Temperature Dependent Hydration Kinetics of Finger Millet (*Eleusine coracana*) and Foxtail Millet (*Setaria italica)* Grains

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ABSTRACT

Hydration kinetics of finger millet (*Eleusine coracana*) and foxtail millet (*Setaria italica)* grains were studied at temperatures between 30 - 70°C by estimating moisture contents at different durations of soaking. Initial moisture content of finger millet and foxtail millet grains were 12.29% (d.b.) and 12.04% (d.b.) and at saturation, attained the moisture content of 53.01 - 60.92% (d.b.) and 40.93 – 46.33% (d.b.), respectively. Finger millet took about 16 h to reach saturation moisture content at soaking temperature of 30°C and 2 hours at 70°C. In the case of foxtail millet, it took 3.5 h at 70°C and 17.5 h at 30°C. The moisture content with respect to duration were well fitted to Lewis, Page, modified Page and Peleg models with coefficient of determination of 0.92 - 0.99. Among these models, Peleg model suggested a good fit for finger millet, and Page and Peleg models for foxtail millet grains. The dependency of the coefficients of the hydration models with soaking temperature was found to be linear for both little and proso millets with coefficient of determination ranging from 0.88 to 0.97.

Key words: Finger millet; Foxtail millet; Hydration kinetics; Soaking in hot water; Model coefficients; Dependence on temperature.

INTRODUCTION

Millet is a group of small seeded annual grasses belonging to the family *Poaceae,* known as "nutri-cereals". The millets are categorised as major and minor based on size of seeds and extent of cultivation. Also they are nutritionally superior 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 baby foods, snack foods and dietary foods (Shobana and Malleshi, 2007).

Hydration or soaking is the process of placing the grains, either in cold or hot water as a treatment, resulting in simultaneous absorption of water and swelling. Hydration is an important unit operation in parboiling and also necessary to condition the grains for dehusking/ pearling, grinding, *etc*. Hence it is necessary to characterise and optimise the hydration phenomena as a function of duration and temperature (Turhan *et al.,* 2002).

Hydration studies on many food grains *viz,* wheat (Shafaei *et al*., 2016), chickpeas (Pramiu *et al*., 2015), soybeans (Pan and Tangratanavalee, 2003), rice (Bakalis *et al*., 2009), brown rice (Bello *et al*., 2010; Balbinoti *et al*., 2018), beans (Miano *et al*., 2018), paddy (Oli *et al*., 2016), were conducted by the earlier researchers and reported. Also the earlier researchers have reported various engineering properties, *viz.,* moisture dependent physical properties (Shinoj and Viswanathan, 2007, Balasubramanian and Visvanathan, 2010; Kumar *et al.* 2016), thermal properties (Shinoj and Viswanathan, 2003), gelatinisation and rheological characteristics (Shinoj *et al*., 2006), of different millets, flours and decorticated finger millet (Shobana and Malleshi, 2007). Hydration studies

(Shirsat *et al.,* 2009a) and pre-milling treatments (Shirsat *et al.,* 2009b) were conducted on kodo millet to determine the saturation moisture content and change in colour after milling, respectively. However no studies on hydration kinetics of millets are reported.

In the absence of such information, the researchers / processors rely every time on small trial experiments. Information on hydration kinetics and models for these millet grains will be much useful in performing hydration treatment as required for milling and any value addition process and therefore, the study was undertaken. -

MATERIALS AND METHODS

Raw material: The bulk grains of finger millet (*Eleusine coracana*) and foxtail millet (*Setaria italica)* obtained from Millet Breeding Station, 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 by measuring the loss (least count 0.001) in mass of 5 g sample by drying at 130 ± 2°C for 2 h (AACC, 2003) in hot air oven.

Hydration studies: A thermostat controlled water bath fitted with a 1000 W capacity immersion heater was used for soaking the grains. The water bath was filled with water upto 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 cm x 10 cm and placed in the water bath, without touching the heater. Temperature of water in the water bath was monitored at 15 minutes interval using a digital thermometer of 0.5°C accuracy.

After 30 minutes 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 mass, bag was again kept in the water until recording the next mass. The interval of soaking was maintained as 30 min for the initial soaking duration of 3 h and varied from 1 h 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 finger millet and foxtail millet were conducted with duplicate samples at the soaking temperatures of 30, 40, 50, 60 and 70°C.

Estimation of moisture content: The saturation moisture content is the moisture content obtained at the end of soaking. The intermediate moisture content at various intervals of soaking and saturation 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, was in the soaked grains is,

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

Moisture content of the grain at time *t* during soaking,

$$M_t = \frac{W_t - W_{ds}}{W_{ds}} x100 \text{ \% d.b.} \quad \ldots(2)$$

When the grain attains saturation at the end of soaking period, W_e be the mass and the moisture content at saturation can be calculated as,

$$M_e = \frac{W_e - W_{ds}}{W_{ds}} x100 \text{ \% d.b} \quad \ldots(3)$$

Where,

M_e = moisture content of the grains at saturation (% d.b.)
M_{go} = initial moisture content of the grain (% d.b.)
M_t = moisture content of the grains at time *t* during soaking (% d.b.)
W_{ds} = bone dry mass of the soaked grain (g)
W_e = mass of the grain at saturation (g)
W_o = initial mass of the grain sample taken for soaking (g)
W_t = mass of the grain sample at any time *t* during soaking (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 (Haladjian *et al.,* 2003):

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

Page model (Eq. 5) and modified page model (Eq. 6) which are simple to use are as follows (Kashaninejad *et al.,* 2007):

$$M_t = M_e + (M_O - M_e)e^{-kt^n} \quad \ldots(5)$$

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

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).

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

In Eq. (7), '±' becomes '+' if the process is absorption or adsorption and '-' if the process is drying or desorption.

Where,
k = hydration rate constant (1/h)
M_e = moisture content of the grains at saturation (% 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
t = soaking duration (h)

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 Raeal, 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.

$$e_s = \sum \frac{100}{N} \frac{(M_t - \overline{M_t})}{\overline{M_t}} \quad \ldots(8)$$

$$e_m = \sqrt{\frac{\sum (M_t - \overline{M_t})^2}{N - 1}} \quad \ldots(9)$$

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 duration t
$\overline{M_t}$ = predicted moisture content of the grain (% d.b.) during soaking at duration t
N = number of data observation.

RESULTS AND DISCUSSION

Soaking duration: The initial moisture content of the finger millet grain and saturation moisture content were 12.29% (d.b.) and 53.01 - 60.92% (d.b.), respectively. The soaking durations for attaining these saturation moisture content values were 16, 13, 7, 3 and 2 h at soaking temperatures of 30, 40, 50, 60 and 70°C, respectively. Foxtail millet grain reached saturation moisture range of 40.93 to 46.33% (db.) from an initial moisture content of 12.04% (db.) in 17.5, 15.5, 10, 6 and 3.5 hours of soaking in soaking temperatures of 30, 40, 50, 60 and 70°C, respectively. As the soaking duration increased, the water absorbed increased and also with increase in soak water temperature, resulting in higher saturation moisture content (Bello *et al*., 2010; Balbinoti *et al*., 2018).

Hydration models: Hydration characteristics of finger millet and foxtail 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. The adequacy of the fit of these models was judged from the coefficient of determination, standard error and mean error as given in Tables 1 and 2.

Finger millet

Lewis model: In Fig.1a, the fit of Lewis model is given for the hydration data of finger millet. All the experimental data fitted well at all temperatures of soaking as seen from the corresponding coefficient of determination (R^2>0.96) values (Table 1). As this model does not incorporate temperature of soaking as a variable, the model was fitted independently for each temperature of soaking. Thus the relationship for each temperature of soaking resulted in the separate values of rate constant (k_{fi}). The value of this rate constant is highly dependent and increased with increase in temperature of soaking. The following regression model gives the relationship between rate constant (k_{fi}) and temperature (θ).

$$k_{fi} = -0.71 + 0.44\theta \quad (R^2 = 0.97) \quad \ldots(10)$$

Table 1: Values of coefficients and statistical parameters for the hydration equations for finger millet at different temperatures of soaking

Hydration model	Soaking temperature (°C)	Coefficients k	n	R^2	Standard error, e_s	Mean error, e_m (%)
Lewis	30	0.76		0.96	3.83	3.18
	40	0.89		0.96	4.34	3.58
	50	1.46		0.98	2.56	2.04
	60	1.99		0.99	0.80	0.73
	70	2.43		0.99	0.80	0.78
Page	30	0.85	0.67	0.98	2.54	2.48
	40	1.0	0.57	0.99	1.88	1.43
	50	1.44	0.68	0.99	0.82	0.63
	60	1.90	0.86	0.99	0.33	0.26
	70	2.71	1.22	0.99	0.03	0.02
Modified Page	30	0.62	1.24	0.96	2.80	2.44
	40	0.67	1.34	0.96	2.53	2.31
	50	0.85	1.71	0.98	2.56	2.04
	60	1.0	2.00	0.99	0.80	0.73
	70	1.10	2.21	0.99	0.80	0.78
Peleg	30	0.02	0.02	0.98	1.95	1.94
	40	0.01	0.02	0.99	1.48	1.10
	50	0.008	0.02	0.99	1.15	0.84
	60	0.006	0.02	0.99	1.29	1.13
	70	0.005	0.018	0.99	2.37	2.26

Table 2: Values of coefficients and statistical parameters for the hydration equations for foxtail millet at different temperatures of soaking

Hydration model	Soaking temperature (°C)	Coefficients k	n	R^2	Standard error, e_s	Mean error, e_m (%)
Lewis	30	0.42		0.96	3.09	3.74
	40	0.56		0.97	2.20	2.67
	50	0.66		0.98	2.08	2.63
	60	0.80		0.99	1.12	1.26
	70	1.15		0.99	1.05	1.31
Page	30	0.53	0.67	0.99	1.50	1.67
	40	0.65	0.68	0.99	1.30	1.38
	50	0.75	0.72	0.99	0.90	0.97
	60	0.85	0.88	0.99	0.60	0.58
	70	1.17	0.93	0.99	1.06	1.23
Modified Page	30	0.46	0.92	0.96	3.09	3.74
	40	0.53	1.05	0.97	2.20	2.67
	50	0.57	1.15	0.98	2.08	2.63
	60	0.63	1.27	0.99	1.12	1.26
	70	0.76	1.52	0.99	1.05	1.31
Peleg	30	0.055	0.032	0.99	1.57	1.74
	40	0.039	0.032	0.99	1.27	1.45
	50	0.032	0.03	0.99	0.79	0.96
	60	0.025	0.027	0.99	1.17	1.18
	70	0.018	0.024	0.99	0.97	1.01

where, θ is the temperature of soaking (°C). The values of standard error, e_s and mean error (%), e_m, of the above fit were 0.136 and 8.94, respectively.

Page model: Experimental data of moisture content and soaking duration fitted well with the Page model (R^2>0.98). The values of the coefficients, k_{fi} and n_{fi} (Table 1) were found dependent of the soak water temperature. The relationship of moisture content and duration of soaking at various temperatures of soaking (Fig.1b). The fit is adequate to represent the hydration behaviour of finger millet as seen from the predicted values lying close to the experimental values.

The dependence of the model constants (k_{fi} and n_{fi}) on temperature of soaking (θ) was linearly represented by the following regression equations.

$$k_{fi} = -0.73 + 0.46\theta \quad (R^2 = 0.94) \qquad ...(11)$$

$$n_{fi} = (2.69 - 0.027\theta)^{-1} \quad (R^2 = 0.91) \qquad ...(12)$$

The values of standard error and mean error of this regression are 0.209 and 11.8, respectively for the coefficient, k_{fi} and 0.096 and 8.62 for the coefficient, n_{fi}.

Modified Page model: The modified Page model (Eq. 6) also fits the hydration data of finger millet grains well at all the temperatures within the study range (Fig.1c). The coefficient of determination (R^2) values for these fit was found to be high (>0.96) -(Table 1). As soak water temperature term was not included in the model, values of model constants (k_{fi} and n_{fi}) were obtained for each temperature (Table 1). The values of the k_{fi} and n_{fi} increased with temperature and thus enabling them in fitting the regression with respect to the soaking temperature. The following regression equations fitted the coefficients k_{fi} and n_{fi} well with the temperature.

$$k_{fi} = 0.2 + 0.01\theta \quad (R^2 = 0.97) \qquad ...(13)$$

$$n_{fi} = 0.4 + 0.03\theta \quad (R^2 = 0.97) \qquad ...(14)$$

The values of standard error and mean error of this regression are 0.036 and 3.09, respectively for the coefficient, k_{fi} and 0.071 and 3.094 for the coefficient, n_{fi}.

Peleg model: The coefficients, both *k* and *n* values decreased with the increase in temperature. The model fitted well for the finger millets with higher coefficient of determination of above 0.98 at all temperatures of soaking. The following regression equations represent the relationships between the values of k_{fi} and n_{fi} with temperature.

$$k_{fi} = 0.028 - 0.0004\theta \quad (R^2 = 0.92) \qquad ...(15)$$

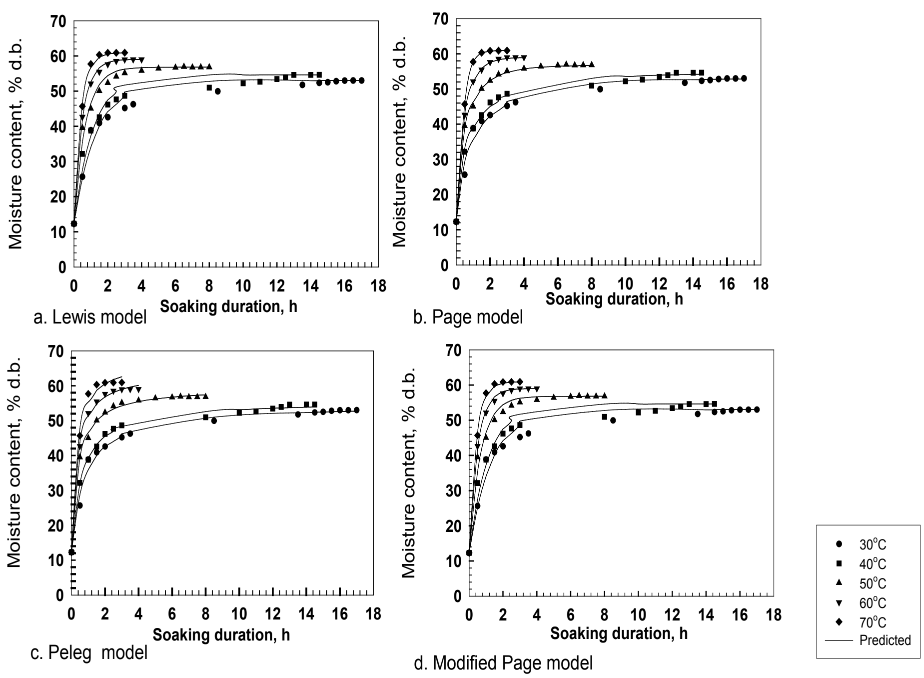

Fig. 1. Hydration characterisitcs of finger millet grains

$$n_{fi} = 0.0283 - 0.0001\theta \quad (R^2=0.97) \qquad ...(16)$$

Values of standard error and mean error of this regression are 0.00187 and 16.3, respectively for the coefficient, k_{fi} and 0.00042 and 1.26 for the coefficient, n_{fi}.

Foxtail millet

Lewis model: The coefficient of determination values (R^2>0.96) – (Fig.2a & Table 2) can be observed that all the experimental data fitted well in Lewis equation at all temperatures of soaking. As this model does not include the temperature of soaking as a variable, the model was tried independently for each temperature resulting in the separate values of rate constant (k_{fo}). The value of this rate constant is found to be highly dependent on the temperature of soaking where it increases along with the soaking temperature.

A regression model is fitted between the values of the rate constants and temperature as given below:

$$k_{fo} = -0.133 + 0.017\theta \quad (R^2=0.92) \qquad ...(17)$$

The values of standard error, e_s and mean error (%), e_m, of the above fit were 0.086 and 8.18, respectively.

Page model: Page model was used to fit the hydration data of foxtail millet (Fig.2b) and the coefficient of determination found to be high (R^2>0.99) and the values of k_{fo} and n_{fo} (Table 2) increased with increase in soak water temperature. The dependence of the model constants (k_{fo} and n_{fo}) and temperature of soaking (t) was found by fitting the following regression equations:

$$k_{fo} = 0.056 + 0.0147\theta \quad (R^2 = 0.92) \qquad ...(18)$$

$$n_{fo} = (1.936 - 0.012\theta)^{-1} \quad (R^2 = 0.92) \qquad ...(19)$$

The values, 0.076 and 6.13 are the standard error and mean error for the coefficient, k_{fo} and 0.039 and 3.36 for the coefficient, n_{fo}, respectively.

Modified Page model: Hydration data of foxtail millets fitted to the modified Page model also resulted a good fit at all the temperatures of soaking from 30-70°C (Fig.2c). The coefficient of determination (R^2) values for these fit was found to be high (>0.96)- (Table 2). It is also observed that the k_{fo} and n_{fo} values are dependent of the temperature. The values of the k_{fo} and n_{fo} were found to increase with the temperature and thus permitting to fit them the following regression equation with respect to temperature values.

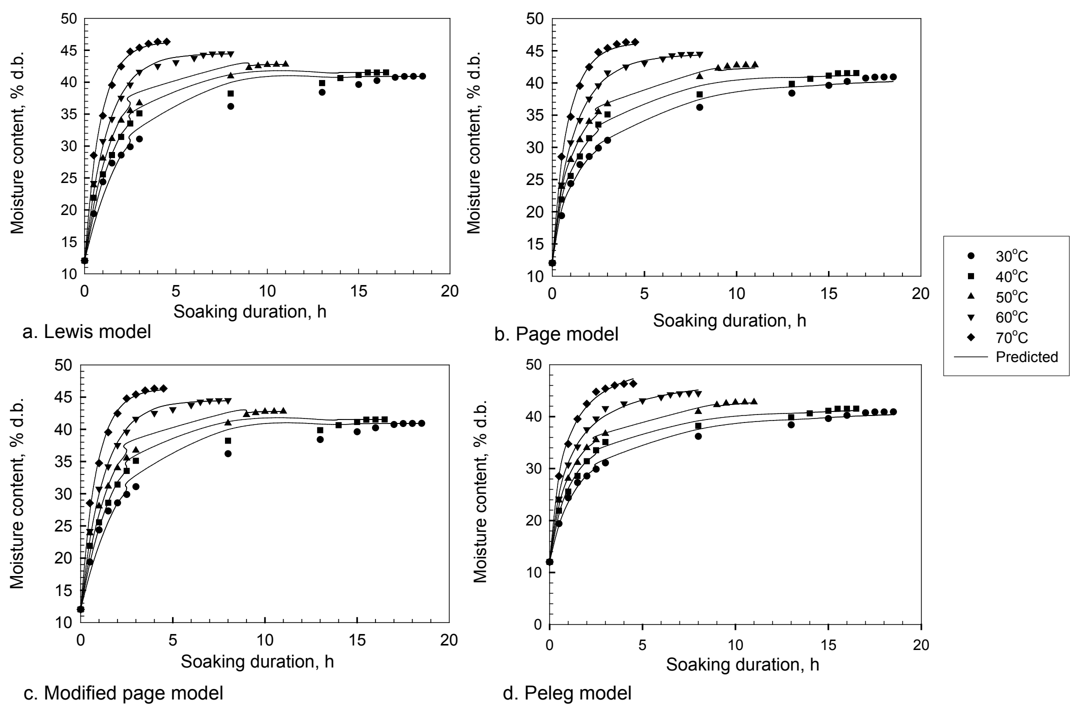

Fig. 2. Hydration characterisitcs of foxtail millet grains

The regression equations found are as follows:

$$k_{fo} = 0.239 + 0.007\theta \quad (R^2 = 0.96) \qquad ...(20)$$

$$n_{fo} = 0.478 + 0.141\theta \quad (R^2 = 0.96) \qquad ...(21)$$

The values of standard error and mean error of this regression are 0.026 and 2.96, respectively for the coefficient, k_{fo} and 0.052 and 2.96 for the coefficient, n_{fo}.

Peleg model: For the foxtail millet, the values of the coefficients k_{fo} and n_{fo} found by fitting the data in model equation (Fig.2d) are presented (Table 2) and observed that the values of these coefficients decreased with increase in temperature.

The following equations relate well the values of k_{fo} and n_{fo} with temperature:

$$k_{fo} = 0.077 - 0.0009\theta \quad (R^2 = 0.95) \qquad ...(22)$$

$$n_{fo} = 0.039 - 0.0002\theta \quad (R^2 = 0.94) \qquad ...(23)$$

The values of standard error and mean error of above regressions for foxtail millet are 0.0034 and 6.81, for the coefficient, k_{fo} and 0.0009 and 2.08 for the coefficient, n_{fo}, respectively.

Selection of model

All the four models used to represent the hydration characteristics of finger millet and foxtail millet grains adequately fitted with higher coefficient of determination of above 0.90. 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. Peleg model and for foxtail millet both Page and Peleg models are more suitable for finger millet, 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.

CONCLUSION

Hydration studies conducted with finger millet and foxtail millet grains and data fitted to four popular models, *viz.,* Lewis, Page, modified Page and Peleg models in the temperature range of 30-70°C showed that data fitted well to these four models. The coefficients of all the models were dependent on the soaking temperature. Peleg model is found suitable for finger millet grains and both Page and Peleg models were suitable for foxtail millet grains.

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