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TEMPERATURE-DEPENDENT HYDRATION KINETICS OF MUNG BEAN (*VIGNA RADIATA* L.) PRIOR TO SPROUTING: SIGMOIDAL, EMPIRICAL AND FICKIAN MODELLING

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ABSTRACT
Soaking is the first and often the slowest step in producing mung bean sprouts, yet there is little quantitative information on how soak-water temperature controls water uptake in this legume. Mung bean (Vigna radiata L.) grains with an initial moisture content of 9.17% d.b. were soaked at 25, 30, 35, 40 and 45 °C, and their moisture content was recorded every 0.5 h for 8 h in triplicate. Every hydration curve was distinctly sigmoidal: uptake was slow at first, accelerated to a peak rate and then levelled off at a terminal moisture content of 118.41–139.80% d.b. Raising the temperature from 25 to 45 °C increased the peak hydration rate from 38.47 to 55.62% d.b. h−1 and shortened the time needed to reach 95% of the total moisture gain from 6.31 to 2.75 h. Terminal moisture, however, did not increase steadily with temperature and was highest at 30 °C. Of five models tested, the Kaptso-type sigmoidal model described the data best (mean R2 = 0.9968; RMSE = 2.32% d.b.), closely followed by the Weibull model (R2 = 0.9961), whereas the Peleg, exponential and one-term Fick-type models, which assume a downward concave curve, performed markedly worse. The inflection time of the sigmoidal model fell from 2.88 to 1.19 h, showing that warmer water shortened the lag phase. Effective moisture diffusivity ranged from 3.59 × 10−11 to 8.20 × 10−11 m2 s−1, and the Arrhenius analysis gave an apparent activation energy of 27.84 kJ mol−1, a value consistent across four independent kinetic indicators (24.3–29.2 kJ mol−1). At 40–45 °C the grains reached a typical steeping target of about 82% d.b. (≈45% w.b.) within 1.6–2.5 h, compared with 3.8 h at 25 °C. These results offer a practical basis for choosing soaking time–temperature combinations for mung bean sprouting.

KEYWORDS: mung bean; hydration kinetics; sigmoidal behaviour; soaking temperature; effective moisture diffusivity; activation energy; sprouting

INTRODUCTION
Mung bean (Vigna radiata L.) is one of the most widely eaten pulses in South and East Asia, valued for a protein fraction comparatively rich in lysine and for being easier to digest than many other legumes (Goyal et al., 2014; Salehi, 2023). Like other food legumes, however, the dry grain carries antinutritional factors such as phytate, tannins and protease inhibitors, and it needs lengthy preparation before it can be eaten (Affrifah et al., 2023; Cargo-Froom et al., 2020). Sprouting is a low-cost way around both problems: germinated legumes generally contain fewer antinutrients, digest better, and are richer in phenolic compounds and soluble protein than the raw seed (Cargo-Froom et al., 2020; Winarsi et al., 2020). Consumer interest has followed, and launches of sprouted-grain products grew steadily between 2006 and 2016 (Pagand et al., 2017).

Every sprouting operation begins with soaking. In controlled sprouting, grains are first steeped to a moisture content of roughly 45%, after which the metabolic activity leading to radicle emergence gets under way (Pagand et al., 2017). This first stage of imbibition is essentially physical; the seed absorbs water whether or not it is alive, and little further water is taken up until germination itself begins (Miano & Augusto, 2018). In practice, soaking is still run on rules of thumb. Pulses are typically soaked for 8–12 h before cooking and 12–24 h before germination (Cargo-Froom et al., 2020), and mung bean sprouts have been prepared after a 12 h soak at 22–25 °C (Goyal et al., 2014). Long soaks occupy vessels and water, allow soluble solids to leach, and give microorganisms time to grow (Miano & Augusto, 2018; Quast & da Silva, 1977). Knowing how quickly the grain actually reaches its target moisture is therefore directly useful for process design.

Raising the water temperature is the simplest way to speed up hydration. Work on red kidney beans (Abu-Ghannam & McKenna, 1997), beans, peas and soybeans (Quast & da Silva, 1977), lentils (Oroian, 2017) and maize (Kumar et al., 2022) consistently shows that warmer water accelerates uptake and shortens the time to equilibrium. The effect on equilibrium moisture is less predictable and, depending on the grain and temperature range, it can rise, fall or stay the same (Miano & Augusto, 2018).

The shape of the hydration curve decides which model is appropriate. Most cereals and many legumes follow a downward concave shape (DCS), in which uptake is fastest at the start and slows steadily; Fick's second law, the first-order equation and the Peleg model are the usual choices for such curves (Miano & Augusto, 2018). Some legumes instead hydrate sigmoidally: uptake is slow at first, speeds up to a maximum and then declines. The initial lag is attributed to a seed coat of low permeability, which forces water to enter mainly through the hilum until the coat itself has been hydrated from the

inside (Miano & Augusto, 2018; Miano et al., 2018). Mung bean belongs to this group. Miano et al. (2016) described its sigmoidal behaviour, and Miano et al. (2018) confirmed it for a commercial mung bean soaked at 25 °C, obtaining an excellent fit with the model of Kaptso et al. (2008). Fitting DCS equations to sigmoidal data can yield parameters with little physical meaning, a problem Miano and Augusto (2018) identified in several published studies.

Data sets for mung bean that span several soaking temperatures and combine sigmoidal and DCS models with effective diffusivity and an Arrhenius analysis nevertheless remain limited; published work has concentrated on a single temperature or on non-thermal treatments such as ultrasound (Miano et al., 2016; Miano et al., 2018). This study therefore aimed to (i) measure the hydration kinetics of mung bean at five temperatures between 25 and 45 °C; (ii) quantify hydration rates, characteristic times and terminal moisture; (iii) compare sigmoidal, Weibull, Peleg, exponential and one-term Fick-type models; (iv) estimate the effective moisture diffusivity and apparent activation energy; and (v) translate these results into practical soaking times for sprouting.

2. MATERIALS AND METHODS

2.1 Raw material and physical characteristics

Mung bean grains were purchased from a local market in New Delhi, India. Visible foreign matter was removed by hand, and the cleaned grains were used without conditioning, so that all treatments started from the same native moisture level. Length (L), breadth (B) and thickness (T) of ten randomly selected grains were measured with a digital vernier caliper (least count 0.1 mm), and the geometric mean diameter (D_g) and sphericity (φ) were calculated as:

$$D_g = (LBT)^{1/3}, \quad \varphi = D_g / L \quad (1)$$

Half of D_g was taken as the equivalent spherical radius (R) for the diffusivity calculation (Section 2.5).

2.2 Hydration experiment

Soaking was carried out in a thermostatically controlled water bath at 25, 30, 35, 40 or 45 °C (accuracy ± 0.5 °C). For each run, 15 g of grain was immersed in distilled water pre-equilibrated to the set temperature at a grain-to-water ratio of 1:10 (w/v). Samples were withdrawn every 0.5 h, blotted gently with tissue paper to remove surface water, and their moisture content was determined with an infrared moisture analyser; masses were recorded on an analytical balance. Soaking continued for 8 h, by which time moisture had stopped changing at every temperature. Each treatment was run in triplicate, and results are reported as mean ± standard deviation (SD). A comparable procedure has been applied to mung bean and other pulses by Miano et al. (2018).

2.3 Moisture ratio, hydration rate and characteristic times

Moisture content was expressed on a dry basis (% d.b.). The final measured value was taken as the operational saturation moisture content (M_s). Where the same value recurred at later sampling times, only its first occurrence was used in model fitting so that plateau points would not dominate the regression; all observations are nevertheless shown in the figures. The forward moisture ratio (MR) and its complement (MR_r) were calculated as:

$$MR = (M_t - M_0) / (M_s - M_0), \quad MR_r = 1 - MR \quad (2)$$

where M_t is the moisture content at time t (h) and M_0 the initial moisture content. The interval hydration rate (HR, % d.b. h^{-1}) was calculated from successive observations and plotted at the midpoint of each interval:

$$HR = (M_{t+\Delta t} - M_t) / \Delta t \quad (3)$$

The mean hydration rate was the total moisture gain divided by the time at which M_s was first reached. Three characteristic times were obtained by linear interpolation of the experimental curve: t_{50} and t_{95}, the times to reach 50% and 95% of the total moisture gain, and t_{82}, the time to reach 81.8% d.b., the dry-basis equivalent of the 45% (w.b.) moisture commonly targeted at the end of steeping in controlled sprouting (Pagand et al., 2017).

2.4 Hydration models

Five models were fitted. The Peleg model (Peleg, 1988), the most widely used equation for DCS curves, is:

$$M_t = M_0 + t / (k_1 + k_2 t) \quad (4)$$

where $1/k_1$ (h^{-1}) relates to the initial hydration rate and $M_0 + 1/k_2$ to the equilibrium moisture (moisture in kg kg^{-1} d.b.). The Kaptso-type sigmoidal model (Kaptso et al., 2008), developed for legumes with a lag phase, is:

$$M_t = M_s / [1 + \exp\{-k_3(t - s)\}] \quad (5)$$

where k_3 (h^{-1}) governs the steepness of the curve and s (h) is the time of the inflection point, marking the end of the lag. The Weibull, exponential (first-order) and one-term Fick-type models were written as:

$$MR_r = \exp[-(t/\beta)^{\alpha}] \quad (6)$$

$$MR_r = \exp(-k_4 t) \quad (7)$$

$$MR_r = A_1 \exp(-Kt) \quad (8)$$

In the Weibull model, β (h) approximates the time to complete about 63% of the process and α is a shape parameter (Miano & Augusto, 2018). The exponential model assumes a rate proportional to the remaining moisture deficit (Abu-Ghannam & McKenna, 1997). Eq. (8) is the first term of the series solution of Fick's second law for a sphere (Crank, 1975), with the pre-exponential coefficient A_1 left free.

2.5 Effective moisture diffusivity and temperature dependence

For an isotropic sphere of radius R, the first term of Fick's solution gives $MR_r = (6/\pi^2) \exp(-\pi^2 D_e t / R^2)$ (Crank, 1975). Comparing this with Eq. (8), the effective moisture diffusivity (D_e, m^2 s^{-1}) follows from the fitted rate constant (converted to s^{-1}):

$$D_e = K R^2 / \pi^2 \quad (9)$$

The same equivalent-sphere approach has been used for sprouted mung beans (Salehi, 2023). Because it assumes regular geometry, isotropy, negligible swelling and purely diffusive transport (Miano & Augusto, 2018), D_e is treated here as a lumped transport coefficient rather than a molecular diffusivity. Its temperature dependence was described by the linearised Arrhenius equation:

$\ln D_e = \ln D_0 - (E_a / R_g)(1/T_{abs})$ (10)

where D_0 is the pre-exponential factor ($m^2 s^{-1}$), E_a the apparent activation energy (J mol^{-1}), R_g the gas constant (8.314 J $mol^{-1} K^{-1}$) and T_{abs} the absolute temperature (K). To check whether E_a depended on model choice, the same regression was applied to the sigmoidal rate constant k_3, the Weibull rate index $1/\beta$, the model-free index $1/t_{95}$ and the Peleg index $1/k_1$. The D_e regression was repeated without the 35 °C point as a sensitivity check. Following Quast and da Silva (1977), a z-value (temperature rise that shortens t_{95} ten-fold) was obtained from the slope of $\log_{10} t_{95}$ against temperature.

2.6 Statistical analysis

Model parameters were estimated by nonlinear least squares (Levenberg–Marquardt algorithm, SciPy curve_fit, Python) on the triplicate mean moisture contents. Goodness of fit was judged by the coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE) and reduced chi-square (χ^2):

$RMSE = [\Sigma(M_{exp} - M_{pre})^2 / N]^{1/2}$, $\chi^2 = \Sigma(M_{exp} - M_{pre})^2 / (N - n_p)$ (11)

where N is the number of observations and n_p the number of parameters. The Akaike and Bayesian information criteria (AIC, BIC) were computed as supplementary measures that penalise extra parameters. The selected model was further checked with a parity plot; a slope near 1 and an intercept near 0 indicate unbiased prediction (Miano et al., 2018). Linear regressions (Arrhenius and z-value) were tested at $p < 0.05$. Because only replicate means and SDs were retained, the models describe the mean response.

3. RESULTS AND DISCUSSION

3.1 Grain characteristics and hydration curves

The grains were small and slightly elongated, with mean length, breadth and thickness of 4.77 ± 0.40, 3.58 ± 0.12 and 3.50 ± 0.13 mm. This gave a geometric mean diameter of 3.910 mm, an equivalent radius of 1.955 mm and a sphericity of 0.82, indicating a moderately rounded, ellipsoidal grain with a near-circular cross-section. Initial moisture was 9.17% d.b. for the bulk sample and varied only between 9.11 and 9.46% d.b. across the five treatment batches (Table 1).

Moisture content rose with soaking time at every temperature along a clear S-shaped path (Fig. 1a). During the first 0.5–1.5 h uptake was slow, particularly at 25 and 35 °C, where moisture increased by only about 8.5–10.6% d.b. in the first hour. The curves then steepened into a near-linear stretch in which most of the water was absorbed, before settling onto a plateau. Higher temperatures moved the whole curve to the left. At 45 °C the lag was barely visible and the plateau (122.62% d.b.) was reached after 4.5 h, whereas at 25 °C moisture was still creeping upward after 7 h and levelled off at 118.41% d.b. only at 8 h. Standard deviations were small relative to the moisture range (at most 5.35% d.b.).

The interval hydration rate (Fig. 1b) makes the sigmoidal character explicit. At every temperature the rate first increased, passed through a maximum and then fell to zero, the signature of a lag followed by rapid uptake; in a DCS process the highest rate would occur in the first interval. First-interval rates were 6.72–35.19% d.b. h^{-1}, whereas peak rates were considerably higher (36.83–55.62% d.b. h^{-1}) and occurred at 1.25–2.75 h (Table 1). At 45 °C the rate collapsed quickly after its peak and was below 3% d.b. h^{-1} from 3.25 h onward, while at 25 °C measurable uptake (7–9% d.b. h^{-1}) continued until almost 7 h. Small secondary peaks at intermediate times should be read as interval estimates from discrete measurements rather than true fluctuations.

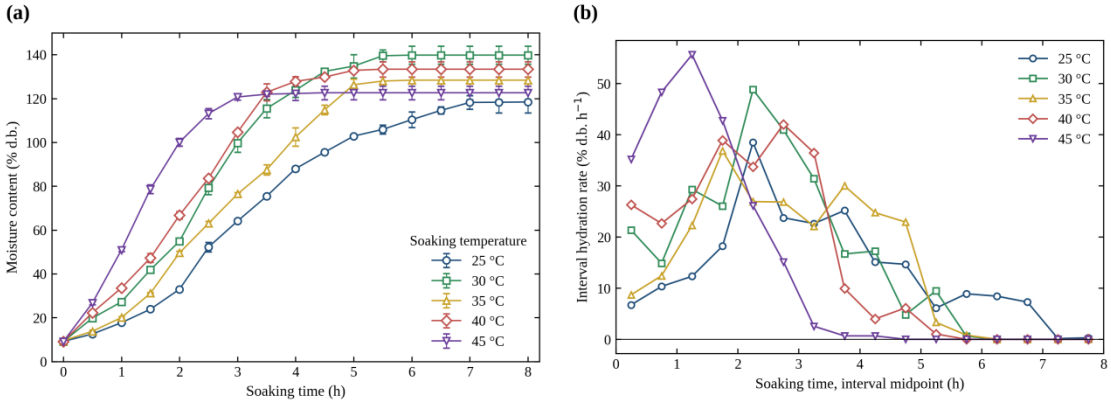


Fig. 1. (a) Moisture content of mung bean during soaking at 25–45 °C (symbols are means of three replicates; bars show ± SD). (b) Interval hydration rate, calculated from successive moisture readings and plotted at the midpoint of each 0.5 h interval.

These observations, together with Weibull shape parameters close to 2 (Section 3.3), show that mung bean hydrates sigmoidally between 25 and 45 °C. This agrees with Miano et al. (2016) and with Miano et al. (2018), who placed mung bean among the legumes with a sigmoidal curve when 22 cereals and pulses were soaked under identical conditions. At 25 °C, Miano et al. (2018) reported an equilibrium moisture of about 140% d.b., a rate constant of 0.62 h^{-1} and a lag time of 4.15 h (R^2 = 0.997); the present grains gave k_3 = 0.92 h^{-1} and s = 2.88 h (R^2 = 0.998) and were therefore somewhat quicker to leave the lag phase. They were also slightly smaller (4.77 × 3.58 × 3.50 mm against 5.11 × 3.80 × 3.62 mm) and drier at the start (9.17 against 13.3% d.b.), but Miano et al. (2018) showed that neither size nor seed-coat colour reliably predicts hydration speed, so differences in cultivar, seed-coat structure and storage history are the more probable causes.

The mechanism behind the lag is well documented. In legumes with a poorly permeable seed coat, water first enters through the hilum, travels to the space between coat and cotyledons, and hydrates the coat from the inside; only once the coat has become permeable can water cross it directly, after which the cotyledons fill by diffusion and capillary flow

(Miano & Augusto, 2018). The slow first stage in Fig. 1a corresponds to hilum-limited entry and the steep middle stage to the period when the whole seed surface conducts water. The final plateau marks the end of physical imbibition (phase I), after which little net uptake occurs while the seed prepares for germination (Miano & Augusto, 2018) - the point at which a sprouting process would move from soaking to germination.

3.2 Terminal moisture and characteristic hydration times

The terminal moisture content did not increase steadily with temperature (Table 1). It was lowest at 25 °C (118.41% d.b.), highest at 30 °C (139.80% d.b.), and fell to 128.36, 133.36 and 122.62% d.b. at 35, 40 and 45 °C. The difference between 25 and 30 °C (about 21% d.b.) was well above the replicate SDs (3–5% d.b.), whereas values at 30–40 °C lay within about 11% d.b. of one another.

The time-based indicators responded clearly to temperature. The time at which the terminal value was first reached fell from 8.0 to 4.5 h between 25 and 45 °C, t_{95} fell 2.3-fold from 6.31 to 2.75 h, and t_{50} dropped from 2.99 to 1.27 h. The time to reach the sprouting target of 81.8% d.b. (t_{82}) decreased from 3.75 to 1.57 h, and the mean hydration rate nearly doubled, from 13.66 to 25.23% d.b. h^{-1}. Regression of $\log_{10} t_{95}$ on temperature gave a z-value of 62.8 °C ($R^2 = 0.898$), equivalent to a Q_{10} of about 1.5.

Table 1. Hydration characteristics of mung bean at different soaking temperatures.

T (°C)	M_0 (% d.b.)	M_s (% d.b.)	t at M_s (h)	t_{50} (h)	t_{95} (h)	t_{82} (h)	$HR_{0–0.5\ h}$	HR_{peak} (time, h)	HR_{mean}
25	9.17	118.41	8.0	2.99	6.31	3.75	6.72	38.47 (2.25)	13.66
30	9.11	139.80	6.0	2.40	4.69	2.56	21.33	48.79 (2.25)	21.78
35	9.46	128.36	6.0	2.72	4.83	3.24	8.69	36.83 (1.75)	19.82
40	9.11	133.36	5.5	2.13	3.94	2.45	26.28	42.02 (2.75)	22.59
45	9.11	122.62	4.5	1.27	2.75	1.57	35.19	55.62 (1.25)	25.23

M_s: terminal (operational saturation) moisture; t_{50}, t_{95}: time to 50% and 95% of total moisture gain; t_{82}: time to reach 81.8% d.b. (≈45% w.b.); HR: interval hydration rate (% d.b. h^{-1}) in the first interval, at its peak, and averaged over the time to M_s.

Non-monotonic equilibrium values are well known in legume hydration; higher soaking temperatures can increase, reduce or leave unchanged the equilibrium moisture (Miano & Augusto, 2018). Increases are usually attributed to expansion of internal pores and greater solubility of grain components, decreases to leaching of solubles, damage to cell walls and membranes, and rapid saturation of outer layers that lowers the driving force for further uptake. Abu-Ghannam and McKenna (1997) found that the equilibrium moisture of red kidney beans fell from 173% d.b. at 20 °C to 103% d.b. at 60 °C, which they linked to greater extraction of solubles and to gases trapped within the bean, and Quast and da Silva (1977) observed that the apparent maximum moisture of black beans occurs when solids loss begins to outweigh water gain. The present data fit this picture of two opposing effects: moderate warming from 25 to 30 °C appears to have opened the grain structure enough to raise its water-holding capacity, whereas above 30 °C faster leaching, quicker saturation of outer tissues and swelling-related structural changes seem to have offset this gain. Garvín et al. (2019) emphasised that grains are anisotropic materials that swell, release air and lose solids during hydration, which helps explain why capacity and rate responded so differently to temperature.

3.3 Model fitting and comparison

All five models reproduced the general rise in moisture, but their accuracy differed widely (Table 2). The sigmoidal model gave the best overall result (mean $R^2 = 0.9968$; RMSE = 2.32% d.b.; MAE = 1.87% d.b.; $\chi^2 = 7.29$), and the Weibull model was almost as good ($R^2 = 0.9961$; RMSE = 2.58% d.b.; $\chi^2 = 9.08$). Weibull was marginally better at 25 and 35 °C and the sigmoidal model at 30, 40 and 45 °C, a pattern confirmed by AIC and BIC (e.g. AIC of 5.44 against 8.94 at 45 °C). Both curves followed the data closely throughout, including the lag and the approach to the plateau (Fig. 2). The three DCS models fitted much less well. Peleg reached R^2 values of 0.960–0.976 but with RMSE of 6.8–8.9% d.b. (mean χ^2 = 75.70), while the Fick-type ($R^2 = 0.906–0.954$) and exponential ($R^2 = 0.873–0.944$) models left errors of 8.8–15.5% d.b., larger than those of the sigmoidal model.

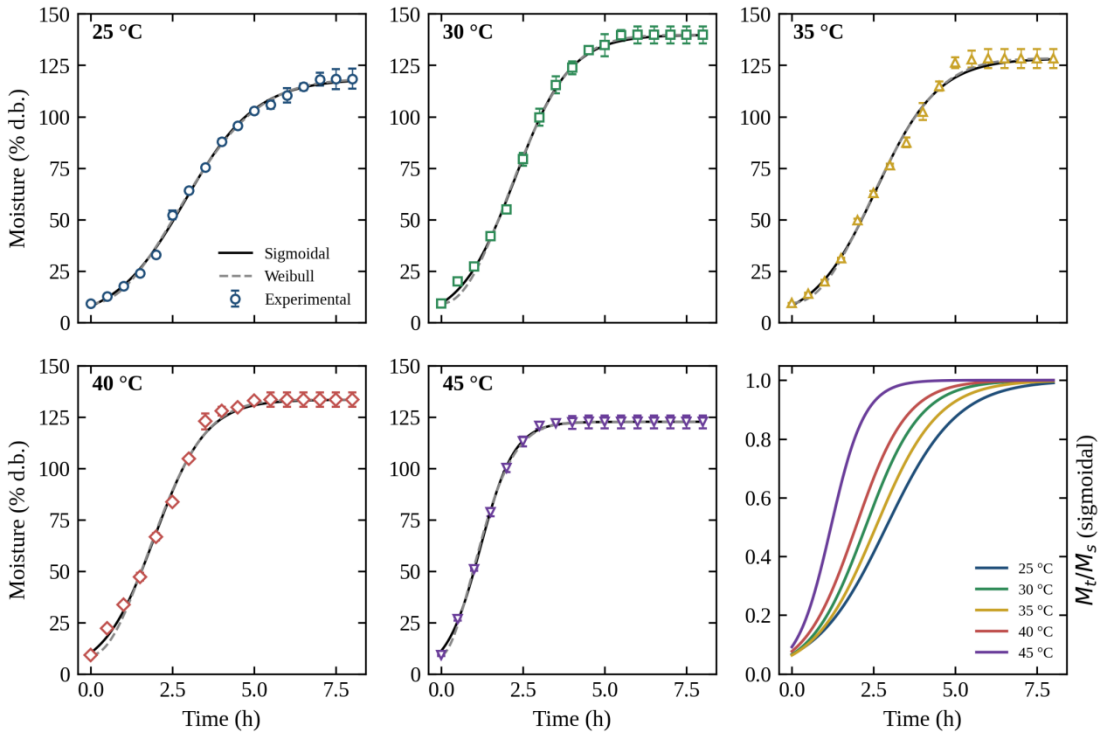


Fig. 2. Experimental moisture content (symbols ± SD) and curves predicted by the sigmoidal (solid) and Weibull (dashed) models at each soaking temperature. The last panel compares the normalised sigmoidal curves (M_t/M_s) for all temperatures.

The ranking follows directly from curve shape. The Peleg, first-order and Fick-type equations were developed for DCS curves, in which the rate is highest at time zero, and none can produce an initial lag (Miano & Augusto, 2018). Forced onto sigmoidal data, they over-predict moisture during the lag, under-predict it during rapid uptake and compensate with distorted parameters. The Peleg model illustrates this. Its R^2 values above 0.96 compare favourably with the 0.909–0.946 accepted for maize by Kumar et al. (2022), yet the capacity constant k_2 showed no consistent trend and settled at its lower bound of zero at 35 °C (unconstrained estimate −0.005, describing a curve that never levels off). The implied equilibrium moisture ($M_0 + 1/k_2$) was 212–556% d.b., 1.7–4 times the measured terminal values, and undefined at 35 °C. A high R^2 alone is therefore not sufficient evidence that a model is appropriate. The Fick-type model shows the same issue differently: for an ideal sphere A_1 should equal $6/\pi^2 \approx 0.61$, but fitted values of 1.10–1.18 (Table 2) mean the curve had to be shifted upward so its decay could start later, which is how a single exponential imitates a lag.

Table 2. Parameters and goodness of fit of the five hydration models at each soaking temperature.

Model	Parameter	25 °C	30 °C	35 °C	40 °C	45 °C	Mean
Sigmoidal	k_3 (h^{-1})	0.917	1.182	1.049	1.271	1.921	–
	s (h)	2.885	2.251	2.567	1.955	1.192	–
	R^2	0.9980	0.9980	0.9936	0.9952	0.9993	0.9968
	RMSE (% d.b.)	1.78	2.13	3.48	3.12	1.07	2.32
Weibull	α (–)	2.074	2.090	2.159	1.992	1.778	–
	β (h)	3.620	2.794	3.195	2.455	1.522	–
	R^2	0.9983	0.9963	0.9946	0.9925	0.9990	0.9961
	RMSE (% d.b.)	1.63	2.90	3.21	3.90	1.28	2.58
Peleg	k_1 (h)	4.765	3.094	4.605	2.694	1.428	–
	k_2 (–)	0.235	0.183	0[a]	0.244	0.492	–
	R^2	0.9601	0.9650	0.9755	0.9668	0.9634	0.9662
	RMSE (% d.b.)	8.00	8.91	6.79	8.21	7.84	7.95
Fick-type	A_1 (–)	1.183	1.147	1.168	1.127	1.096	–
	K (h^{-1})	0.334	0.423	0.370	0.481	0.762	–
	D_e ($\times 10^{-11}$ m^2 s^{-1})	3.59	4.55	3.98	5.18	8.20	–

Model	Parameter	25 °C	30 °C	35 °C	40 °C	45 °C	Mean
	R^2	0.9266	0.9191	0.9063	0.9236	0.9541	0.9259
	RMSE (% d.b.)	10.85	13.55	13.29	12.46	8.78	11.79
Exponential	k_4 (h^{-1})	0.286	0.374	0.318	0.432	0.707	–
	R^2	0.8933	0.8953	0.8728	0.9056	0.9444	0.9023
	RMSE (% d.b.)	13.09	15.41	15.49	13.85	9.67	13.50

Peleg constants fitted on the kg kg^{-1} d.b. scale; D_e from Eq. (9) with R = 1.955 mm. [a]Constrained at the lower bound of zero (unconstrained estimate −0.005); the Peleg equilibrium is not identifiable at 35 °C. Standard errors, MAE, reduced χ^2, AIC and BIC are given in the Supplementary material (Tables S1–S2).

The sigmoidal and Weibull models both have enough flexibility to follow the lag, rapid stage and plateau, and their parameters behaved coherently. The sigmoidal rate constant k_3 increased from 0.92 to 1.92 h^{-1} between 25 and 45 °C, and the inflection time s fell from 2.88 to 1.19 h, so the lag ended about 1.7 h earlier at the highest temperature; the model-predicted t_{95} (6.10 to 2.73 h) agreed closely with interpolated experimental values. The Weibull β decreased from 3.62 to 1.52 h, and α stayed between 1.78 and 2.16; a shape parameter greater than 1 describes an accelerating-then-decelerating curve, independently confirming sigmoidal behaviour, and the lowest α at 45 °C matches the weaker lag at that temperature. Because the statistical performance of the two models was nearly identical, the choice can rest on interpretation. We prefer the sigmoidal model because its parameters describe the process directly, with k_3 for the hydration rate and s for the end of the lag, as Miano and Augusto (2018) also recommend for sigmoidal grains.

3.4 Effect of temperature on hydration rate and lag phase

Warmer water consistently accelerated hydration, shortening t_{95} 2.3-fold and bringing the inflection point forward by 1.7 h. This agrees with every study in the reference set that examined temperature: Abu-Ghannam and McKenna (1997) found that the hydration rate constant of unblanched red kidney beans was almost 20 times higher at 60 °C than at 20 °C, Quast and da Silva (1977) reported shorter soaking times with increasing temperature for several beans, peas and soybeans, and Oroian (2017) and Kumar et al. (2022) found the same for lentils and maize. Heat lowers water viscosity, dilates tissues and pores, and partly dissolves some components, enlarging the pore network (Miano & Augusto, 2018). For sigmoidal grains in particular, heat accelerates hydration of the seed coat itself and lowers the moisture at which coat polymers pass from a glassy to a rubbery, more permeable state. The steady decrease in s is a direct measure of this effect in mung bean, and matches the shorter lag times reported for other sigmoidal legumes soaked in warm water (Kaptso et al., 2008; Miano & Augusto, 2018).

The largest single increases in k_3 and D_e, and the largest drop in s, occurred between 40 and 45 °C. Abu-Ghannam and McKenna (1997) observed that kidney bean seed coats became rubbery at about 40 °C and above, and that this plasticising effect largely accounted for faster uptake. A similar softening of the mung bean seed coat in the 40–45 °C range would explain why the lag almost disappeared at 45 °C.

The 35 °C treatment was the only clear departure from the trend: its first-interval rate, k_3, $1/k_1$ and D_e were all lower than at 30 °C. Initial moisture cannot explain this, because the 35 °C batch started slightly wetter (9.46% d.b.), and a higher initial moisture tends to shorten the lag of sigmoidal grains (Miano & Augusto, 2018). A more plausible explanation is variation in seed-coat permeability between sub-samples. Individual legume seeds can differ markedly in this respect, and some beans show a hard-shell character that resists water uptake (Abu-Ghannam & McKenna, 1997); even a small share of such seeds would lower the average rate of a sub-sample. Such seed-to-seed variability is the main reason hydration behaviour is hard to generalise across lots and cultivars (Miano et al., 2018). Importantly, removing the 35 °C point hardly changed the activation energy (Section 3.5).

3.5 Effective moisture diffusivity and activation energy

The Fick-type rate constant K increased from 0.334 to 0.762 h^{-1} between 25 and 45 °C, corresponding to effective diffusivities of 3.59–8.20 × 10^{-11} m^2 s^{-1}, a 2.3-fold increase (Table 2). Diffusivity rose at each step except between 30 and 35 °C and rose most sharply between 40 and 45 °C. Given the fitted A_1 values, these D_e values are best regarded as lumped coefficients that include hilum-controlled entry, capillary flow, swelling and non-spherical geometry, all of which violate the assumptions of Fick's law (Miano & Augusto, 2018); they remain useful for comparing temperatures. They are of a plausible order for water transport in whole legume seeds. Salehi (2023), using the same spherical solution for sprouted mung beans (radius 2.25 mm), obtained 1.36–1.88 × 10^{-10} m^2 s^{-1} during hot-air drying at 70 °C; the values are not strictly comparable, but the higher figure is consistent with the higher temperature and the more open structure of germinated seed.

Regression of ln D_e on $1/T_{abs}$ gave ln D_e = −12.872 − 3348.4 ($1/T_{abs}$) (R^2 = 0.754; p = 0.056), corresponding to D_0 = 2.57 × 10^{-6} m^2 s^{-1} and E_a = 27.84 kJ mol^{-1} (Fig. 3a). The fit was only moderate because the 35 °C point lies well below the line (residual −0.21). When it was omitted, R^2 rose to 0.871 but E_a barely moved (27.97 kJ mol^{-1}), so this point weakens the fit without biasing the slope. Activation energies from the other indicators were remarkably similar (Fig. 3b): 24.33 kJ mol^{-1} from k_3 (R^2 = 0.759), 29.15 kJ mol^{-1} from $1/\beta$ (R^2 = 0.764) and 28.82 kJ mol^{-1} from the model-free $1/t_{95}$, which gave the most precise fit (R^2 = 0.893; p = 0.015). Omitting 35 °C changed each of these by less than 0.2 kJ mol^{-1}. Only the Peleg index $1/k_1$ gave a noticeably higher value (39.85 kJ mol^{-1}) with the weakest fit (R^2 = 0.665), consistent with that model's poorer description of the data.

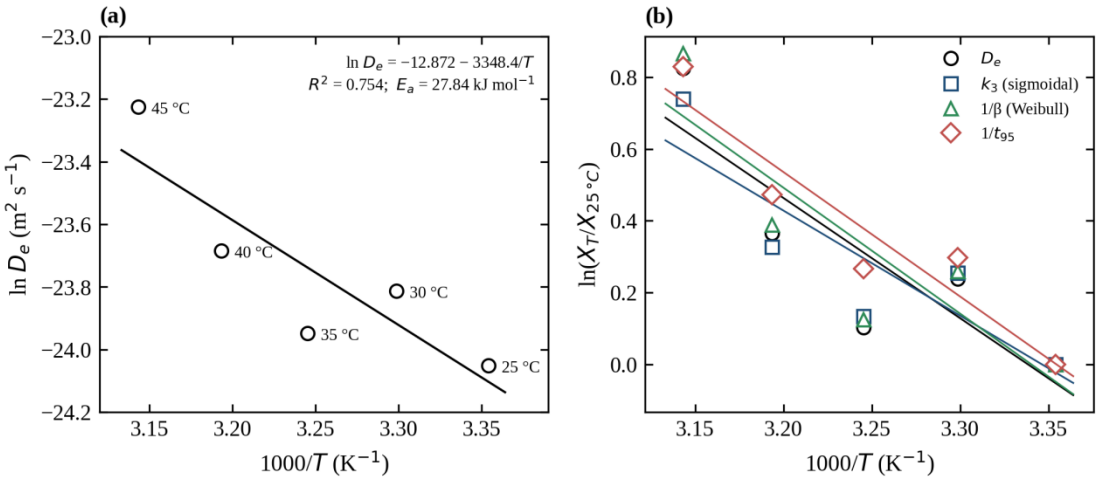


Fig. 3. (a) Arrhenius plot of effective moisture diffusivity; (b) Arrhenius plots of four kinetic indicators, each normalised to its value at 25 °C, showing nearly parallel slopes.

An apparent activation energy of about 28 kJ mol^{-1} falls within the range reported for legume hydration. For red kidney beans, Abu-Ghannam and McKenna (1997) obtained about 59.6 kJ mol^{-1} for unblanched beans but only about 27.1 kJ mol^{-1} after a short blanching treatment had plasticised the seed coat. The mung bean value is close to the latter, suggesting that between 25 and 45 °C water entry into mung bean is less temperature-sensitive than in unblanched kidney beans, whose seed coat presents a stronger barrier. Much lower values (7.7–10.6 kJ mol^{-1}) have been reported for corn semolina, a milled product with no seed coat (Bhattacharya, 1994, as cited in Kumar et al., 2022). Agreement among four independent indicators (24.3–29.2 kJ mol^{-1}) gives confidence in the estimate even though each individual fit was only moderate, which is common in grain hydration: Quast and da Silva (1977) found that log hydration time was often not linear in temperature, and Garvín et al. (2019) noted that wide confidence intervals are to be expected for Arrhenius parameters of grain hydration. The z-value of 62.8 °C is of the same order as the value of about 50 °C reported for bean hydration by Quast and da Silva (1977).

3.6 Validation of the sigmoidal model

In the parity plot (Fig. 4a), predicted and observed moisture contents for all 65 fitted points lie close to the 1:1 line. Regressing predicted on observed values gave a slope of 0.989, an intercept of 0.32% d.b. and R^2 = 0.997, indicating negligible bias and agreeing closely with the slope of 1.01 reported for mung bean by Miano et al. (2018) using the same model. Residuals (Fig. 4b) were within ±4% d.b. for 88% of the points; the largest (+7.2% d.b.) occurred at 35 °C and 5.0 h, where the measured curve bends into the plateau more sharply than the symmetric logistic function allows. Residuals tended to be positive near the end of the rapid-uptake stage and around the onset of the plateau, suggesting a slightly asymmetric transition. For a three-parameter model describing a biological material this deviation is small and does not affect the model's usefulness for predicting soaking times.

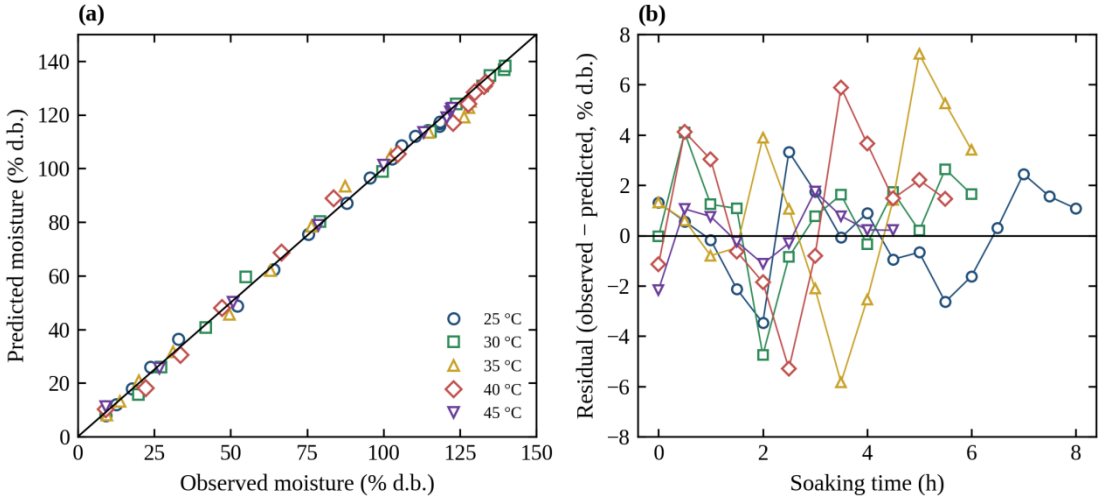


Fig. 4. Validation of the sigmoidal model: (a) predicted versus observed moisture content, with the 1:1 line; (b) residuals as a function of soaking time.

3.7 Practical implications for soaking before sprouting

For a sprouting operation, the most useful figures are the times needed to reach the steeping target and the full plateau. At 45 °C the grains reached about 82% d.b. (≈45% w.b.) in 1.6 h and their terminal moisture in 4.5 h; at 25 °C the same targets took 3.8 and 8 h (Table 1). All of these are well short of the 12 h soak used before sprouting mung bean (Goyal et

al., 2014) and of the 8–12 h or longer periods commonly recommended for pulses (Cargo-Froom et al., 2020). Under the present conditions, soaking time could therefore be shortened considerably without leaving the grain under-hydrated.
The choice of temperature involves trade-offs. Soaking at 45 °C is fastest, but microbial growth responds more steeply to temperature than hydration does (a z-value of roughly 20 °C against about 50 °C; Quast & da Silva, 1977), so warm soak water may favour microorganisms proportionally more than it speeds up water uptake. Higher temperatures also increase leaching of solids, with soaking above 60 °C associated with a three- to four-fold rise in losses of sugars, minerals and water-soluble vitamins (Kon, 1979, as cited in Abu-Ghannam & McKenna, 1997), and heating adds to processing costs (Miano & Augusto, 2018). Some leaching is beneficial, however, as it contributes to the reduction of phytate, tannins and trypsin inhibitors (Cargo-Froom et al., 2020; Kadam & Salunkhe, 1985). Within the range tested, 30 °C gave the highest terminal moisture and reached the steeping target in about 2.6 h, while 40 °C gave a similar t_{82} with a shorter t_{95}. A soaking temperature of 30–40 °C therefore appears a sensible starting point, in consideration with soaking regime.

4. CONCLUSIONS

Mung bean grains soaked at 25–45 °C hydrated along a sigmoidal path, with a lag phase, a period of rapid uptake and a plateau at 118–140% d.b. Raising the temperature from 25 to 45 °C increased the peak hydration rate from 38.5 to 55.6% d.b. h^{-1}, shortened the lag (inflection time from 2.88 to 1.19 h) and reduced the time to 95% moisture gain from 6.31 to 2.75 h. Terminal moisture, in contrast, was highest at 30 °C, reflecting a balance between greater water-holding capacity and greater leaching and structural change at higher temperatures. The Kaptso-type sigmoidal model (mean $R^2 = 0.9968$, RMSE = 2.32% d.b.) and the Weibull model described the data accurately, whereas the Peleg, exponential and Fick-type models, which assume a downward concave curve, gave larger errors and, for Peleg, physically unrealistic equilibrium values. The sigmoidal model is recommended for mung bean because its parameters directly express the hydration rate and the duration of the lag phase. Effective moisture diffusivity rose from 3.59 to 8.20 × 10^{-11} m^2 s^{-1}, and an apparent activation energy of about 28 kJ mol^{-1} was confirmed by independent kinetic indicators. In practice, mung bean reaches a typical steeping moisture of ≈45% w.b. within 1.6–3.8 h and its full soaking plateau within 4.5–8 h, considerably shorter than the soaking periods commonly used before sprouting; a soaking temperature of 30–40 °C is proposed as a starting point.

Supplementary material

Tables S1–S4 (goodness-of-fit statistics at each temperature, parameter standard errors, activation energies from all kinetic indicators, and the full experimental hydration data) and Figs. S1–S4 (terminal moisture and characteristic times, model performance, temperature dependence of model parameters, and effective diffusivity) are provided as supplementary material.

REFERENCES

1. Abu-Ghannam, N., & McKenna, B. (1997). Hydration kinetics of red kidney beans (Phaseolus vulgaris L.). Journal of Food Science, 62(3), 520–523.
2. Affrifah, N. S., Uebersax, M. A., & Amin, S. (2023). Nutritional significance, value-added applications, and consumer perceptions of food legumes: A review. Legume Science, 5, e192. https://doi.org/10.1002/leg3.192
3. Cargo-Froom, C., Shoveller, A.-K., Marinangeli, C. P. F., & Columbus, D. A. (2020). Methods for processing pulses to optimize nutritional functionality and maximize amino acid availability in foods and feeds. Cereal Foods World, 65(6). https://doi.org/10.1094/CFW-65-6-0068
4. Crank, J. (1975). The mathematics of diffusion (2nd ed.). Oxford: Clarendon Press.
5. Garvín, A., Augusto, P. E. D., Ibarz, R., & Ibarz, A. (2019). Kinetic and thermodynamic compensation study of the hydration of faba beans (Vicia faba L.). Food Research International, 119, 390–397. https://doi.org/10.1016/j.foodres.2019.02.002
6. Goyal, A., Siddiqui, S., Upadhyay, N., & Soni, J. (2014). Effects of ultraviolet irradiation, pulsed electric field, hot water and ethanol vapours treatment on functional properties of mung bean sprouts. Journal of Food Science and Technology, 51(4), 708–714. https://doi.org/10.1007/s13197-011-0538-2
7. Kadam, S. S., & Salunkhe, D. K. (1985). Nutritional composition, processing, and utilization of horse gram and moth bean. CRC Critical Reviews in Food Science and Nutrition, 22(1), 1–26.
8. Kaptso, K. G., Njintang, Y. N., Komnek, A. E., Hounhouigan, J., Scher, J., & Mbofung, C. M. F. (2008). Physical properties and rehydration kinetics of two varieties of cowpea (Vigna unguiculata) and bambara groundnuts (Voandzeia subterranea) seeds. Journal of Food Engineering, 86(1), 91–99.
9. Kumar, K., Singh, J., Chandra, S., Singh, B. R., Chauhan, N., & Yadav, M. K. (2022). Hydration kinetic of maize grain under varying temperature. The Pharma Innovation Journal, SP-11(5), 689–692.
10. Miano, A. C., & Augusto, P. E. D. (2018). The hydration of grains: A critical review from description of phenomena to process improvements. Comprehensive Reviews in Food Science and Food Safety, 17(2), 352–370. https://doi.org/10.1111/1541-4337.12328
11. Miano, A. C., Pereira, J. C., Castanha, N., da Matta Júnior, M. D., & Augusto, P. E. D. (2016). Enhancing mung bean hydration using the ultrasound technology: Description of mechanisms and impact on its germination and main components. Scientific Reports, 6, 38996. https://doi.org/10.1038/srep38996
12. Miano, A. C., Pereira, J. C., Sabadoti, V. D., & Augusto, P. E. D. (2018). Hydration kinetics of cereal and pulses: New data and hypothesis evaluation. Journal of Food Process Engineering, 41(1), e12617. https://doi.org/10.1111/jfpe.12617
13. Oroian, M. (2017). The temperature hydration kinetics of Lens culinaris. Journal of the Saudi Society of Agricultural Sciences, 16, 250–256. https://doi.org/10.1016/j.jssas.2015.08.004

14. Pagand, J., Heirbaut, P., Pierre, A., & Pareyt, B. (2017). The magic and challenges of sprouted grains. Cereal Foods World, 62(5), 221–225. https://doi.org/10.1094/CFW-62-5-0221
15. Peleg, M. (1988). An empirical model for the description of moisture sorption curves. Journal of Food Science, 53(4), 1216–1217.
16. Quast, D. G., & da Silva, S. D. (1977). Temperature dependence of hydration rate and effect of hydration on the cooking rate of dry legumes. Journal of Food Science, 42(5), 1299–1303.
17. Salehi, F. (2023). Effects of ultrasonic pretreatment and drying approaches on the drying kinetics and rehydration of sprouted mung beans. Legume Science, 5, e211. https://doi.org/10.1002/leg3.211
18. Winarsi, H., Septiana, A. T., & Wulandari, S. P. (2020). Germination improves sensory, phenolic, protein content and anti-inflammatory properties of red kidney bean (Phaseolus vulgaris L.) sprouts milk. Food Research, 4(6), 1921–1928. https://doi.org/10.26656/fr.2017.4(6).188