Hydration kinetics of little millet and proso millet grains: effect of soaking temperature

Sagar Patil Balkrishna¹ · R. Visvanathan²

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Abstract Hydration characteristics of little millet (*Panicum sumatrense*) and proso millet (*Panicum miliaceum*) were studied at different soaking temperatures (30, 40, 50, 60 and 70 °C) and fitted into hydration models. From the initial moisture contents of 11.02 (d.b.) and 10.45% (d.b.), little millet and proso millet grains attained the equilibrium moisture content of 38–50.17% (d.b.) and 39.11–47.15% (d.b.), respectively. Little millet took 18.5 h to reach equilibrium moisture content at soaking temperature of 30 °C and 3.5 h at 70 °C. For proso millet, it took 4 h at 70 °C and 19 h at 30 °C. The data of moisture content with time fitted to Lewis, Page, modified Page and Peleg models shown higher coefficient of determination values ranging from 0.92 to 0.99. Among the models, the Peleg model is more suitable for the little millet grains and both Page and Peleg models are more suitable for the proso millet grains, to represent the hydration kinetics in the soak water temperature range of 30–70 °C. The dependency of the coefficients of the hydration models with temperature of soaking was found to be linear for both little and proso millets with coefficient of determination values ranging from 0.88 to 0.97.

Keywords Little millet · Proso millet · Hydration kinetics · Soaking in hot water · Model coefficients · Dependence on temperature

Introduction

Millets are a group of small seeded annual grasses belonging to family *Poaceae* and are nutritionally comparable to rice and wheat and the presence of all the required nutrients in millets makes them suitable for industrial scale utilisation in the manufacture of food stuffs, viz, baby foods, snack foods and dietary foods. Among the millets, little millet (*Panicum sumatrense*) and proso millet (*Panicum miliaceum*) and proso millet are utilised in the form of grains and flour in the production of various forms of food preparations, snack foods, baby foods, etc. During processing, these millet grains undergo number of pre-treatments/unit operations, viz, soaking, gelatinisation, drying, dehushing/pearling, grinding, cooking, etc. For the soaking treatments, the time—moisture absorption relationship (hydration kinetics) is essential.

Hydration or soaking is the process of simultaneous absorption of water and swelling. This is basically a diffusion process and the result of different phenomena, such as, molecular absorption, capillary absorption and hydration. Hydration studies were conducted by the earlier researchers on various food grains, viz, wheat, chickpeas, soybeans, amaranthus seed, sesame seeds, rice, beans and paddy and reported the various models to predict the hydration behaviour. However studies on hydration kinetics of millets are limited. Though various engineering properties, viz, thermal properties (Shinoj and Viswanathan 2003), gelatinisation and rheological characteristics (Shinoj et al. 2006), bulk density and friction coefficients (Shinoj and Viswanathan 2007) and moisture dependent physical properties of different millets and flours (Balasubramanian and Visvanathan 2010) and decorticated finger millet (Shobana and Malleshhi 2007) were studied and reported, no work on hydration of millets has been reported. In the

✉ R. Visvanathan
drrviswanathan@gmail.com

¹ Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, India

² A D Agricultural College and Research Institute, Tamil Nadu Agricultural University, Tiruchirappalli 620 027, India

absence of such information, the researchers and processors rely on trial and error method to achieve desired level of moisture content during soaking treatments. Many models have also been proposed by the earlier researchers for the absorption of water in foodstuffs and categorised as empirical and theoretical. Theoretical models describing water absorption in foods are usually based on the diffusion of water through a porous medium.

Since information on hydration kinetics and models for little millet and proso millet grains will be much useful in performing hydration treatment as required for any value addition process, the reported study has been undertaken to study the hydration kinetics of these grains at different soaking temperatures.

Materials and methods

The bulk grains of little millet (*Panicum sumatrense*) and proso millet (*Panicum miliaceum*) obtained from Department of Millets, Tamil Nadu Agricultural University, Coimbatore, India, were dried, cleaned and stored in air tight containers for use in experiments. Initial moisture content of raw grains was determined for the triplicate samples by measuring the loss in weight of 5 g sample by drying at $130 \pm 2^\circ\text{C}$ for 2 h (AACC2003) in hot air oven. All the weights were measured using an electronic balance with the least count of 0.001 g.

Hydration studies

A thermostat controlled water bath of $24.5\text{ cm} \times 20.5\text{ cm} \times 19\text{ cm}$ size fitted with a 1000 W capacity immersion heater was used for soaking the grains to study the hydration characteristics. The water bath was filled with water up to three-fourth of its volume, followed by setting the thermostat to desired temperature. About 200 g of grain sample weighed to an accuracy of 0.01 g was taken in a cloth bag of $20\text{ cm} \times 10\text{ cm}$ and placed in the water bath, without touching the heater. Temperature of water in the water bath was measured at 15 min interval using a digital thermometer of 0.5°C accuracy.

After 30 min of soaking, bag with the grains was taken out of the water and surface moisture was removed by placing in a power operated centrifuge at 2800 rpm, for 2 min. It was followed by weighing the grains along with the bag to an accuracy of 0.01 g. After recording the weight, bag was again kept in the water until recording the next weight. The interval of soaking was maintained as 30 min for the initial soaking duration of 3 h and varied from 1 to 5 h depending on the soaking temperature and duration. The sample was soaked in water until it attained saturation as indicated by the constant mass of the grain

sample between the consecutive weighing. Hydration studies on little millet and proso millet were conducted with duplicate samples at the soaking temperatures of 30, 40, 50, 60 and 70°C .

Estimation of moisture content

The equilibrium moisture content or moisture content at saturation is the moisture content obtained at the end of soaking. The intermediate moisture content at various intervals of soaking and equilibrium moisture content were estimated using the following relationships.

Let W_o be the mass of the grain taken for soaking at moisture content of M_{go} (% d.b). Then the corresponding mass of dry matter in the soaked grains is,

$$W_{ds} = \frac{W_o}{\left(1 + \frac{M_{go}}{100}\right)} \quad (1)$$

where W_{ds} = bone drymass of the soaked grain (g), M_{go} = initial moisture content of the grain(% d.b) and W_o = initial mass of the grain sample taken for soaking (g).

Moisture content of the grain at time t during soaking,

$$M_t = \frac{W_t - W_{ds}}{W_{ds}} \times 100\% \text{ d.b.} \quad (2)$$

where M_t = moisture content of the grains at time t during soaking (% db), W_t = mass of the grain sample at any time t during soaking (g) and W_{ds} = bone dry mass of the soaked grain (g). When the grain attains equilibrium at the end of soaking period, W_e be the mass and the moisture content at equilibrium can be calculated as,

$$M_e = \frac{W_e - W_{ds}}{W_{ds}} \times 100\% \text{ d.b} \quad (3)$$

where M_e = moisture content of the grains at equilibrium (% db), W_{ds} = bone drymass of the soaked grain (g) and W_e = mass of the grain at equilibrium (g).

Hydration models

Many models have been proposed for the absorption of water in food grains. The following models are particularly popular for the empirical description of water intake in cereals.

First-order asymptotic Lewis model:

$$M_t = M_e + (M_o - M_e)e^{-kt} \quad (4)$$

Page model (Eq. 5) and modified page model (Eq. 6) which are simple to use are as follows:

$$M_t = M_e + (M_o - M_e)e^{-ktn} \quad (5)$$

$$M_t = M_e + (M_o - M_e)e^{-(kt)^n} \quad (6)$$

Peleg (1988) proposed a two-parameter sorption equation and tested its prediction accuracy during water vapour adsorption and soaking of whole rice, popularly known as Peleg equation (Eq. 7).

$$M_t = M_o \pm \frac{t}{k + nt} \quad (7)$$

where k = hydration rate constant (1/h), M_e = moisture content of the grains at equilibrium (% d.b), M_o = initial moisture content of the grains (% d.b), M_t = moisture content of the grains during soaking at time t (% d.b), n = constant and t = soaking time (h).

In Eq. (7), ‘ $\pm$ ’ becomes ‘ $+$ ’ if the process is absorption or adsorption and ‘ $-$ ’ if the process is drying or desorption.

The above hydration models, viz., Lewis, Pages, modified Pages and Peleg’s model were fitted to the moisture content data using Sigma Plot 8 (Jandel Scientific, San Rael, CA, USA). In addition to the various coefficients of the models, standard error, e_s and mean relative error, e_m were determined as given below to judge the fit.

$$e_s = \sum \frac{100(M_t - \bar{M}_t)}{N \bar{M}_t} \quad (8)$$

$$e_m = \sqrt{\frac{\sum (M_t - \bar{M}_t)^2}{N - 1}} \quad (9)$$

where e_m = mean relative error, e_s = standard error of moisture content, M_t = moisture content of the grains (% d.b) during soaking at time t , $\bar{M}_t$ = predicted moisture content of the grain (%d.b) during soaking at time t and N = number of data observation.

Results and discussion

Soaking duration and equilibrium moisture content

The initial moisture content and equilibrium moisture content of the little millet grain were 11.02% (d.b.) and 38–49.8% (d.b.), respectively. The soaking durations for attaining these equilibrium moisture content values were 18.5, 17, 15, 8 and 3.5 h at soaking temperatures of 30, 40, 50, 60 and 70 °C, respectively. Proso millet grain reached equilibrium moisture range of 39.11 to 47.15% (db.) from an initial moisture content of 10.45% (db.) in 19, 17, 15, 8, and 4 h of soaking at the same soaking temperatures, respectively. As the soaking period increased, the amount of water absorbed increased with increase in temperature (Bello et al. 2010; Balbinoti et al. 2018) and thus increase in saturation moisture content.

Hydration models

Hydration characteristics of little millet and proso millet grains were fitted to four hydration models viz. Lewis, Page, Modified Page and Peleg models and all the models were found to suit well for the hydration data.

Little millet

In Fig. 1a, the fit of Lewis model is given for the hydration data of little millet. All the experimental data fitted well at all temperatures of soaking. The rate constant, coefficient of determination, standard error and mean error, ranged 0.473 to 1.548, 0.93 to 0.98, 1.776 to 5.118 and 1.93 to 5.12, respectively. For little millet, the experimental data of moisture content and soaking time also fitted well with the Page model (Fig. 1b) at all temperatures of soaking. The values of the coefficients, k_{lm} and n_{lm} ranged from 0.624 to 1.517 and 0.567 to 0.752, respectively. The statistical parameters, viz, coefficient of determination, standard error and mean error, ranged 0.97 to 0.99, 0.877 to 1.556 and 0.99 to 1.75, respectively.

The modified Page model also fits the hydration data of little millet well at all the temperatures within the study range (Fig. 1c). The values of the coefficients, k_{lm} and n_{lm} ranged from 0.486 to 0.880 and 0.973 to 1.760, respectively. The coefficient of determination (R^2), standard error and mean error, ranged 0.93 to 0.98, 1.777 to 5.118 and 1.93 to 5.12, respectively. In the Peleg model, the coefficients, both the k_{lm} and n_{lm} decreased with the increase in temperature and the data fitted well (Fig. 1d) compared to other models for the little millets. The coefficients, k_{lm} and n_{lm} , decreased from 0.048 to 0.01 and 0.036 to 0.023, respectively with temperature. The coefficient of determination (R^2), standard error and mean error, ranged 0.98 to 0.99, 0.686 to 2.367 and 0.66 to 2.96, respectively.

These hydration models do not include temperature of soaking as a variable thus the coefficients of the models are different with the temperature. The values of this rate constant are found highly dependent and increased linearly with increase in temperature of soaking for the Lewis, Page and modified Page models. In the Peleg model, the model coefficients, linearly decreased with temperature. The regression equations fitted between the coefficients of the models and the temperature of soaking, along with the statistical parameters of the fit are given in Table 1.

Proso millet

In Fig. 2a, the fit of the Lewis model for proso millet is presented. The coefficient of the model, k_{pm} varied from 0.478 to 1.155 linearly with the temperature. The coefficient of determination, standard error and mean error

Fig. 1 Relationship of moisture content and soaking time for various hydration models at indicated temperatures of soaking for little millet grains

Table 1 Relationship between the model coefficients and soaking temperature for little millet and proso millet grains

Hydration model	Relationship between model coefficient and temperature	R^2	Standard error, e_s	Mean error, e_m (%)
Little millet				
Lewis	$k_{lm} = 0.024 \theta - 0.34$	0.89	0.098	8.12
Page	$k_{lm} = 0.02 \theta - 0.047$	0.91	0.92	0.0474
	$n_{lm} = 0.228 \theta + 0.403$	0.92	0.047	5.02
Modified page	$k_{lm} = 0.0087 \theta + 0.203$	0.84	0.055	5.58
	$n_{lm} = 0.017 \theta + 0.405$	0.84	0.0983	5.58
Peleg	$k_{lm} = -0.0009 \theta + 0.071$	0.93	0.0044	12.5
	$n_{lm} = -0.00035 \theta + 0.046$	0.88	0.0023	5.87
Proso millet				
Lewis	$k_{pm} = 0.0175 \theta - 0.137$	0.90	0.136	10.93
Page	$k_{pm} = 0.0164 \theta + 0.0265$	0.94	0.0812	6.99
	$n_{pm} = 0.196 \theta + 0.476$	0.92	0.0792	4.46
Modified page	$k_{pm} = 0.007 \theta + 0.244$	0.92	0.037	4.46
	$n_{pm} = 0.0142 \theta + 0.488$	0.92	0.074	4.46
Peleg	$k_{pm} = -0.0009 \theta + 0.073$	0.97	0.0024	8.2
	$n_{pm} = -0.0002 \theta + 0.04$	0.95	0.0009	2.03

θ —soaking temperature ($^{\circ}\text{C}$); lm —little millet; pm —proso millet

Fig. 2 Relationship of moisture content and soaking time for various hydration models at indicated temperatures of soaking for proso millet grains

ranged from 0.92 to 0.98, 2.130 to 4.845 and 2.48 to 5.16, respectively. The hydration data of proso millet fitted to Page model is shown in Fig. 2b. The values of the coefficient, k_{pm} and n_{pm} ranged 0.588 to 1.210 and 0.545 to 0.768, respectively and highly dependent on soaking temperature. The coefficient of determination, standard error and mean error ranged from 0.98 to 0.99, 0.829 to 1.827 and 0.79 to 2.16, respectively.

Modified Page model also shown a good fit of the hydration data of proso millets at all the temperatures of soaking from 30 °C–70 °C (Fig. 2c). The coefficients, k_{pm} and n_{pm} ranged linearly 0.489 to 0.760 and 0.978 to 1.520, respectively. The coefficient of determination (R^2), standard error and mean error ranged from 0.92 to 0.98, 2.137 to 4.845 and 2.48 to 5.16, respectively. The hydration data of proso millet fitted to Peleg's model is shown in Fig. 2d. Like the other models, Peleg model also fitted well as seen from the coefficient of determination and other statistical parameters. The coefficients, k_{pm} and n_{pm} decreased linearly from 0.048 to 0.016, 0.033 to 0.024, respectively. The coefficient of determination (R^2), standard error and mean

error ranged from 0.98 to 0.99, 0.933 to 2.544 and 0.98 to 2.56, respectively.

Like the little millet grains, the model coefficients for proso millets were also highly dependent on the temperature of soaking, where it increased with the soaking temperature for the Lewis, Page and modified Page models and decreased with the Peleg model. The regression equations fitted between the model coefficients and temperature are given in Table 1 along with the statistical parameters.

Selection of model

All the four models used to represent the hydration characteristics of little millet and proso millet grains were found to adequately fit with higher coefficient of determination of above 0.92. The coefficients of these models as influenced by the soaking temperature were also represented adequately with higher coefficients of determination. Standard error and mean error are the other parameters used to select the appropriate model. The variation in the hydration properties noted in these two millet grains may be due to the influence of the size of

starch granules and thickness of protein matrix in cotyledon which varied with grain size (Sharma et al. 2015). Thus for little millet grains Peleg model and for proso millet grains both Page and Peleg models are more suitable to represent the hydration kinetics in the soak water temperature range of 30–70 °C.

For soaking these millet grains at any temperature in the range of 30–70 °C, the coefficients for these models can be calculated by substituting the temperature desired for soaking. Using the model constants and the initial moisture content of the grain, the soaking duration required for the desired final moisture content can be estimated. This provides an appropriate method of soaking the grains to the calculated duration rather than by trial and error method.

Conclusion

Hydration studies were conducted with little millet and proso millet grains and data were fitted to four popular models, viz, Lewis, Page, modified Page and Peleg model models in the temperature range of 30–70 °C. The hydration data fitted well to these four models with higher coefficients of fit. The coefficients of all the models were dependent on the soaking temperature. Peleg model is found suitable for little millet grains and both Page and Peleg models were suitable for proso millet grains in the soak water temperature range of 30–70 °C.

References

- AACC (2003) Approved methods of the American Association of Cereal Chemists, Method No. 44-15A. American Association of Cereal Chemists, St. Paul
- Balasubramanian S, Viswanathan R (2010) Influence of moisture content on physical properties of minor millets. J Food Sci Technol 47(2):1–6
- Balbinoti TCV, Jorge LMM, Jorge RMM (2018) Modeling the hydration step of the rice (*Oryza sativa*) parboiling process. J Food Eng 216:81–89
- Bello M, Tolaba MP, Aguerre RJ, Suarez C (2010) Modeling water uptake in a cereal grain during soaking. J Food Eng 97:95–100
- Peleg M (1988) An empirical model for description of moisture sorption curves. J Food Sci 53:1216–1219
- Sharma S, Singh N, Virdi AS, Rana JC (2015) Himalayan kidney bean germplasm: grain-flour characteristics, structural-functional properties and in vitro digestibility of starches. Food Res Int 77:498–505
- Shinoj S, Viswanathan R (2003) Thermal properties of minor millet grains and flours. Biosyst Eng 84(3):289–296
- Shinoj S, Viswanathan R (2007) Bulk density and friction coefficients of selected minor miller grain and flour. J Food Eng 81:118–126
- Shinoj S, Viswanathan R, Sajeev MS, Moorthy SN (2006) Gelatinisation and rheological characteristics of minor millet flours. Biosyst Eng 95(1):51–59
- Shobana S, Malleshi NG (2007) Preparation and functional properties of decorticated finger millet (*Eleusine corracana*). Food Eng 79:529–538

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