstrated for some food materials.

Materials and methods

Paddy varieties as listed in Tables were procured from Agricultural Produce Marketing Corporation (APMC Market) and Basmati paddy was gift from L.T. Overseas, Pvt. Ltd, Amritsar, India. Commercial rice and some rice samples stored in the cold room at around 7°C were also used. Maize (*Zea mays*), sorghum (*Sorghum vulgare*) (white as well as red variety) and wheat (*Triticum sativum*) were procured from the market. Ragi (*Elusine coracana*), foxtail millet (*Setaria italica*), and bajra (*Pennisetum typhoideum*), (obtained from two sources and labeled as bajra 1 and bajra 2) were also procured from local market.

Moisture content: The grains were soaked in water and removed after different time intervals and after removing surface moisture by compressing between filter paper moisture was estimated at 130°C for 1 h as per AACC (2000) procedure. For each grain 3 replications were carried out.

Modeling of hydration behaviour: A simplified equation was proposed by Peleg (1988) to fit sorption data, and its application has been demonstrated for some food materials (Roman-Gutierrez et al. 2002).

Modeling: Peleg (1988) proposed that

$$M_t = M_0 + t/(k_1 + k_2 t) \qquad \ldots (1)$$

$$\text{As } t \rightarrow \infty \qquad M_E = M_0 + 1/k_2$$

where M_0 = Initial moisture content on dry basis, M_t = Moisture content at time t on dry basis, M_E = Equilibrium moisture content on dry basis, and k_1 and k_2 are Peleg's constants

The equation is applicable to the curvilinear segment of the sorption curve because beyond this region (M_t–M_0) is constant. Rearranging equation (1), we get

$$t / (k_1 + k_2 t) = M_t - M_0$$

$$\text{Hence, } t/(M_t - M_0) = k_1 + k_2 t$$

Therefore, by plotting t/(M_t–M_0) against time 't' in hours gives a straight line with k_1 as the ordinate intercept and k_2 the gradient line. With this plot characteristics of the constants could be studied.

Average values of k_1 and k_2 were calculated and they have been substituted in equation (1), to predict the average moisture content (M_t) on dry basis, which is named as modified Peleg's equation. All modeling discussions are based on the moisture content estimated and converted to dry basis.

Results and discussion

Hydration behaviour of paddy grains: In all paddy varieties initial moisture content varied from 9 to 11% (Table 1). At 5 min soaking, the moisture pick up was 2 to 5%. The moisture absorption increased slowly and at 3 h the moisture content varied from 18 to 21%. At 9 h maximum moisture content reached in all grains and EMC varied from 25 to 35%; highest was in 'IR 64' and least in 'IR 30864'. Different paddy varieties absorbed moisture to different extents; coarse varieties showed less EMC compared to fine varieties.

Hydration behaviour of brown and milled rice: In non-waxy brown rice, initial moisture content varied from 11 to 17% (Table 2). In waxy rice it was 17%. At 5 min soaking, highest moisture pick up was in 'Agonibora'. Increase in absorption was maximum at 3 h. Finally at 24 h, EMC of each grain varied from 27 to 35%, highest being in brown rice of waxy variety 'Agonibora'.

In parboiled brown rice absorption was comparatively fast and at each observation higher moisture content was noticed compared to other raw brown rice varieties. EMC of parboiled brown rice was ~52% indicating the behaviour of retrograded starch in the parboiled rice.

Table 1 Hydration behaviour of various paddy varieties and their equilibrium moisture content (EMC)

Variety	Moisture content (% w b) with time								
	Initial	5 min	30 min	1 h	3 h	5 h	7 h	9 h	EMC
'Basmati'	9.9 ± 0.11	14.6 ± 0.02	16.4 ± 0.89	18.1 ± 0.89	20.8 ± 0.71	22.8 ± 0.04	24.7 ± 0.21	25.3 ± 0.31	29.4 ± 0.21
'IR64'	10.2 ± 0.02	13.3 ± 0.20	15.6 ± 0.45	16.7 ± 0.48	17.9 ± 0.52	19.8 ± 0.43	21.7 ± 0.54	22.6 ± 0.1	34.9 ± 0.33
'IR 30864'	9.2 ± 0.04	12.3 ± 0.34	14.9 ± 0.14	15.0 ± 0.52	18.8 ± 0.04	19.4 ± 0.14	21.2 ± 0.23	21.6 ± 0.47	24.8 ± 0.14
'Jyothi'	11.1 ± 0.14	13.0 ± 0.03	14.4 ± 0.41	15.2 ± 0.33	18.2 ± 0.03	20.4 ± 0.45	21.2 ± 0.53	22.4 ± 0.15	24.7 ± 0.47
'Rashi'	10.7 ± 0.45	12.7 ± 0.53	13.9 ± 0.04	14.3 ± 0.12	17.6 ± 0.09	20.1 ± 0.42	21.1 ± 0.12	21.2 ± 0.34	25.9 ± 0.19
'Sona mahsuri'	11.2 ± 0.03	13.8 ± 0.18	16.0 ± 0.09	17.2 ± 0.54	19.9 ± 0.03	23.5 ± 0.23	24.0 ± 0.13	25.4 ± 0.03	27.1 ± 0.36

In wheat initial moisture content was ~9%, the absorption rate was fast and at the end of 3 h the moisture content was 27% and final EMC was above 43% (Table 2), which is perhaps due to gluten protein which absorbs higher amount of moisture.

In milled rice varieties the moisture content varied from 10 to 16%. At 5 min, the absorption increase was 4 to 6% (Table 3). Higher absorption was evident in waxy milled rice because of higher amylopectin content. In milled parboiled rice the EMC was ~55% due to different types of starch present in the grain. Irrespective of size and shape of the grain, EMC values in rice varieties were almost in the same range except in the waxy rice.

Modeling of sorption data of paddy, brown and milled rice: Table 4 shows the experimental data and predicted data by using Peleg's equation and moisture data predicted from the average values of Peleg's constants k_1 and k_2 of various paddy varieties. The relevant data are presented for brown rice (Table 5) as well as for milled rice (Table 6).

From the linear regression analysis the coefficient of variant r^2 were worked out which varied from 0.9496 to 0.9795 for paddy, 0.9296 to 0.9897 for brown rice and 0.9949 to 0.9985 for milled rice and these proved the validity of Peleg's equation.

In paddy grains (Table 4) hydration was continued up to 9 h, as the hydration was very slow for 3 h, which may

Table 2 Hydration behaviour of various brown rice, wheat and their EMC

Variety	Moisture content (% w b) with respect to time						
	Initial	5 min	30 min	1 h	2 h	3 h	EMC
'Agonibora' (Waxy)	16.7 ± 0.77	19.6 ± 0.04	23.1 ± 0.21	26.1 ± 0.22	29.6 ± 0.21	31.0 ± 0.22	34.8 ± 0.12
'Basmati'	16.5 ± 0.11	19.2 ± 0.14	22.5 ± 0.21	24.7 ± 0.21	27.3 ± 0.33	28.0 ± 0.06	30.4 ± 0.14
'IR 64'	11.3 ± 0.31	13.4 ± 0.13	17.2 ± 0.07	20.5 ± 0.26	23.5 ± 0.28	25.5 ± 0.28	30.0 ± 0.02
'IR 30864'	12.2 ± 0.12	14.8 ± 0.32	17.7 ± 0.14	18.6 ± 0.48	22.4 ± 0.17	24.0 ± 0.37	28.0 ± 0.04
'Jaya'	12.6 ± 0.09	16.0 ± 0.22	19.1 ± 0.04	21.6 ± 0.02	24.6 ± 0.03	26.4 ± 0.1	29.0 ± 0.03
'Jyothi' raw dehusked	12.8 ± 0.06	15.1 ± 0.08	18.6 ± 0.13	20.9 ± 0.18	23.6 ± 0.13	24.9 ± 0.12	28.0 ± 0.04
'Jyothi' dehusked, parboiled	10.9 ± 0.07	17.0 ± 0.04	23.4 ± 0.11	29.7 ± 0.06	35.1 ± 0.65	39.7 ± 0.54	52.0 ± 0.38
'Mandya Vijaya'	12.0 ± 0.08	15.0 ± 0.04	19.4 ± 0.24	22.5 ± 0.38	25.1 ± 0.02	26.2 ± 0.24	29.8 ± 0.22
'Rashi'	12.0 ± 0.06	14.9 ± 0.32	18.3 ± 0.52	20.7 ± 0.27	22.8 ± 0.05	24.3 ± 0.00	29.0 ± 0.04
'Sona mahsuri'	14.5 ± 0.02	18.7 ± 0.21	20.3 ± 0.21	22.5 ± 0.13	24.8 ± 0.08	25.8 ± 0.06	29.0 ± 0.09
'SR 26-B'	14.0 ± 0.07	16.7 ± 0.13	20.3 ± 0.04	22.7 ± 0.16	25.9 ± 0.18	26.2 ± 0.06	26.8 ± 0.21
Wheat	9.4 ± 0.00	13.5 ± 0.60	16.4 ± 0.01	21.0 ± 0.28	24.1 ± 0.56	27.1 ± 0.00	42.5 ± 0.30

EMC = Equilibrium moisture content

Table 3 Hydration behaviour of various milled rice and their EMC

Variety	Moisture content (% w b) with time						
	Initial	5 min	30 min	1 h	2 h	3 h	EMC
'ADT-27'	14.0 ± 0.21	18.5 ± 0.06	22.9 ± 0.21	24.6 ± 0.04	25.9 ± 0.29	25.7 ± 0.03	26.2 ± 0.20
'Agonibora' (Waxy)	16.4 ± 0.18	22.2 ± 0.13	29.2 ± 0.04	32.4 ± 0.03	33.6 ± 0.18	34.4 ± 0.04	34.6 ± 0.03
'Basmati'	12.3 ± 0.29	17.5 ± 0.11	25.2 ± 0.12	27.5 ± 0.11	27.4 ± 0.03	28.2 ± 0.13	28.2 ± 0.01
'IR 64'	12.7 ± 0.36	16.2 ± 0.05	27.4 ± 0.24	28.7 ± 0.05	28.7 ± 0.01	28.4 ± 0.07	28.9 ± 0.14
'IR 30864'	12.5 ± 0.02	16.3 ± 0.06	22.6 ± 0.01	25.0 ± 0.06	25.6 ± 0.00	25.6 ± 0.08	26.0 ± 0.03
'Jaya'	12.9 ± 0.14	17.3 ± 0.23	26.4 ± 0.12	27.8 ± 0.18	27.9 ± 0.08	27.6 ± 0.26	28.0 ± 0.01
'Jyothi' parboiled	10.1 ± 0.41	20.4 ± 0.47	34.1 ± 0.14	40.7 ± 0.37	46.5 ± 0.26	49.1 ± 0.74	54.9 ± 0.04
'Jyothi' raw	13.7 ± 0.02	19.5 ± 0.41	26.5 ± 0.28	28.3 ± 0.75	27.9 ± 0.03	28.1 ± 0.12	29.0 ± 0.03
'Mandya Vijaya'	11.9 ± 0.10	17.6 ± 0.02	25.3 ± 0.03	27.0 ± 0.06	28.0 ± 0.14	28.0 ± 0.03	28.6 ± 0.11
'Rashi'	13.0 ± 0.14	17.8 ± 0.14	25.4 ± 0.23	27.6 ± 0.14	28.3 ± 0.05	28.2 ± 0.12	29.5 ± 0.12
'Sona mahsuri'	14.5 ± 0.24	19.7 ± 0.11	24.9 ± 0.13	25.8 ± 0.21	26.9 ± 0.13	26.5 ± 0.13	27.1 ± 0.09
'SR 26-B'	15.1 ± 0.11	20.7 ± 0.04	26.5 ± 0.04	27.1 ± 0.13	27.2 ± 0.14	27.3 ± 0.14	27.6 ± 0.02
'T(N)-3'	13.7 ± 0.22	18.3 ± 0.12	23.6 ± 0.12	26.6 ± 0.20	27.9 ± 0.03	28.3 ± 0.03	28.6 ± 0.13
'T-65'	14.9 ± 0.24	20.2 ± 0.31	27.5 ± 0.50	29.9 ± 0.01	30.6 ± 0.06	30.4 ± 0.02	30.9 ± 0.04

EMC = Equilibrium moisture content

Table 4 Experimental and predicted hydration behaviour of different paddy varieties

Variety		Moisture content (% d b) with time							
		Initial	5 min	30 min	1 h	3 h	5 h	7 h	9 h
'Basmati'	Expt*	11.0	17.1	19.60	22.1	26.2	29.5	32.8	33.9
	Pred	11.0	13.0	19.3	23.3	29.2	31.1	32.1	32.7
	Avg	11.0	12.2	16.6	19.7	24.7	26.5	27.5	28.0
'IR64'	Expt	11.4	15.3	18.5	20.1	21.9	24.8	27.8	29.2
	Pred	11.4	12.7	17.3	20.4	25.0	26.6	27.4	27.9
	Avg	11.4	12.6	17.0	20.1	25.1	26.9	27.9	28.4
'IR 30864'	Expt	10.1	14.0	17.5	17.6	23.2	24.0	27.0	27.5
	Pred	10.1	11.7	16.8	19.9	24.4	25.8	26.5	26.9
	Avg	10.1	11.3	15.7	18.8	23.9	25.7	26.6	27.2
'Jyothi'	Expt	12.4	15.0	16.9	7.9	22.3	25.6	26.9	28.8
	Pred	12.4	13.3	16.9	19.5	24.1	25.9	26.8	27.4
	Avg	12.4	13.7	18.0	21.1	26.2	28.0	28.9	29.5
'Rashi'	Expt	12.0	14.5	16.1	16.6	21.4	25.1	26.8	26.9
	Pred	12.0	12.8	16.0	18.5	23.1	25.0	25.9	26.1
	Avg	12.0	13.3	17.6	20.7	25.8	27.6	28.5	29.1
'Sona mahsuri'	Expt	12.6	16.0	19.0	20.8	24.8	30.7	31.6	34.0
	Pred	12.6	13.9	18.9	22.5	28.6	30.8	32.0	32.7
	Avg	12.6	13.8	18.2	21.3	26.4	28.2	29.1	29.7

*Exp: Experimental, Pred: Predicted as per Peleg's equation, Avg: Predicted by using the average values of k_1 and k_2 which were calculated by using the modified Peleg's equation

be due to the presence of space between the lemma, palea (husk) and the endosperm. Initially, the absorption was very slow, and hence, the predicted moisture content was less but with increase of time of hydration the difference between the predicted and the experimental values minimized. Majority of the measurements showed that the predicted values were lower than experimental values. However, the differences between experimental and predicted values were still high in fine paddy varieties which varied between 0.1 and 3.8 % for 'Sona masuri' and 0.3 to 4.1% for 'Basmati' (Table 4).

Predicted values were less by 0.8 to 5.5% up to the EMC. However, in 'Basmati', the EMC was less by about 11%, and the values for hydration period was less from 0.5 to 11%, which needs further study. Marginally higher prediction values were seen in 'Rashi', 'Jyothi', 'IR 30864' between 1 and 7 h (Table 4).

As the equilibrium moisture of brown rice (Table 5) could reach in almost 3 h, the predicted values were lower (0.0 to 1.9% db) in 'Jaya', 'IR-64', and 'Basmati'. Generally, up to 10 to 15 min, the predicted values were lower by 0 to 1.9% (Table 5). In 'Rashi' brown rice all predicted values of moisture content were lower than experimental values. At higher duration of hydration, the predicted values were almost equal to the experimental values.

The average values of k_1 and k_2 were 2.9×10^{-2} and 4.2×10^{-2} for rice varieties studied. The predicted values were within experimental errors. The variation was from 0.2 to 4.7% higher compared to Peleg's equation values. The r^2 value varied from 0.9296 to 0.9897, thus proving the suitability of Peleg's equation for prediction of hydration behaviour of various brown rice samples.

In contrast the k_1 and k_2 values in wheat were reversed compared to brown rice values. Even though the r^2 was 0.9849, the experimental and predicted values from M_{24} and M_E, showed a difference of ~23%, where M_E was lower. Thus Peleg's equation was not applicable for wheat.

In milled rice, predicted moisture content was almost equal to the experimental values. Among the different varieties of rice, milled rice hydration behaviour was as expected and Peleg's equation was applicable suitable. Even at 3 h, the observed data were equal to the experimental data.

The k_1 and k_2 values were calculated for different varieties of rice. Overall average k_1 values for rice were lower compared to paddy and brown rice. The r^2 values varied from 0.9982 to 0.9995, thus proving a very good fit to the experimental data suggesting that Peleg's equation could be applied to sorption of milled rice.

Generalized equations for predicting the moisture content during the course of absorption at any time for paddy, brown rice and milled rice are as follows:

Modified Peleg's Equation:

For paddy

k_1=0.0635, k_2=0.0515

$$M = M_0 + \frac{1000*t}{(64 + 52*t)}$$

Table 5 Experimental and Predicted hydration behaviour of various brown rice varieties

Variety		Moisture content (% d b) with time					
		Initial	5 min	30 min	1 h	2 h	3 h
'Agonibora' (Waxy)	Expt*	20.0	24.4	30.1	35.3	41.9	45.0
	Pred	20.0	22.8	31.7	37.0	42.0	44.3
	Avg	20.0	22.6	30.0	34.1	37.7	39.4
'Basmati'	Expt	19.7	23.8	29.0	32.8	37.6	38.9
	Pred	19.7	22.5	30.0	33.9	37.2	38.7
	Avg	19.7	22.3	29.7	33.8	37.4	39.1
'IR 64'	Expt	12.8	15.4	20.7	25.7	30.7	34.2
	Pred	12.8	14.7	21.6	26.3	31.2	33.7
	Avg	12.8	15.4	22.8	26.9	30.5	32.2
'IR 30864'	Expt	13.9	17.3	21.4	22.8	28.9	31.6
	Pred	13.9	16.0	22.3	25.9	29.1	30.5
	Avg	13.9	16.5	23.9	28.0	31.6	33.3
'Jaya'	Expt	14.4	19.0	23.6	27.6	32.6	35.9
	Pred	14.4	17.1	25.1	29.4	33.2	34.9
	Avg	14.4	17.0	24.4	28.5	32.1	33.8
'Jyothi' raw dehusked	Expt	14.6	17.7	22.8	26.3	30.9	33.1
	Pred	14.6	16.9	23.7	27.6	31.1	32.8
	Avg	14.6	17.2	24.6	28.7	32.3	34.0
'Jyothi' parboiled dehusked	Expt	12.2	20.5	30.5	42.2	54.1	65.8
	Pred	12.2	17.0	33.5	44.8	56.7	62.8
	Avg	12.2	12.2	20.3	22.7	27.0	30.9
'Mandya Vijaya'	Expt	13.6	17.6	24.0	29.0	33.5	35.5
	Pred	13.6	16.6	25.1	29.6	33.5	35.2
	Avg	13.6	16.2	23.6	27.7	31.3	33.0
'Rashi'	Expt	13.6	17.6	24.0	29.0	33.5	35.5
	Pred	13.6	16.2	23.4	27.1	30.2	31.6
	Avg	13.6	16.2	23.6	27.7	31.3	33.0
'Sona mahsuri'	Expt	17.0	22.9	25.4	29.0	33.0	34.8
	Pred	17.0	19.9	27.2	30.5	33.1	34.2
	Avg	17.0	19.6	27.0	31.1	34.7	36.4
'SR 26-B'	Expt	16.2	20.0	25.4	29.3	35.0	35.5
	Pred	16.2	19.0	26.7	30.6	34.0	35.6
	Avg	16.2	18.8	26.2	30.3	33.9	35.6

*As in Table 4

For brown rice
k_1=0.0288, k_2=0.0420

$$M\ (t) = M_0 + \frac{1000{*}t}{(30 + 42{*}t)}$$

For milled rice
k_1=0.0083, k_2=0.0397

$$M_t = M_0 + \frac{1000{*}t}{(8 + 40{*}t)}$$

These equations are useful to predict the moisture content of paddy and rice, such that modeling of sorption data finds usefulness.

Hydration of millets: Initial moisture content in millets varied from 10 to 15% (Table 7). Maize grits (big) had higher moisture content (15%) which may be due to addition of moisture during milling. Maize after dry milling yields grits and germ portions, and the grits have both small and big sizes. Moisture absorption was fast in big grits up to 30 min (Table 7). After 24 h, another 2% pick up was seen and

Table 6 Experimental and predicted hydration behaviour of various milled rice varieties

Variety		Moisture content (% d b) with time					
		Initial	5 min	30 min	1 h	2 h	3 h
‘ADT-27’	Expt*	16.3	22.7	29.8	32.6	34.9	34.7
	Pred	16.3	21.1	29.6	32.4	34.3	35.0
	Avg	16.3	23.8	34.9	38.1	40.2	41.0
‘Agonibora’ (Waxy)	Expt	19.6	28.6	41.2	47.9	50.6	52.3
	Pred	19.6	26.9	41.4	46.9	50.8	52.3
	Avg	19.6	27.1	38.2	41.4	43.5	44.3
‘Basmati’	Expt	14.0	21.2	33.7	37.9	37.7	39.2
	Pred	14.0	21.6	32.9	36.2	38.3	39.1
	Avg	14.0	21.5	32.6	35.8	37.9	38.7
‘IR 64’	Expt	14.5	19.4	37.8	40.3	40.3	39.7
	Pred	14.5	21.9	33.7	37.3	39.6	40.5
	Avg	14.5	22.0	33.1	36.3	38.4	39.2
‘IR 30864’	Expt	14.3	19.5	29.2	33.2	34.4	34.3
	Pred	14.3	19.7	28.9	31.9	33.9	34.7
	Avg	14.3	21.8	32.9	36.1	38.2	39.0
‘Jaya’	Expt	14.7	20.8	35.9	38.5	38.7	38.0
	Pred	14.7	23.6	33.9	36.5	38.0	38.6
	Avg	14.7	22.2	33.3	36.5	38.6	39.4
‘Jyothi’ raw milled	Expt	15.9	24.2	36.1	39.5	38.7	39.0
	Pred	15.9	25.1	35.0	37.3	38.7	39.2
	Avg	15.9	23.4	34.5	37.7	39.8	40.6
‘Jyothi’ Parboiled milled	Expt	11.2	25.6	51.7	68.6	86.7	96.6
	Pred	11.2	22.1	54.1	71.8	87.5	94.7
	Avg	11.2	18.7	29.8	33.0	35.1	35.9
‘Mandya Vijaya’	Expt	13.5	21.4	33.9	37.0	38.9	38.9
	Pred	13.5	21.8	33.3	36.4	38.4	39.2
	Avg	13.5	21.0	32.1	35.3	37.4	38.2
‘Rashi’	Expt	14.9	21.6	34.0	38.1	39.4	39.2
	Pred	14.9	22.5	34.3	37.8	40.1	41.0
	Avg	14.9	22.4	33.5	36.7	38.8	39.6
‘Sona mahsuri’	Expt	16.9	24.5	33.1	34.8	36.7	36.1
	Pred	16.9	24.8	33.0	34.9	36.0	36.4
	Avg	16.9	24.3	34.8	37.8	39.7	40.5
‘SR 26-B’	Expt	17.7	26.0	36.0	37.2	37.4	37.5
	Pred	17.7	28.6	35.5	36.7	37.3	37.6
	Avg	17.7	25.2	36.3	39.5	41.6	42.4
‘T(N)-3’	Expt	15.8	22.4	30.9	36.2	38.6	39.5
	Pred	15.8	21.2	31.8	35.7	38.5	39.6
	Avg	15.8	23.3	34.4	37.6	39.7	40.5
‘T-65’	Expt	17.5	25.3	37.9	42.7	44.1	43.6
	Pred	17.5	26.4	38.2	41.4	43.3	44.1
	Avg	17.5	25.0	36.1	39.3	41.4	42.2

*As in Table 4

Table 7 Hydration behaviour of millets and their EMC

Variety	Moisture content (% w b) with time						
	Initial	5 min	30 min	1 h	2 h	3 h	EMC
Bajra 1	12.4 ± 0.56	19.8 ± 0.03	31.2 ± 0.12	34.2 ± 0.03	35.4 ± 0.21	36.0 ± 0.02	37.7 ± 0.01
Bajra 2	10.8 ± 0.21	17.9 ± 0.02	23.5 ± 0.32	25.1 ± 0.87	30.5 ± 0.12	31.9 ± 0.45	37.1 ± 0.12
Bajra (polished)	10.6 ± 0.12	17.9 ± 0.04	27.7 ± 0.03	31.2 ± 0.12	31.8 ± 0.03	32.8 ± 0.12	33.0 ± 0.32
Foxtail millet	9.7 ± 0.62	13.2 ± 0.06	14.8 ± 0.14	17.3 ± 0.08	19.1 ± 0.21	21.4 ± 0.03	28.3 ± 0.01
Maize grits (small)	10.1 ± 0.14	19.9 ± 0.17	25.5 ± 0.02	28.3 ± 0.18	30.8 ± 0.42	30.8 ± 0.44	32.0 ± 0.04
Maize grits (big)	15.0 ± 0.32	20.3 ± 0.26	23.0 ± 0.01	25.2 ± 0.36	27.1 ± 0.38	27.5 ± 0.23	29.5 ± 0.23
Ragi	13.2 ± 0.03	16.1 ± 0.03	22.9 ± 0.33	27.2 ± 0.48	31.2 ± 0.32	32.9 ± 0.22	38.7 ± 0.46
Sorghum red	10.5 ± 0.32	15.5 ± 0.05	19.5 ± 0.14	23.3 ± 0.06	26.7 ± 0.02	29.4 ± 0.41	36.9 ± 0.32
Sorghum white	10.4 ± 0.13	15.1 ± 0.08	18.0 ± 0.11	20.7 ± 0.42	22.4 ± 0.10	24.5 ± 0.22	33.1 ± 0.11
Sorghum (polished)	10.8 ± 0.42	23.1 ± 0.36	29.6 ± 0.32	30.8 ± 0.06	31.8 ± 0.68	32.4 ± 0.31	36.9 ± 0.29

Table 8 Experimental and predicted hydration behaviour of different millets

Millets		Moisture content (% d b) with time					
		Initial	5 min	30 min	1 h	2 h	3 h
Bajra 1	Expt*	14.2	24.8	45.4	51.9	54.8	56.3
	Pred	14.2	25.0	44.1	50.6	54.9	56.6
	Avg	14.2	18.9	30.2	35.1	39.0	40.6
Bajra 2	Expt	12.1	21.8	30.6	33.5	43.8	46.8
	Pred	12.1	17.8	31.9	38.4	43.5	45.7
	Avg	12.1	16.8	28.1	33.0	36.9	38.5
Foxtail millet	Expt	10.7	15.2	17.4	20.9	23.6	27.1
	Pred	10.7	13.0	19.1	22.2	24.8	25.9
	Avg	10.7	15.4	26.7	31.6	35.5	37.1
Maize grits (Small)	Expt	11.2	24.8	34.2	39.4	44.5	44.4
	Pred	11.2	21.3	36.3	40.7	43.5	44.5
	Avg	11.2	15.9	27.2	32.1	36.0	37.6
Maize grits (Big)	Expt	17.7	25.4	29.8	33.7	37.1	37.9
	Pred	17.7	22.5	31.5	34.7	36.9	37.8
	Avg	17.7	22.4	33.7	38.6	42.5	44.1
Ragi	Expt	15.2	19.2	29.8	37.4	45.3	49.0
	Pred	15.2	18.8	30.5	38.0	45.2	48.8
	Avg	15.2	19.9	31.2	36.1	40.0	41.6
Sorghum Red	Expt	11.7	18.3	24.2	30.4	36.4	41.7
	Pred	11.7	15.6	26.6	32.6	37.7	40.1
	Avg	11.7	16.4	27.7	32.6	36.5	38.1
Sorghum white	Expt	11.6	17.8	22.0	26.1	28.9	32.5
	Pred	11.6	15.1	23.5	27.2	30.2	31.4
	Avg	11.6	16.3	27.6	32.5	36.4	38.0
Sorghum (Polished)	Expt	12.1	30.0	42.0	44.5	46.6	47.9
	Pred	12.1	28.6	42.6	45.4	47.1	47.7
	Avg	12.1	16.8	28.1	33.0	36.9	38.5

*As per Table 4

the final moisture content was ~30%. In starch manufacture maize is soaked for about 3 days at 48–50°C to soften grain for easy liberation of starch granules from protein matrix. Polished bajra showed higher absorption capacity compared to unpolished one. Highest EMC was noticed in ragi and least was in foxtail millet. EMC value reached in 3 h in bajra 1 but not in bajra 2. Similar observations were also made in foxtail millet, finger millet, sorghum red, sorghum white and polished sorghum.

Modeling for sorption data of millets: Predicted values of moisture content of millets were coinciding with the experiment values to a great extent (Table 8). In polished sorghum at 3 h the predicted values were almost equal to the experimental values, thereby suggesting the validity of Peleg's equation.

The average Peleg's constant values were 1.476×10^{-2} (k_1) and 3.31×10^{-2} (k_2), the r^2 varied between 0.948 and 0.999 indicating the validity of Peleg's equation. Experimental moisture absorption values are equal to the predicted values.

Using average k_1 and k_2 values, the moisture content could be predicted. Generalized equation for the millet is as follows:

k_1=0.0148, k_2=0.033

$$M_t = M_0 + \frac{1000*t}{(15 + 33*t)}$$

Conclusion

Among cereals, brown rice hydrated slowly, whereas milled rice hydrated fast. Maximum absorption for rice occurred at 3 h of soaking. Waxy rice had highest moisture content among raw rice samples. Parboiled rice showed highest absorption because of the retrograded starch. Wheat showed highest absorption at the end of 24 h. Coarse cereals hydrated slowly, almost 70% of EMC reached in 3 h and maximum absorption could occur at the end of 24 h. There were distinct differences among the EMC for rice, wheat and millets. Modeling of sorption data could be applied easily to milled rice and with limitation to wheat. Among millets hydration behaviour of bajra could easily be fitted to Peleg's equation. Generalized equations formed will help to predict the moisture content at any time.

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