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Water absorption in dried beans

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Abstract: Water absorption in dried beans has been investigated. Diffusion equations based on wetting theory are proposed and an analytical solution was obtained using Duhamel's theorem. The green bean, red bean, California small white bean and soybean are considered. Some green beans and red beans were irradiated by gamma-rays. The theoretical predictions are in excellent agreement with the experimental data. The diffusion coefficients of water in green bean and red bean satisfy the Arrhenius equation. The testa wetting was analyzed on a thermodynamic basis. The wetting time of water molecules from water reservoir to embryo of green bean and red bean via testa was found to satisfy a modified Arrhenius equation. The activation energy of diffusion is greater for non-irradiated red bean than for irradiated red bean, but the energy barrier of wetting is smaller for non-irradiated red bean than for irradiated red bean. However, the effects of gamma-rays on diffusion and wetting in green bean are not pronounced. The time to cook the green bean until well done was analyzed and the effect of water uptake on cooking time is discussed. The water transport in hulled green bean was also investigated. The wetting behavior was not observed in the hulled green bean. This is direct evidence of the wetting behavior of the testa. The water uptake in the hulled green bean is greater than that in the coated green bean.

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Keywords: diffusion; testa wetting; Arrhenius equation; embryo; cooking

INTRODUCTION

Study of the absorption process is often described by the Fickian law of diffusion. The water uptake in wetting of green beans is based on the moisture gradient to the center of the bean.[1] It is known that water diffusivity is a complex function of the microstructure, chemical composition, moisture content and temperature of the beans.[1] Microstructural features, such as thin bean coat, coat pore, large and open micropyle and hilum, tend to influence their sorption rates.[2,3] The bean coat composition may also affect the imbibition rate.[4–6]

Theoretical models have been analyzed by several researchers. Hsu proposed a model of water diffusion in cotyledons[7] by assuming that (1) the bean coat for resisting water sorption was a gradually increasing by surface moisture (first-order process) and (2) the diffusivity increased exponentially. Schwartzberg and Chao have reviewed the mathematics of mass transport processes in food materials.[8] Del Valle *et al* proposed a modified first-order reaction kinetic model[9] to describe the transient mass sorption in beans. Their model composed of an initial linear kinetic phase followed by a diffusion-controlled phase. The initial linear kinetic phase assumes that the amount of water is linearly proportional to time. The diffusivity in the later stage of diffusion is a function of chemical reaction rate and concentration. However, the diffusivity in these models is a function of diffusion time and concentration arrived at in order to fit the experimental data.

Caprez *et al* studied the water uptake of modified yellow pea hulls.[10] Their data showed that the total amount of water increased with increasing time until saturation. Del Valle *et al* used the modified first-order reaction kinetic model to fit transient water absorption curves for different kinds of beans.[9] They did not discuss the switching of mechanisms from the initial linear kinetic phase to the diffusion-controlled phase. This prompted us to investigate the water absorption in dried beans. In the next two sections, we propose the water absorption model and coat wetting theory based on Fick's law and on thermodynamics. The diffusion equation incorporated with coat wetting is solved in closed form. In the section, following these the preparation of materials and the experimental procedure are described. The experimental results are then compared with the mathematical model and the physical meanings of these parameters are explained. Evidence of the wetting behavior of testa is provided.

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The results of analytical and experimental findings are summarized in the final section.

WATER ABSORPTION THEORY

A spherical dried bean of radius a is immersed into a water bath maintained at a constant temperature. The bean is composed of an outer coat, the testa, and an inner structure, the embryo. For symmetry, the water absorption in the dried bean is along the radial direction in a spherical coordinate system. The water uptake follows the Fickian equation

$$D\left(\frac{\partial^2 C}{\partial r^2}+\frac{2}{r}\frac{\partial C}{\partial r}\right)=\frac{\partial C}{\partial t} \tag{1}$$

where D and C are the diffusion coefficient of water in the embryo of dried bean and the water concentration, respectively, and r and t are radial variable and time. At the initial time no water is inside the embryo, ie

$$C(r,t=0)=0 \tag{2}$$

Before water is absorbed in the embryo, it must penetrate the testa. The concentration at the outer coat (or testa) is related to testa wettability and is assumed to follow the equation,

$$C(r=a,0\le t\le t_0)=\frac{\mathrm{e}^{t/\tau}-1}{\mathrm{e}^{t_0/\tau}-1}C_0 \tag{3}$$

where τ and t_0 are relaxation time and wetting time, respectively. Both τ and t_0 are inter-related with the properties of water and the dried bean. The wetting time t_0 will be discussed in details in the next section. The relaxation time τ, which is related to the hardness of testa, will be studied in a subsequent paper. At t_0 the testa is fully wetted. Thus water does not encounter any barrier at testa after wetting time, ie

$$C(r=a,t_0\le t)=C_0 \tag{4}$$

The solution of eqn (1) with initial condition eqn (2) and boundary equations, eqn (3) and eqn (4), is obtained using the Duhamel method and the separation of variable method.[11] After tedious calculation, the solution yields

$$C=\frac{C_0}{(\mathrm{e}^{t_0/\tau}-1)}\left[\frac{a}{r}\frac{\sinh(r/\sqrt{D\tau})}{\sinh(a/\sqrt{D\tau})}\mathrm{e}^{t/\tau}-1+\frac{2a^3}{D\tau r}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n\pi(n^2\pi^2+a^2/D\tau)}\times\sin\frac{n\pi r}{a}\mathrm{e}^{-Dn^2\pi^2 t/a^2}\right]\quad\text{for}\quad 0\le t\le t_0 \tag{5a}$$

and

$$C=C_0\left\{1-2\frac{a}{r}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n\pi}\times\sin\frac{n\pi r}{a}\mathrm{e}^{Dn^2\pi^2(t_0-t)/a^2}+\frac{2a}{(\mathrm{e}^{t_0/\tau}-1)r}\times\sum_{n=1}^{\infty}(-1)^{n+1}\mathrm{e}^{-Dn^2\pi^2 t/a^2}\sin\frac{n\pi r}{a}\times\left[\frac{\mathrm{e}^{Dn^2\pi^2 t_0/a^2}(n^2\pi^2\mathrm{e}^{t_0/\tau}-n^2\pi^2-a^2/D\tau)}{n\pi(n^2\pi^2+a^2/D\tau)}+\frac{a^2/D\tau}{n\pi(n^2\pi^2+a^2/D\tau)}\right]\right\}\quad\text{for}\quad t_0\le t \tag{5b}$$

If $t_0=0$, ie wetting behavior does not occur and eqn (5) is reduced to the solution with constant surface concentration,

$$C=C_0\left\{1+\frac{2a}{r}\sum_{n=1}^{\infty}\frac{(-1)^n}{n\pi}\sin\frac{n\pi r}{a}\mathrm{e}^{-Dn^2\pi^2 t/a^2}\right\} \tag{6}$$

which is the same as that obtained by Crank.[12]

Fig 1 illustrates the concentration distributions at different normalization times Dt/a^2 at $D\tau/a^2=0.3$ and $Dt_0/a^2=0.5$. The concentration level moves upward at longer times. The concentration at the outer coat follows eqns (3) and (4). When Dt/a^2 is greater than or equal to 0.5, the surface concentration is maintained at C_0. The concentration gradient at the center is zero for all times because of the spherical symmetry.

Integrating eqn (5) from $r=0$ to $r=a$ with the weighting factor $4\pi r^2$, the total amount of water inside the green bean after time t is

$$M(t)=\frac{M_0}{\mathrm{e}^{t_0/\tau}-1}\left[3\left(\frac{\sqrt{D\tau}}{a}\coth\frac{a}{\sqrt{D\tau}}-\frac{D\tau}{a^2}\right)\mathrm{e}^{t/\tau}-1+\frac{6a^2}{D\tau}\sum_{n=1}^{\infty}\right.$$

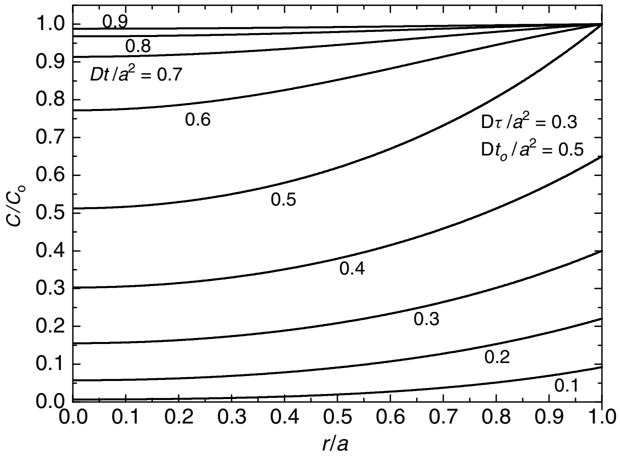

Figure 1. The concentration profiles at different times for a given $D\tau/a^2=0.3$ and $Dt_0/a^2=0.5$.

$$\left. \times \frac{\mathrm{e}^{-Dn^2\pi^2 t/a^2}}{n^2\pi^2(n^2\pi^2 + a^2/D\tau)}\right] \quad \text{for} \quad 0 \le t \le t_0 \tag{7a}$$

and

$$M(t) = M_0 \left\{ 1 - 6\sum_{n=1}^{\infty} \frac{1}{n^2\pi^2} \mathrm{e}^{Dn^2\pi^2(t_0 - t)/a^2} + \frac{6}{\mathrm{e}^{t_0/\tau} - 1} \sum_{n=1}^{\infty} \frac{\mathrm{e}^{-Dn^2\pi^2 t/a^2}}{n^2\pi^2(n^2\pi^2 + a^2/D\tau)} \times \left[(n^2\pi^2 \mathrm{e}^{t_0/\tau} - n^2\pi^2 - a^2/D\tau) \times \mathrm{e}^{Dn^2\pi^2 t_0/a^2} + \frac{a^2}{D\tau} \right] \right\} \quad \text{for} \quad t_0 \le t \tag{7b}$$

Here M_0 is the saturated amount of water in the embryo. Equation (7a) is equal to eqn (7b) at $t = t_0$. Furthermore, t_0 is the inflection point of the curve $M(t)$ versus t.

If $t_0 = 0$, ie no wetting behavior is observed, eqn (7) is reduced to the total amount with constant surface concentration,

$$M(t) = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \mathrm{e}^{-Dn^2\pi^2 t/a^2} \tag{8}$$

Equation (8) is the same as that obtained by Crank.[12]

The effect of wetting time on water uptake is shown in Fig 2(a) just at $D\tau/a^2 = 0.1$. The dashed line is obtained from eqn (8). For a given time, the amount of mass uptake decreases with increasing Dt_0/a^2. The S-shape of mass uptake is more pronounced at increasing Dt_0/a^2. When t_0 is less than or equal to τ, the S-curves are no longer shown. The extreme case shown in Fig 2(a) by the dashed line is at the constant surface concentration, $t_0 = 0$, for which the S-shape is absent. Alongside this, in Fig 2(b) is plotted the curve of M versus Dt/a^2 with various values of $D\tau/a^2$ and $Dt_0/a^2 = 0.6$. Note that dashed line corresponds to the surface constant concentration, $t_0 = 0$. For a given time, the amount of mass uptake decreases with increasing $D\tau/a^2$. The reciprocal of the relaxation time is responsible for restraining the water penetration to the testa, so that the amount at a given time $t \le t_0$ increases with increasing values of τ.

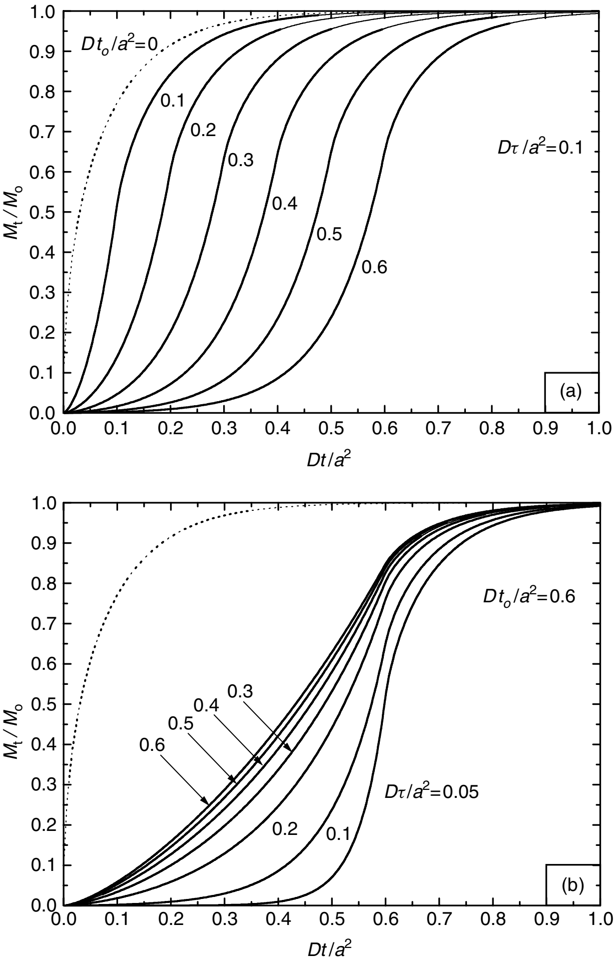

Figure 2. (a) The effect of wetting time on water uptake at $D\tau/a^2 = 0.1$; and (b) The effect of relaxation time on water uptake at $Dt_0/a^2 = 0.6$. The dashed line represents the constant surface concentration ($t_0 = 0$).

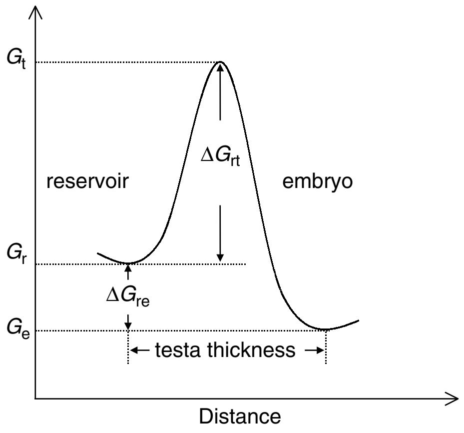

Figure 3. Gibbs free energy diagram of water molecule near the testa between water reservoir and embryo.

TESTA WETTING THEORY

During the water absorption process, the testa wetting is a critical phenomenon in which the water molecule moves from water reservoir to the embryo across the testa. The more water present, the softer is the testa. The Gibbs free energy of water molecule near the testa between water reservoir and embryo is defined and shown in Fig 3. To cross the testa the water molecules must overcome an energy barrier $\Delta G_{\mathrm{rt}} (= G_{\mathrm{t}} - G_{\mathrm{r}})$ and arrive at the embryo, which has a lower Gibbs free energy. The minimal energies of water molecules in the water reservoir and the embryo are G_{r} and G_{e}, respectively. That is, the energy difference of water between reservoir and embryo is $\Delta G_{\mathrm{re}} (= G_{\mathrm{r}} - G_{\mathrm{e}})$.

The water flux, I, from reservoir to embryo across the testa is equal to the molecule movement to and from the embryo,

$$I = Sf\exp(-\Delta G_{\mathrm{rt}}/RT) - Sf\exp(-(\Delta G_{\mathrm{rt}} + \Delta G_{\mathrm{re}})/RT) \qquad (9)$$

where S and f are the number of molecules per unit area facing testa, and molecular vibration frequency, respectively, and T and R are the Kelvin temperature and gas constant.

The velocity, v, of water molecules crossing the testa is

$$v = \frac{\lambda I}{S} \qquad (10)$$

where λ is the thickness of the testa. Substituting eqn (9) into eqn (10) yields

$$v = \lambda f \frac{\Delta G_{\mathrm{re}}}{RT}\exp(-\Delta G_{\mathrm{rt}}/RT) \qquad (11)$$

where ΔG_{re} is assumed to be much smaller than RT. The total time, t_0, of water moves from reservoir to embryo via the testa is

$$\frac{1}{t_0} = \frac{v}{\lambda} = \frac{f\Delta G_{\mathrm{re}}}{RT}\exp(-\Delta G_{\mathrm{rt}}/RT) \qquad (12)$$

Equation (12) is a modified Arrhenius equation which will be used in a subsequent section. According to eqn (12), the activation energy of water across the testa is obtained by plotting $\log(T/t_0)$ versus $1/T$. Substituting eqn (12) into eqn (10) yields

$$I = \frac{S}{t_0} \qquad (13)$$

Before full wetting, S is assumed to be proportional to $(\mathrm{e}^{t/\lambda} - 1)$ and after full wetting S is λC_0, so that eqn (13) becomes

$$I = vC_0(\mathrm{e}^{t/\lambda} - 1)/(\mathrm{e}^{t_0/\lambda} - 1) \quad \text{for} \quad t \le t_0 \qquad (14a)$$

and

$$I = vC_0 \quad \text{for} \quad t_o \le t \qquad (14b)$$

Equations (14) show the surface concentration related to the flux at the testa. Thus the characteristics of the testa play an important role in water absorption in beans.

EXPERIMENTAL PROCEDURE

To test the theoretical model presented above, a set of experimental measurements was conducted. Two kinds of green bean and red bean were obtained from a local supermarket. Some green and red beans were irradiated with 7 kGy by a Co^{60} gamma-ray source at the Isotope Center, National Tsing Hua University, with dose rate $1.37\,\mathrm{kGy\,h^{-1}}$. The geometry of both beans is generally ellipsoidal. In order to simplify the calculation, a sphere is used instead of an ellipsoid. The radius of sphere is the geometric mean of three semi-axes. Roughly spherical dried green beans have radius $a = 0.24 \pm 0.01$ cm and mass 75.6 ± 5.0 mg while dried red beans have radius $a = 0.35 \pm 0.01$ cm and mass 206 ± 19 mg. Both beans were preweighed and preheated to the elevated temperature of the water uptake study. The bean was then immersed in a distilled-water-filled glass bottle in a thermostatted water-bath both at the same test temperature. The bean was taken out periodically. Its surface was blotted and its mass was measured using an Ohaus Analytical Plus digital balance. After weighing, the bean was immediately returned to the water-bath until the next measurement. The excess mass (or the amount of water in the bean) was recorded. This process was repeated until the weight gain of bean reaches plateau or decreases. Then change the temperature and repeat the above process of mass uptake.

After a certain amount of water absorption, a total of 100 green beans were immersed into the water-filled beaker on a heating stage with electric power 700 W. Six green beans were taken out periodically. Each bean was tasted by one of six people in turn to decide whether they were well done and then discarded. This process was repeated until the well-done green bean was found. The cooking time was recorded. Note that the 'well-done green bean or green bean ready to eat' must be agreed by more than three of the six people.

RESULTS AND DISCUSSION

Two sets of soaking data were used to investigate the theoretical model. The first set of soaking data for the green bean and red bean were measured in the present study. The second set of soaking data of California small white bean and soybean were obtained from the literature. The detailed analysis is now addressed:

Green bean

The spherical radii of green bean are 0.24 cm for $20\,°\mathrm{C} < T < 55\,°\mathrm{C}$. The amount of water in the non-irradiated and irradiated embryo at different times and temperatures is shown in Fig 4(a) and (b), respectively, with different symbols. These data can be fitted using eqn (7). The solid lines are obtained by the mass transport theory stated above and the corresponding parameters, D, τ and t_0 of non-irradiated and irradiated green bean are listed in Tables 1 and 2. It can be seen from Fig 4 that the theoretical predictions are in excellent agreement with the experimental data. The diffusion coefficients of water in non-irradiated and irradiated green beans listed in Tables 1 and 2 are plotted in Fig 5 with solid square and spherical symbols. Comparing Table 1 and Table 2, the diffusion coefficient of water in irradiated bean is greater than that in non-irradiated bean at a given temperature, but the wetting time has the opposite trend to the diffusion coefficient. It was found that the diffusion coefficients satisfy the Arrhenius equation (solid line in Fig 5) and the corresponding activation energies of non-irradiated

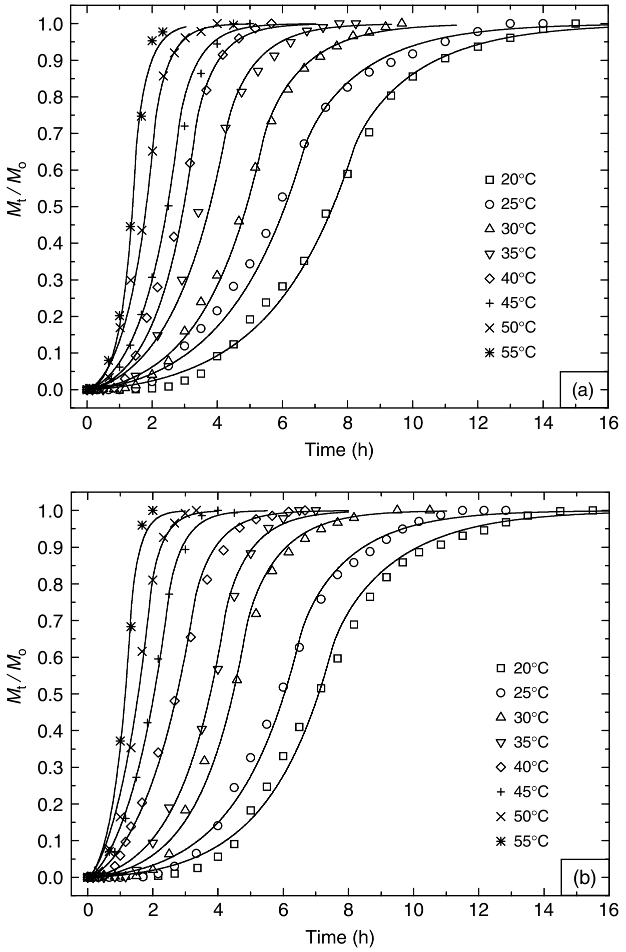

Figure 4. (a) The water sorption in non-irradiated dried green beans; and (b) The water sorption in irradiated dried green beans: (Symbols and solid lines represent the experimental data and theory, respectively.).

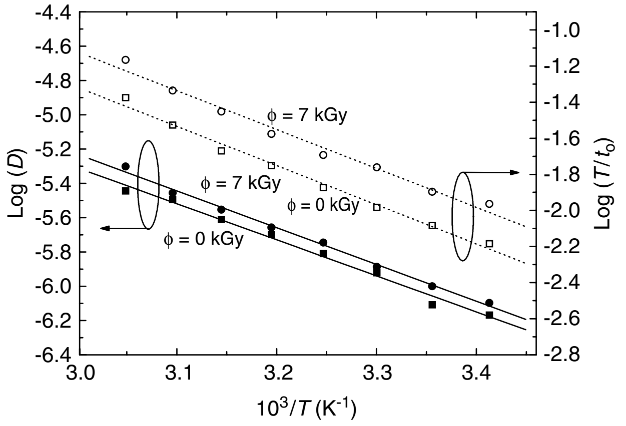

Figure 5. Plots of D and t_0 versus $1/T$ by solid and dashed lines, respectively. The units of D, t_0 and T are cm^2 s^{-1}, s and K, respectively.

Table 1. Diffusion coefficient D, saturated amount M_0 of water in non-irradiated green bean, relaxation time τ and wetting time t_0 of water across testa

Temperature (°C)	$D \times 10^6$ (cm^2 s^{-1})	τ (s)	t_0 (s)	M_0 (g)
20	0.68	9000	29 500	0.0886
25	0.78	8500	24 000	0.0884
30	1.20	6500	19 500	0.0841
35	1.55	6000	15 500	0.0826
40	2.0	4000	12 000	0.0720
45	2.45	3500	10 200	0.0679
50	3.2	3000	7500	0.0750
55	3.6	1500	5400	0.0693

Table 2. Diffusion coefficient D, saturated amount M_0 of water in irradiated green bean with a dose of 7kGy, relaxation time τ and wetting time t_0 of water across testa

Temperature (°C)	$D \times 10^6$ (cm^2 s^{-1})	τ (s)	t_0 (s)	M_0 (g)
20	0.8	7000	27 000	0.0871
25	1.0	6800	23 500	0.0880
30	1.3	5000	17 500	0.0858
35	1.8	4500	15 200	0.0797
40	2.2	4500	11 800	0.0737
45	2.8	4000	9000	0.0788
50	3.5	3000	7000	0.0727
55	5.0	2000	4800	0.0666

and irradiated beans were calculated as 40.3 kJ mol^{-1} and 41.1 kJ mol^{-1}. The effect of gamma-rays on the activation energy of water in green bean is negligible. The wetting times in Tables 1 and 2 are also shown in Fig 5 by the open square and spherical symbols. The wetting times satisfy the modified Arrhenius equation, eqn (12) (see the dashed line). The corresponding energy barriers of water crossing the testa of non-irradiated and irradiated beans are 41.6 kJ mol and 41.2 kJ mol. The effect of gamma-rays on the energy barrier of water crossing the testa is not pronounced. The saturated amounts at different temperatures are also listed in Tables 1 and 2. It is worth mentioning that sometimes the water uptake reaches a maximum instead of a plateau at longer times. This is because the testa peels off and the element of the embryo dissolves into the water reservoir. Often the water changes its color from colorless to green. The weight loss of the embryo is not distinguished from water uptake in this experiment. When the non-irradiated green bean is immersed in water, budding is observed for 600, 450 and 390 min at 25, 30 and 35 °C, respectively. When the temperature is above 40 °C, the non-irradiated green bean dies during such long times of immersion. However, budding is never observed when the irradiated bean is immersed in water.

Figure 6 shows the effect of water uptake on cooking time. Square and circle symbols represent the data of cooking time and mass uptake at 50 °C, respectively. It was found that the uptake curve has a trend opposite to that of the cooking curve. That is, the more the water inside the green bean before cooking, the shorter the cooking time. In order to save energy or electric power, it is better to soak the bean in water to maximum saturation before cooking. However, water saturation in the green bean at room temperature requires a long

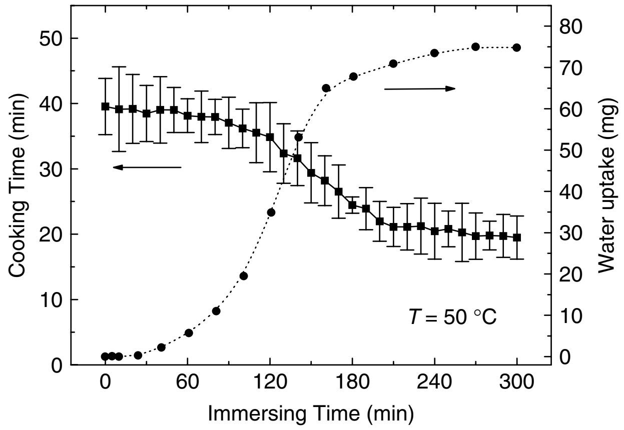

Figure 6. Water sorption at $T = 50\,°C$ and cooking time versus immersion time.

time. In order to save cost, cooking and soaking must be properly adjusted.

Red bean

Figures 7(a) and (b) shows the amount of water on non-irradiated and irradiated embryo of red bean at different times and temperatures, respectively. These data are well fitted with eqn (7) and the corresponding parameters D, τ and t_0 are listed in Tables 3 and 4 for non-irradiated red bean and irradiated red bean with a dose of 7 kGy, respectively. Comparing Table 3 and Table 4, the diffusion coefficient of water in irradiated red bean is greater than that in non-irradiated red bean at a given temperature, but the wetting time has an opposite trend to the diffusion coefficient. The diffusion coefficient (solid symbol) and wetting time (hollow symbol) of non-irradiated and irradiated red bean are plotted in Fig 8 by square and spherical symbols, respectively. The diffusion coefficient and wetting time satisfy the Arrhenius equation and modified Arrhenius equation. The activation energy of diffusion is $27.9\,\mathrm{kJ\,mol^{-1}}$ for non-irradiated bean and $23.1\,\mathrm{kJ\,mol^{-1}}$ for irradiated bean. This implies that the water diffusion is easier in irradiated bean than in non-irradiated bean. The energy barrier of water crossing testa is $39.6\,\mathrm{kJ\,mol^{-1}}$ for non-irradiated bean and $46.0\,\mathrm{kJ\,mol^{-1}}$ for irradiated bean. Although water requires less energy to cross testa for non-irradiated bean than for irradiated bean, the pre-exponent factor of reciprocal of wetting time for non-irradiated bean is less than that for irradiated bean. Thus the wetting time is greater for the non-irradiated bean than for the irradiated bean. When red bean was immersed in water, budding was observed for the beans are that saturated at 30 and 35 °C. However, when temperature was above 40 °C, no budding appeared in non-irradiated bean. In contrast, budding is not observed in irradiated bean immersed in water at all temperatures.

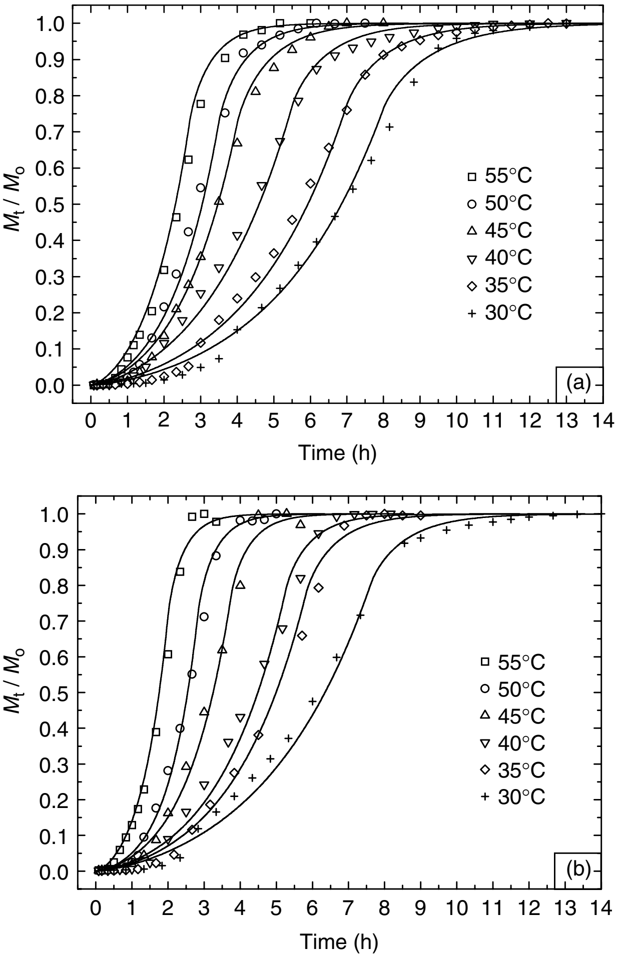

Figure 7. (a) The water sorption in non-irradiated dried red beans; and (b) The water sorption in irradiated dried red beans. (Symbols and solid lines represent the experimental data and theory, respectively.).

Table 3. Diffusion coefficient D, saturated amount M_0 of water in non-irradiated red bean, relaxation time τ and wetting time t_0 of water across testa

Temperature (°C)	$D \times 10^6$ ($\mathrm{cm^2\,s^{-1}}$)	τ (s)	t_0 (s)	M_0 (g)
30	2.1	11 000	28 800	0.2014
35	2.5	10 000	25 200	0.2050
40	3.0	9000	19 800	0.2369
45	3.5	6000	14 400	0.2272
50	4.0	5000	12 600	0.1935
55	5.0	4500	9720	0.2013

White bean and soybean

The soaking data of California small white bean[13] and soybean[7] are shown in Fig 9 by circle and square symbols, respectively. The solid lines were obtained using eqn (7) with corresponding D, τ and t_0 listed in Table 5. It can be seen from Fig 9 that the experimental data are in good agreement with the theoretical prediction. However, the wetting time and diffusion coefficient do not satisfy the Arrhenius equation because the white bean after immersion in water is soon dead at high temperature and live for a long time at low temperature. Because the radii of both California small white bean and soybean are unknown, the diffusion coefficients listed in Table 5 are in terms of bean radius, a.

Table 4. Diffusion coefficient D, saturated amount M_0 of water in irradiated red bean with a dose of 7kGy, relaxation time τ and wetting time t_0 of water across testa

Temperature (°C)	$D \times 10^6$ (cm^2 s^{-1})	τ (s)	t_0 (s)	M_0 (g)
30	3.4	11 000	27 500	0.2542
35	4.2	7500	21 000	0.2484
40	4.5	6800	19 000	0.1999
45	5.5	4500	13 500	0.1839
50	6.0	3000	10 200	0.1856
55	7.0	2800	7200	0.1742

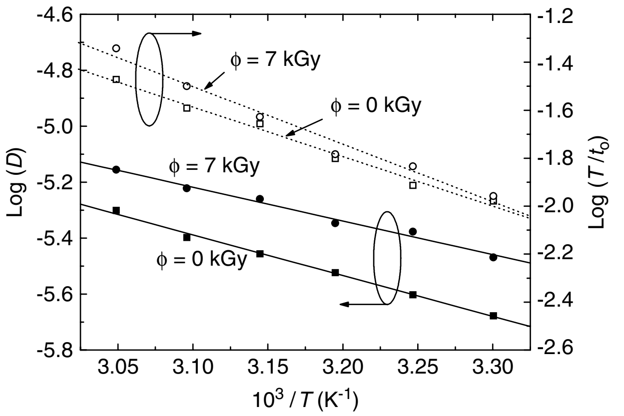

Figure 8. Plots of D and t_0 versus $1/T$ by solid and dashed lines, respectively. The units of D, t_0 and T are cm^2 s^{-1}, s and K.

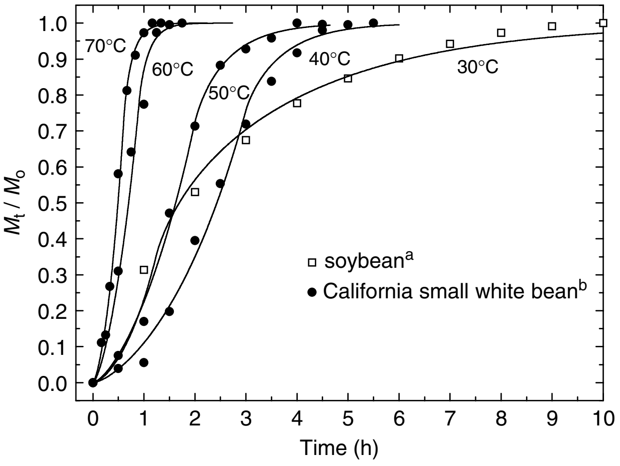

Figure 9. The water sorption in soybean and California small white beans. Symbols and solid lines correspond to the experimental data and theory, respectively. Superscripts a and b represent data from KH Hsu[7] and S Kon,[13] respectively.

Effect of testa on water uptake

In order to understand the role of testa in water soaking, a comparison of coated green bean and hulled green bean was made. Note that the coated green bean means the green bean with the testa. The solid and hollow symbols in Fig 10 represent the water uptake in the coated and hulled green beans, respectively. The data at temperatures below 45 °C are not shown in Fig 10 because budding occurs and the green bean grows during the immersion. The data of coated green bean are copied from Fig 4(a) and D, t_0 and τ were listed in Table 1. The data of hulled green bean were fitted by eqn (8) and plotted in Fig 10 by dashed lines. The uptake data are in good agreement with the theoretical model. The corresponding diffusion coefficients of water in hulled bean are 5.5×10^{-6} and 3.2×10^{-6} cm^2 s^{-1} for 55 °C and 50 °C. This is a direct evidence that the wetting behavior of the testa disappears during the hulled green bean immersion in water. Comparing the water uptakes in both coated and hulled green beans at a given temperature, the former is smaller than the latter. This implies that the testa restrains the mass transport in green bean. When the dashed lines shift distances 4950 s and 6160 s for 55 °C and 50 °C, respectively, to the longer time, solid and dashed lines overlap. According to Table 1, the wetting times are 5400 s and 7500 s for 55 °C and 50 °C, respectively. The wetting time is greater than the shift time at a given temperature.

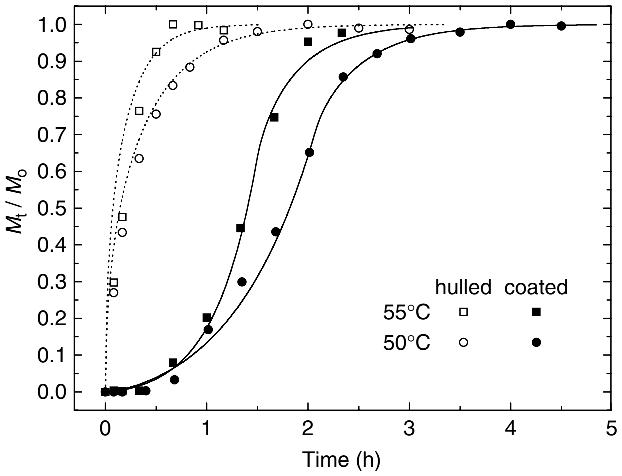

Figure 10. The water sorption in coated and hulled green beans. Solid and dashed lines correspond to theoretical curves of coated and hulled green beans, respectively.

Table 5. Data of Diffusion coefficient D/a^2, τ and t_0 of soybean and California small white bean

	Temp (°C)	$D/a^2 \times 10^5$ (s^{-1})	τ (s)	t_0 (s)
Soybean[a]	30	0.094	3800	4500
Calif small white bean[b]	40	3.6	7200	10 800
	50	4.0	6600	7200
	60	13	3000	3300
	70	15	1800	2200

[a] Data taken from KH Hsu.[7]
[b] Data taken from S Kon.[13]

SUMMARY AND CONCLUSIONS

Water uptake of dried beans has been investigated. Water absorption followed the Fickian law in spherical coordinates. The boundary condition of water absorption is derived from the testa wetting, which was derived on a thermodynamic basis. The concentration at the outer coat increased exponentially with time during wetting and remained constant after saturation. An analytical solution was obtained from diffusion equations based on the Duhamel method. Four kinds of green bean, red bean, soybean and California small white bean were considered. Some of green beans and red beans were irradiated by gamma-rays. This solution was used to fit the water uptake data at temperatures of 20–55 °C. The diffusion coefficients of green bean and red bean satisfy the Arrhenius equation and the wetting times satisfy the modified Arrhenius equation. The activation energy of water diffusion is greater for non-irradiated red bean than for irradiated red bean, but the energy barrier of water crossing testa has the opposite trend. However, the effects of gamma-rays on activation energy of water diffusion and energy barrier of water crossing testa are negligible. Comparing the water sorption in coated and hulled green bean, we prove the wetting behaviour of the testa. However, the green bean with different amounts of water content was cooked until it was well done. Cooking time increased with decreasing amount of water uptake before cooking. For cost reduction, the cooking and soaking times must be well balanced.

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REFERENCES

1 Vertucci CW, The kinetics of seed imbibition: controlling factors and relevance to seeding vigor, in *Seed Moisture*, ed by Stanwood PC and McDonald MB. Crop Science Society of America, Madison, WI, pp 93–115 (1989).
2 Deshpande SS and Cheryan M, Microstructure and water uptake of Phaseolus and winged beans. *J Food Sci* **51**:1218–1223 (1986).
3 Agbo GN, Hosfield GL, Uebersax MA and Klomparens K, Seed microstructure and its relationship to water uptake in isogenic lines and a cultivar of dry beans (Phaseolus vulgaris L). *Food Microstruc* **6**:91–102 (1987).
4 Marbach T and Mayer AM, Permeability of seed coats as related to drying conditions and metabolism of phenolics. *Plant Physiol* **54**:817–820 (1974).
5 Marbach T and Mayer AM, Changes in catechol oxidase and permeability of water in seed coats of Pisum elatius during seed development and maturation. *Plant Physiol* **56**:93–96 (1975).
6 Tully RE, Musgrave ME and Leopold AC, The seed coat as a control of imbibitional chilling injury. *Crop Sci* **21**:312–317 (1981).
7 Hsu KH, A diffusion model with a concentration-dependent diffusion coefficient for describing water movement in legumes during soaking. *J Food Sci* **48**:618–622, 645 (1983).
8 Schwartzberg HG and Chao RY, Solute diffusivities in leaching processes. *Food Technol* **36**:73–86 (1982).
9 Del Valle JM, Stanley DW and Bourne MC, Water absorption and Swelling in dry bean seeds. *J Food Proc Preserv* **16**:75–98 (1992).
10 Caprez A, Arrigoni E, Neukom H and Amado R, Improvement of the sensory properties of two different dietary fibre sources through enzymatic modification. *Lebensm -Wiss u -Technol* **20**:245–250 (1987).
11 Carslaw HS and Jaeger JC, *Conduction of Heat in Solids*, 2nd edn. Oxford University Press, Oxford, UK, p 30 (1959).
12 Crank J, *The Mathematics of Diffusion*, 2nd edn. Oxford University Press, Oxford, UK, p 91 (1975).
13 Kon S, Effect of soaking temperature on cooking and nutritional quality of beans. *J Food Sci* **44**:1329–1340 (1979).