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Modelling of soybean hydration kinetics during hot-water soaking at different temperatures (40, 50 and 60 °C) using peleg's model

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Abstract

Soybean soaking is an important pre-processing operation that significantly influences hydration behaviour, grinding efficiency, and the quality of soymilk. To optimize the soaking process and reduce processing time, the present study investigated the hydration behaviour of soybean during hot-water soaking at 40, 50, and 60 °C using Peleg's equation. Hydration characteristics are influenced by soaking temperature, soaking duration, and the water-to-soybean ratio (Penaranda and Reitmeier, 2001) [7]. Soybean variety JS-9305 was soaked at a water-to-soybean ratio of 3:1 (w/v), and the effects of soaking temperature on grain weight, water absorption, moisture content, and hydration kinetics were evaluated. Grain weight, water absorption, and moisture content increased progressively with soaking time at all temperatures. Equilibrium water absorption of 130.84% and moisture content of 163.57% (db.) were attained after 10, 8, and 5 h at 40, 50, and 60 °C, respectively. The reduction in soaking time with increasing temperature indicated accelerated hydration, which may be attributed to increased seed-coat permeability and enhanced moisture diffusion.

Peleg's equation adequately described the hydration behaviour of soybean during hot-water soaking. The Peleg rate constant (K_1) decreased from 0.0081 at 40 °C to 0.0031 at 60 °C, indicating a higher rate of water absorption at elevated temperatures. The close agreement between the experimental and predicted values further confirmed the suitability of the model for describing soybean hydration kinetics. Among the tested temperatures, soaking at 60 °C was found to be the most effective, achieving equilibrium hydration within 5 h, compared with 8 h at 50 °C and 10 h at 40 °C. Thus, hot-water soaking at 60 °C can be considered an effective condition for reducing soybean soaking time while achieving the desired hydration level.

Keywords: Soybean (*Glycine max*), hot water soaking, hydration behaviour, soaking temperature, water absorption, moisture content, hydration kinetics, peleg's equation, equilibrium moisture content, soymilk processing

Introduction

Soybean (*Glycine max* (L.) Merr.) is a leguminous crop belonging to the family Leguminosae and subfamily Papilionaceae. The accepted botanical nomenclature of cultivated soybean, *G. max* (L.) Merrill, was proposed by Ricker and Morse (1948), as reported by Gazzoni (1994) [4]. Soybean is considered an important agricultural commodity owing to its valuable nutritional composition, particularly its high-quality protein and edible oil content. It has been traditionally utilized in Asian countries and other regions for producing a wide range of foods, including tofu, soymilk, soy sauce, and miso (Probst and Judd, 1973) [9]. Soybean and its derived products, including soybean meal, are widely valued for their nutritional significance (Pratap *et al.*, 2012) [8]. Consumption of soy foods and isoflavones has also been associated with several potential health benefits, such as alleviation of menopausal symptoms and reduced risks of cardiovascular disorders and breast cancer. Processing operations such as soaking, heating, and fermentation are commonly employed to improve the nutritional quality of soybean products by reducing antinutritional constituents (Christopher and Aziz, 2014) [2].

Soymilk is a water-based extract obtained from whole soybeans and is comparable to dairy milk in appearance and nutritional characteristics. It provides high-quality protein, essential amino acids, vitamins, and polyunsaturated fatty acids, making it a suitable plant-based alternative to dairy milk, particularly for lactose-intolerant consumers (Snyder and Wilson,

2003) [11]. Conventional soymilk preparation involves soaking soybeans to facilitate hydration, followed by grinding with water, heat treatment of the resulting slurry, and filtration to separate the liquid extract from the insoluble residue, commonly known as okara (Snyder and Wilson, 2003) [11]. The quality and yield of soymilk are affected by several processing and raw-material factors, including soaking conditions, storage conditions, and enzymatic activity (Penaranda and Reitmeier, 2001) [7].

Soybean soaking is generally performed for several hours or overnight to obtain adequate hydration prior to grinding and extraction. However, prolonged soaking increases processing time and may limit the efficiency of commercial soymilk production. Therefore, optimizing the soaking process is important for achieving rapid and uniform hydration while maintaining desirable processing characteristics. In the present study, the effect of soaking water temperature on soybean hydration was investigated using Peleg's model to characterize water absorption behaviour. The relationship between soaking temperature and the time required for hydration was also evaluated. The findings demonstrated that an increase in soaking temperature accelerated water absorption and reduced the time required to approach equilibrium moisture content. Thus, soaking temperature plays an important role in controlling the hydration kinetics of soybean and can be effectively considered for optimizing the soaking operation.

Materials and Methods

Materials

The JS-9305 soybean variety was procured from the APMC Market, Rahuri, Maharashtra. The seeds were manually cleaned and sorted to remove broken grains, stones, and other foreign materials. The cleaned and graded soybeans were used for the soaking experiments.

Soybean Soaking Process

Cleaned soybean grains (50 g) were soaked in water at a grain-to-water ratio of 1:3 (w/v). The soaking experiments were conducted at three different temperatures, i.e., 40, 50, and 60 °C, using a hot water bath. Soaking was continued until the samples reached saturation.

Determination of Soaking Characteristics

1. Weight of Soaked Sample

The weight of the soaked soybean sample was recorded at one-hour intervals throughout the soaking period. Prior to weighing, the soaked grains were drained properly to remove excess surface water.

2. Water Absorption (%)

The hydration behaviour of soybean during soaking was assessed based on the percentage of water absorbed. Water absorption was calculated using the change in sample weight before and after soaking, following the method reported by Munu *et al.* (2016) [6].

The percentage of water absorption was calculated as:

$$\%W = \frac{W_f - W_0}{W_0} \times 100 \quad (1)$$

Where, %W = Percentage water absorption

W_f = Soybean weight after soaking, gm

3. Moisture Content (% db.)

The moisture content of soybean grains was determined using the hot air oven method as per ASAE

Standard S352.2 (ASAE, 1997). A known quantity of soybean sample was heated in a hot air oven at 100–110 °C for 24 h. After drying, the sample was cooled in a desiccator and weighed. The moisture content on a dry basis was calculated using the following equation,

$$\text{Moisture Content (db.), \%} = \frac{\text{Initial Weight of sample (W}_1\text{)} - \text{Final Weight of sample (W}_2\text{)}}{\text{Final Weight of sample (W}_2\text{)}} \quad (2)$$

Results and Discussion

The hydration behaviour of soybean grains was studied by soaking them in a hot water bath maintained at 40 °C, 50 °C, and 60 °C. Changes in grain weight were measured at predetermined time intervals to assess the rate and extent of water absorption. The soaking characteristics of soybean grains at different temperatures are presented in Table 1.

Table 1: Variation in soybean grain weight during soaking at 40, 50, and 60 °C in a hot water bath

Time, h	Weight of grain, g		
	40 °C	50 °C	60 °C
0	50.00	50.00	50.00
1	90.94	91.30	105.00
2	99.50	104.09	111.07
3	103.38	112.02	112.78
4	106.05	112.19	114.00
5	106.10	112.92	115.42
6	106.75	112.98	115.42
7	108.78	114.67	115.42
8	109.84	115.42	-
9	113.00	115.42	-
10	115.42	115.42	-
11	115.42	-	-
12	115.42	-	-

Table 2: Hydration behaviour of soybean grains at 40, 50, and 60 °C in a hot water bath

Time, h	Water Absorption, %		
	40 °C	50 °C	60 °C
0	0	0	0.00
1	81.87	82.44	110.00
2	99.00	115.14	122.14
3	106.75	123.90	125.56
4	112.10	124.09	128.00
5	112.20	125.54	130.84
6	113.49	125.73	130.84
7	117.56	129.24	130.84
8	125.89	130.84	-
9	128.00	130.84	-
10	130.84	130.84	-
11	130.84	-	-
12	130.84	-	-

Soybean samples were soaked in a hot water bath maintained at 40, 50, and 60 °C. The water absorption of the grains increased with an increase in soaking duration at all the temperatures studied, indicating progressive hydration throughout the soaking period (Table 2). The influence of soaking temperature and duration on water absorption is illustrated in Fig. 1. Water uptake was relatively rapid during the initial stage of soaking and gradually decreased as the grains approached hydration equilibrium. At 40 °C, water absorption increased from 0 to 130.84% and reached equilibrium after 10 h. At 50 °C, the same equilibrium level was attained within 8 h, whereas at 60 °C, equilibrium was reached in only 5 h. The enhanced hydration rate at higher

temperatures may be associated with increased seed coat permeability and improved diffusion of water into the internal tissues of the grains.

The findings indicate that soaking temperature substantially influenced the rate of soybean hydration. Increasing the temperature accelerated water uptake and reduced the time required to reach equilibrium. However, the equilibrium water absorption remained the same (130.84%) at all three temperatures, indicating that temperature primarily affected the hydration rate rather than the final water absorption capacity of the grains. From a processing standpoint, soaking at 60 °C was the most efficient treatment, reducing the soaking period by approximately 5 h and 3 h compared with 40 °C and 50 °C, respectively. The shorter soaking duration can contribute to improved processing efficiency and throughput while facilitating subsequent grinding and soymilk extraction operations.

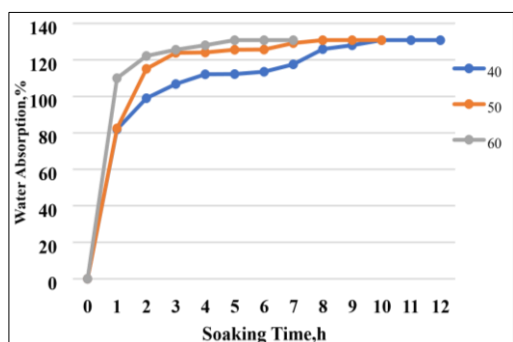


Fig 1: Effect of soaking temperature on water absorption of soybean grains in a hot water bath

Changes in soybean moisture content during hydration at different soaking temperatures

The changes in moisture content of soybean grains during soaking at 40 °C, 50 °C, and 60 °C are presented in Table 3. Monitoring moisture content throughout the soaking period provides an indication of the hydration progress and helps characterize the water absorption behaviour of soybean grains.

Table 3: Temperature-dependent moisture content of soybean during hydration

Time, h	Moisture Content, % d. b		
	40 °C	50 °C	60 °C
0	13.43	13.43	13.43
1	79.05	109.08	116.26
2	118.63	132.81	153.14
3	138.44	143.60	157.25
4	141.60	144.70	162.45
5	145.70	152.19	163.57
6	151.19	154.49	163.57
7	155.49	162.30	163.57
8	162.19	163.57	-
9	162.01	163.57	-
10	163.57	163.57	-
11	163.57	-	-
12	163.57	-	-

The moisture content of soybean grains increased progressively with increasing soaking time at all the temperatures studied (40, 50, and 60 °C), indicating continuous moisture uptake during hot-water soaking (Table 3). The influence of soaking temperature and duration on moisture content is presented in Fig. 2. The initial moisture content of the soybean grains was 13.43%, which increased

rapidly during the early stage of soaking and subsequently showed a gradual tendency towards equilibrium. At 40 °C, the moisture content reached 163.57% after 10 h of soaking, while the same equilibrium value was attained within 8 h at 50 °C and 5 h at 60 °C. The rapid moisture gain during the initial phase can be associated with the substantial difference in moisture concentration between the soaking medium and the soybean grains, which facilitated water movement into the grain matrix. With continued soaking, moisture uptake gradually declined as the internal tissues became increasingly hydrated and the driving force for water diffusion decreased. These observations indicate that soaking temperature had a considerable influence on the hydration rate, with higher temperatures accelerating moisture uptake and shortening the time required to attain equilibrium. Among the temperatures evaluated, soaking at 60 °C resulted in the fastest hydration, reducing the required soaking period by approximately 5 h and 3 h compared with 40 °C and 50 °C, respectively. Despite the difference in hydration rate, the equilibrium moisture content was the same (163.57%) at all temperatures, suggesting that temperature primarily influenced the rate of moisture uptake rather than the final moisture-holding capacity of soybean grains. From a processing perspective, faster hydration at elevated temperatures can reduce soaking time, improve grain softening, and facilitate subsequent grinding and extraction operations during soymilk production.

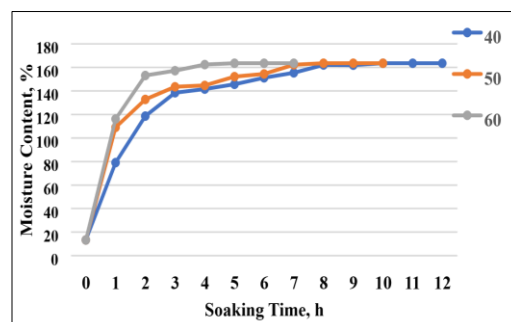


Fig 2: Variation in moisture content of soybean grains during soaking at 40, 50, and 60 °C in a hot water bath

Peleg model constants and hydration kinetics parameters of soybean grains at different soaking temperatures (40, 50, and 60 °C)

$$\text{Peleg's equation: } M_t = M_o + \frac{t}{K_1 + K_2 t} \quad (3)$$

Where:

M_t = Moisture content at time t , % d.b.,

M_o = Initial moisture content, % d.b.

t = Soaking time, h

K_1 = Peleg rate constant, h/% (d.b.)

K_2 = Peleg capacity constant, 1/% (d.b.)

Linearized form of Peleg's equation

$$\frac{t}{M_t - M_o} = K_1 + K_2 t$$

Peleg's model was employed to characterize the hydration kinetics of soybean during soaking in a hot water bath at 40, 50, and 60 °C. The experimentally measured moisture content at different soaking intervals was fitted to Peleg's equation to evaluate the hydration pattern of soybean. The rate constant (K_1) and capacity constant (K_2) were estimated

using the linearized form of the model. The estimated model parameters along with the corresponding goodness-of-fit results for each soaking temperature are presented in the respective tables. The experimental moisture content and the corresponding values predicted by Peleg's model for soybean soaked at 40 °C are presented in Table 4. A gradual increase in moisture content was observed with an increase in soaking duration, reflecting progressive water uptake by the soybean grains until the hydration process approached equilibrium. The experimental and predicted values were used to estimate the Peleg model constants and evaluate the effectiveness of the model in representing the hydration behaviour of soybean.

Table 4: Peleg's Equation Fitting for Soybean Hydration (40 °C) at hot water bath

Time (h)	Moisture Content (Mt)	(Mt-Mo)	$\left(\frac{t}{Mt - Mo}\right)$
1	79.05	65.62	0.0152
2	118.63	105.2	0.019
3	138.44	125.01	0.024
4	141.6	128.17	0.0312
5	145.7	132.27	0.0378
6	151.19	137.76	0.0436
7	155.49	142.06	0.0493
8	162.19	148.76	0.0538
9	162.01	148.58	0.0606
10	163.57	150.14	0.0666

Table 5: Peleg's Equation Fitting for Soybean Hydration (50 °C) at hot water bath

Time (h)	Moisture Content (Mt)	(Mt-Mo)	$\left(\frac{t}{Mt - Mo}\right)$
1	109.08	95.65	0.0105
2	132.81	119.38	0.0168
3	143.6	130.17	0.023
4	144.7	131.27	0.0305
5	152.19	138.76	0.036
6	154.49	141.06	0.0425
7	162.3	148.87	0.047
8	163.57	150.14	0.0533

Table 6: Peleg's Equation Fitting for Soybean Hydration (60 °C) at hot water bath

Time, t (h)	Mt	Mt-Mo	$\left(\frac{t}{Mt - Mo}\right)$
1	116.26	102.83	0.0097
2	153.14	139.71	0.0143
3	157.25	143.82	0.0209
4	162.45	149.02	0.0268
5	163.57	150.14	0.0333

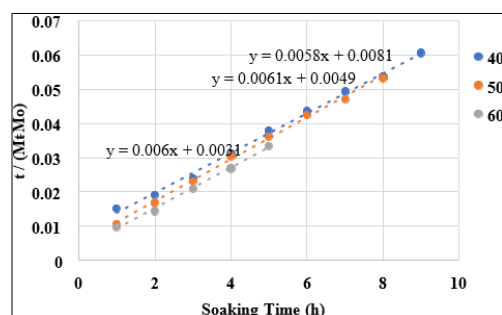


Fig 3: Peleg equation fitting for soybean hydration at 40, 50, and 60 °C in hot water bath

The estimated Peleg rate constant (K_1) was 0.0081, 0.0049, and 0.0031, whereas the capacity constant (K_2) was 0.0058, 0.0061, and 0.0060 at soaking temperatures of 40 °C, 50 °C, and 60 °C, respectively. The decline in K_1 with an increase in soaking temperature indicates that soybean grains absorbed water more rapidly at higher temperatures. The K_2 values showed comparatively small variation among the treatments, suggesting a temperature-dependent change in the water absorption capacity of the grains at equilibrium. The relatively lower K_2 value observed at 60 °C indicates greater moisture uptake at equilibrium compared with the lower soaking temperatures. Based on the estimated Peleg constants, the hydration behaviour of soybean grains at different temperatures was expressed using the following equations:

$$\text{For 40 °C: } Mt = M_o + \frac{t}{0.0081 + 0.0058t} \quad (3)$$

$$\text{For 50 °C: } Mt = M_o + \frac{t}{0.0049 + 0.0061t} \quad (4)$$

$$\text{For 60 °C: } Mt = M_o + \frac{t}{0.0031 + 0.006t} \quad (5)$$

The moisture content values predicted using Peleg's model were in close agreement with the experimentally observed values over the entire soaking period, indicating that the model adequately represented the hydration kinetics of soybean. The linear relationship between $\left(\frac{t}{Mt - Mo}\right)$ and soaking time further supported the applicability of Peleg's approach for describing the hydration process. The fitting of Peleg's equation to the experimental observations is illustrated in Fig. 3. The results demonstrated that an increase in soaking temperature accelerated water uptake and increased the overall moisture gain of soybean grains. This behaviour may be attributed to enhanced molecular movement and improved diffusion of water into the grain structure at elevated temperatures.

Where t ($M_t - M_o$) is the moisture content at time, t (% dry basis), M_o is the initial moisture content (% dry basis), and t is the soaking time (h).

Conclusions

1. The hydration behaviour of soybean grains in a hot water bath was significantly influenced by soaking temperature. Grain weight, water absorption, and moisture content increased progressively with soaking time at all temperatures (40 °C, 50 °C, and 60 °C). The equilibrium water absorption (130.84%) and moisture content (163.57% db.) remained constant, while the time required to attain equilibrium decreased from 10 h at 40 °C, 8 h at 50 °C and 5 h at 60 °C. This reduction in soaking time at higher temperatures may be attributed to increased seed coat permeability, enhanced molecular mobility, reduced water viscosity, and accelerated diffusion of water into the cotyledon tissues (Turhan *et al.*, 2002; Miranda *et al.*, 2019) [5, 12].

2. The Peleg model adequately described the hydration kinetics of soybean, with the rate constant (K_1) decreasing from 0.0081 at 40 °C to 0.0031 at 60 °C, indicating a higher initial water absorption rate at elevated temperatures (Turhan *et al.*, 2002) [12]. The close agreement between experimental and predicted values confirmed the suitability of the model for describing soybean hydration behaviour (Quicazan *et al.*, 2012; Miranda *et al.*, 2019) [5, 10]. Among

the treatments, soaking at 60 °C was the most effective, achieving equilibrium hydration within 5 h due to faster moisture diffusion and enhanced grain softening, thereby improving processing efficiency. Soaking at 50 °C provided a balanced hydration condition, attaining equilibrium in 8 h with efficient water uptake and moderate thermal exposure, whereas soaking at 40 °C required 10 h and resulted in gradual hydration, allowing sufficient grain softening for subsequent grinding and soymilk extraction operations (Deshpande and Damodaran, 1989) ^[3].

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