Moisture-Absorption Characteristics of Laird Lentils and Hardshell Seeds

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ABSTRACT

Moisture absorption and water imbibition tests were conducted to investigate the characteristics of moisture uptake in Laird lentils (*Lens culinaris* Medik.) and to study the role of moisture content in the development of hardshell lentils. The widths of lentil hilum openings at a range of lentil moisture contents were examined using scanning electron microscopy. The initial moisture contents of lentils markedly affected the route of moisture migration, rate of water absorption, imbibition time, and proportion of hardshell lentils. At moisture contents of 16-24% (on a dry basis), moisture diffused mainly through the seedcoat, and the absorption behavior was predicted accurately by a one-dimensional diffusion equation. The permeability of lentil seedcoat decreased with decreasing moisture content because of reduced pore and fissure sizes in the cuticle layer over the seed surface. When lentil moisture content was at 12%, the hilum opening was the dominant route for moisture to enter lentils. The widths of lentil hilum openings also decreased with moisture content, some hila were closed at 12% moisture content. Impermeable seedcoat and concurrent closing of the hilum opening resulted in hardshell lentils. Increasing the soaking temperature from 12 to 22°C resulted in greater seedcoat permeability and reduced the percentage of hardshell lentils by about one half over the 24-hr soaking period.

Lentils (*Lens culinaris* Medik.) are a high-protein pulse crop used mainly for human consumption as whole or split lentil. As for other legumes, appropriate thermal processing for raw lentils is necessary because of the presence of mildly toxic constituents and antinutritional factors that interfere with digestive processes (Liener 1976). Soaking is a preliminary step common to methods of preparing legumes for consumption. However, the presence of hardshell lentils, defined as lentils that fail to imbibe water after a reasonable length of time (Swanson et al 1985), increases steeping and cooking time, impairs uniformity, and reduces cooking quality. An understanding of the fundamental moisture-absorption characteristics of lentils and development of hardshell lentils would be helpful in controlling product quality.

It is generally recognized that the seedcoat, hilum, and micropyle contribute to moisture uptake in legumes (Sefa-Dedeh and Stanley 1979). In spite of extensive studies on the moisture-absorption characteristics of legumes, there is still controversy as to the actual route for water migration (Swanson et al 1985). Heil et al (1992) noted the important role of the seedcoat porosity on the rate of water uptake by dry pinto beans during imbibition. However, due to the hygroscopic nature of legumes, the porosity in the seedcoat changes with moisture content. Lentils of 24% moisture content exhibited 12% volume reduction when dried to 10% moisture content (Tang and Sokhansanj 1993a). The seedcoat permeability of these lentils decreased by four orders of magnitude as a result of the shrinkage (Tang and Sokhansanj 1993b). It may be hypothesized that moisture content is a major parameter influencing the moisture-absorbing characteristics of lentils and, thus, development of hardshell lentils. The objectives of this investigation were to study the moisture-absorbing characteristics of the Laird lentils at various moisture contents and to correlate moisture content to the development of hardshell lentils.

The two distinctive types of hardness present in legumes, hard-to-cook and hardshell, were reviewed by Swanson et al (1985) and Stanley (1992). Lentils are a temperate crop; there are few reports of the hard-to-cook characteristic occuring in beans under tropical conditions (Bhatty 1988, Stanley 1992).

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MATERIALS AND METHODS

Lentil Preparation

The cultivar Laird, which accounts for 75% of lentil production in Canada, was selected for the experiments. Lentils at 12-24% moisture contents (db) were harvested by hand from a commercial field at the University of Saskatchewan, Saskatoon, SK. Lentil moisture contents were determined by an air-oven method, and the lentils were stored in air-tight containers at 4°C.

To isolate the effects of the seedcoat and hilum during water imbibition, waxed lentils of 12-16% moisture content were evaluated. In preparing waxed lentils, the portion of lentil where the hilum, micropyle, and raphe are located was dipped into a 0.1-mm layer of melted paraffin wax (60°C congealing point) maintained at ~80°C. The region of the hilum, micropyle, and raphe was sealed with a thin layer of wax (0.2 ± 0.05% of lentil weight). Each waxed lentil was examined under an illuminated magnifying glass for completeness of sealing before being placed in a 10-ml vial, covered to prevent moisture loss, and stored at 4°C for at least two weeks. Before the experiments, the vials containing the lentils were removed from storage and held at room temperature (22 ± 2°C) for 24 hr.

Seed Moisture Content Determination

The moisture content of whole lentils was determined in duplicate by an air-oven procedure (ASAE 1990). The air temperature was set at 130°C, and whole lentils were dried for 20 hr (Tang and Sokhansanj 1991).

Moisture-Absorption Tests

Lentils of several different moisture contents (12, 16, 19, 22, and 24%, db) were monitored for rates of moisture absorption in two humid environments: 1) 12°C, 92% rh for 400 hr; 2) 22°C, 87% rh for 190 hr. The tests were performed in a walk-in environmental chamber. The monitoring apparatus (Fig. 1) consisted of a multicup plate with 10 removable screen-bottomed sample cups, a plenum, and a backward-type centrifugal fan. Gravel was placed in the plenum below the sample cups to ensure a uniform air flow across the lentils. The thickness of the gravel bed was adjusted so that the air velocity was ~0.5 m/sec. This velocity was chosen based on the reports of Hutchinson and Otten (1983), who found that moisture transfer within soybeans and white beans is independent of the air velocity >0.2 m/sec.

About 15 g of lentils were placed in the sample cups in duplicate. The weights were periodically monitored with an electronic balance (±0.01 g). The transient moisture content was determined using the equation:

$$M = (W/W_o)(100 + M_o) - 100 \quad (1)$$

where, M and M_o in percent (db) were the transient and initial moisture contents, respectively; W and W_o were the transient and initial lentil weights, respectively.

During the moisture absorption tests at 22°C, the relative humidity of the environment was reduced from 87 to 22% rh in the period from 80 to 116 hr after the start of the tests. This was achieved by taking the equipment and the lentils out of the environment chamber and placing them in an ambient room environment.

Estimation of Moisture Diffusivity

Assuming that moisture diffused mainly through the seedcoat of lens-shaped lentils, the moisture-absorption pattern can be described by Fick's Law of Diffusion for a simplified slab geometry (Crank 1975):

$$\frac{\partial C(t, x)}{\partial t} = \frac{\partial}{\partial x}\left[D_{eff}\left\{\frac{\partial C(t, x)}{\partial x}\right\}\right] \quad (2)$$

where, $C(t, x)$ is the moisture concentration at distance x from the plan of symmetry, t is time, and D_{eff} is the effective moisture diffusivity in lentils. Assuming a constant D_{eff} and, under a constant boundary condition at the surface of the lentils, $C(t, x = a) = M_e$, and an initial condition $C(t = 0, x) = M_o$, a general solution for the average moisture content, M, of the lentil can be determined:

$$\frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\left[\frac{1}{(2n-1)^2}\, e^{\frac{-(2n-1)^2\pi^2 D_{eff}\, t}{4a^2}}\right] \quad (3)$$

where M_e is the equilibrium moisture content (the moisture content that lentils will eventually reach under a given air condition), and a is the equivalent half thickness of the slab. For Laird lentils, a is about 0.63 mm (Tang and Sokhansanj 1993b).

The moisture-absorption data for each initial moisture content and air condition was fitted to Equation 3 by adjusting the value of D_{eff} to minimize the sum of the squared differences between the estimated moisture contents and the experimental data. The goodness of fit was evaluated by the relative mean square errors (RMS) defined as:

$$RMS = 100\%\sqrt{\frac{1}{N}\sum_{i=1}(\frac{M_i' - M_i}{M_i'})^2} \quad (4)$$

in which, M_i is the predicted moisture content, M_i' is the moisture absorption data, and N is the number of data points.

Water Imbibition Tests

Water imbibition tests were performed at 22 and 12°C on control and waxed lentils. Both tests were performed in a walk-in environmental chamber. In each test, 100 lentils were placed in distilled water; lentils showing no sign of water uptake after a given period were counted as hardshell lentils. The tests were performed in duplicate for up to 48 hr.

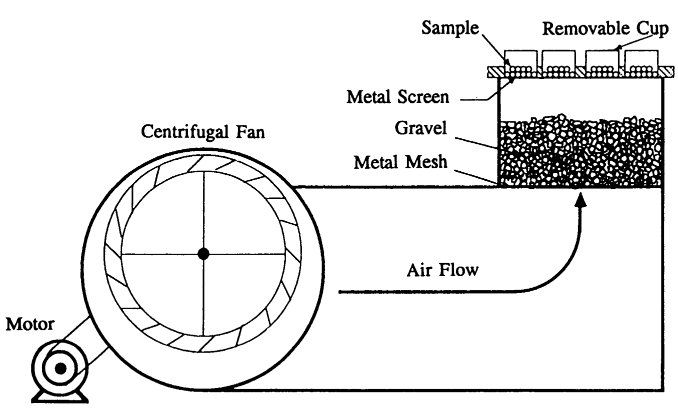

Fig. 1. Schematic of apparatus used in moisture-absorption tests.

Examination of Microstructure

The hilum and seedcoat of lentils at three moisture contents (12, 14, 24%) were examined using scanning electron microscopy (SEM). In preparation for SEM, lentils were glued to circular aluminum stubs. The specimens were sputter-coated with gold (model S150B, Edwards High Vacuum Inc., West Sussex, England). They were then viewed and photographed with the SEM 505 (Phillips, Eindhoven, The Netherlands). At least four lentils from each treatment were examined.

SEM was also used to examine the hilum and seedcoat of hardshell lentils of 12% moisture content. Before selection, the hardshell lentils were soaked overnight in distilled water at 22°C.

Lentil Weight

Lentils of 12% moisture content were collected from swathed plants at two separate times (12 and 14 days after swathing). Another batch of lentils, also at 12% moisture content, was obtained from chemically desiccated plants 12 days after spraying with diquat at a rate of 2L/ha. Swathing and chemical desiccation were performed at the same time. Detailed information on the moisture history of the lentils on the swathed and desiccated plants in the field up to the dates of collection was reported elsewhere (Tang et al 1992). The lentils were stored in air-tight containers at 20°C until the tests. Hardshell lentils were selected after soaking 1 kg of lentils in distilled water (1:10, w/v) for 10 hr. The surfaces of the hardshell lentils were blotted dry with paper towels. Lentils were selected randomly from the untreated lentils for the control. From each sample, 130 lentils were individually weighed on an analytical balance (±0.001 mg).

RESULTS

Moisture Absorption

The moisture-absorption patterns of lentils in two humid environments (12°C, 92% rh and 22°C, 87% rh) are presented in Figures 2 and 3, respectively. Lentils of different initial moisture contents, except for 12%, showed similar trends of moisture increase with time to approach a maximum moisture content of about 26%. Larger initial moisture contents and temperature corresponded to greater absorption rates. The lentils at 22°C required about half as much time to reach 90% of the maximum absorption as did the lentils at 12°C.

After 80 hr at 22°C and 87% rh, the lentils with initial moisture contents of 16–24% reached the same moisture content of about 26%. These lentils followed a single pattern of moisture decline

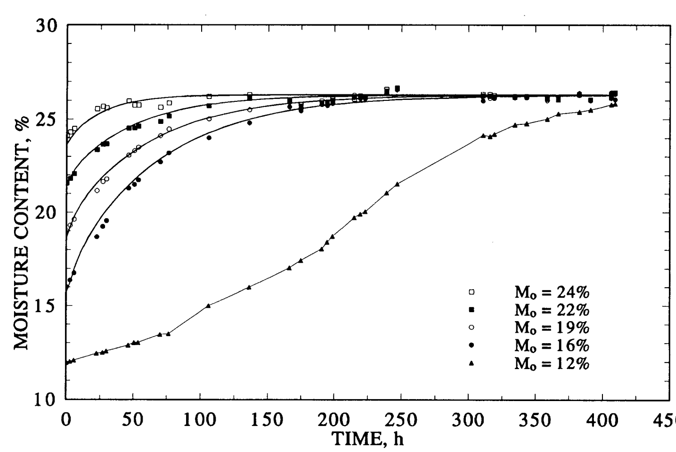

Fig. 2. Moisture absorption of lentils in environment at 12°C and 92% rh. Transient moisture contents are averages of two replicates that differed by <0.2 percentage points. The solid curves for lentils of 16–24% initial moisture contents (M_o) are from Equation 3.

(Fig. 3) when removed into a dry environment of 22°C and 22% rh. They also had a common trend of moisture increase when placed back in the environment of 87% rh. Thus, the moisture absorption of lentils was dependent only upon the transient moisture content, not the moisture history.

The lentils of 12% initial moisture content had different moisture-absorption patterns from the lentils of 16–24% initial moisture contents (Figs. 2 and 3), and they had much smaller moisture absorption rates, suggesting a different route of moisture migration.

Water Imbibition

Percentages of lentils failing to imbibe water (hardshell lentils) after progressively longer soaking periods at two temperatures (12 and 22°C) are listed in Table I for the control and waxed lentils of 12, 14, and 16% moisture contents. Smaller number of hardshell lentils corresponded to longer imbibition time, higher temperature, and larger initial moisture content (Table I). No hardshell lentils were observed in the control and waxed lentils of initial moisture contents greater than 16% after 2 hr of soaking.

In the control lentils of 16% initial moisture content at 22°C, the percentage of hardshell lentils decreased to 1% after 2 hr of imbibition time; that percentage decreased to 0% after 4 hr of soaking (Table I). Among the lentils of 14% initial moisture content, 2 and 0% hardshell lentils were observed after 8 and 10 hr of soaking, respectively. Of the lentils of 12% initial moisture content, 7% did not imbibe water after 8 hr, and 1% did not imbibe water after 48 hr.

A period of 13 hr was required to eliminate hardshell lentils in the waxed lentils of 16% initial moisture content at 22°C, as compared to 4 hr in the control (Table I). Hardshell lentils disappeared more slowly in the lentils of 14 and 12% initial moisture contents. After 48 hr, 3 and 14% of the waxed lentils remained hardshelled among the lentils of 14 and 12% initial moisture contents, respectively. Higher percentages of hardshell lentils in the waxed lentils of 12–16% moisture contents, compared to the controls, indicate that the hilum, micropyle, and raphe contributed to moisture migration.

Similar effects of initial moisture content and waxing on the percent of hardshell lentils were observed in the lentils soaked at 12°C (Table I). At this temperature, percentages of hardshell lentils were almost double the values obtained for lentils soaked at 22°C.

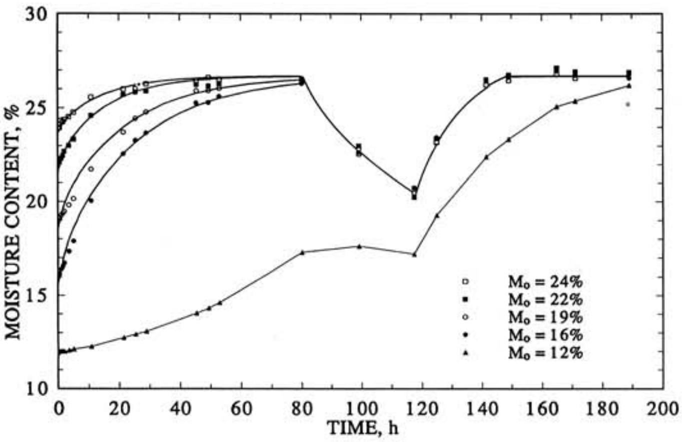

Fig. 3. Moisture absorption of lentils in environment at 22°C and 87% rh. Solid curves for lentils of 16–24% initial moisture contents (M_o) are from Equation 3. The large drop in moisture content between 80 and 116 hr corresponded to a sudden drop in relative humidity from 87 to 22% rh.

SEM Examination

Microscopic examination showed that the raphe and micropyle of Laird lentils were closed at moisture contents ranging from 10 to 19%, which confirmed the observation of Hughes and Swanson (1986) with other lentil cultivars. However, the width of the hilum opening of lentils at 24% moisture content was about 8 μm (Fig. 4A). The width of the hilum opening was reduced to about 4 μm at 14% moisture content (Fig. 4B) and about 2 μm at 12% moisture content (Fig. 4C). The hila of the hardshell lentils at 12% moisture content were closed (Fig. 4D). There were no differences in the seedcoat thickness of the hardshell and control lentils.

TABLE I
Imbibition Time, Initial Moisture Content (M_o), and Hardshell Lentils (%) at Soaking Temperatures of 22 and 12°C[a]

Temperature (°C)	Imbibition Time (hr)	Hardshell Lentils, % M_o = 16% Control	M_o = 16% Waxed	M_o = 14% Control	M_o = 14% Waxed	M_o = 12% Control	M_o = 12% Waxed
22	2	1	15	17	84	55	96
	4	0	13	15	61	20	92
	6		3	12	35	13	89
	8		3	2	26	7	77
	10		3	0	22	5	70
	13		0		16	2	54
	20				12	2	40
	23				8	2	33
	26				7	2	30
	29				7	2	26
	32				6	2	20
	37				4	2	19
	48				3	1	14
12	2	3	19	29	90	75	95
	4	3	16	17	75	54	93
	6	0	10	14	42	31	91
	8		7	7	33	16	85
	10		4	4	26	9	83
	13		2	3	20	7	72
	20		0	0	15	7	64
	23				11	6	45
	26				11	6	42
	29				9	6	33
	32				9	5	33
	37				7	5	33
	48				7	5	31

[a]The values are averages of duplicate samples (standard deviation < 5%).

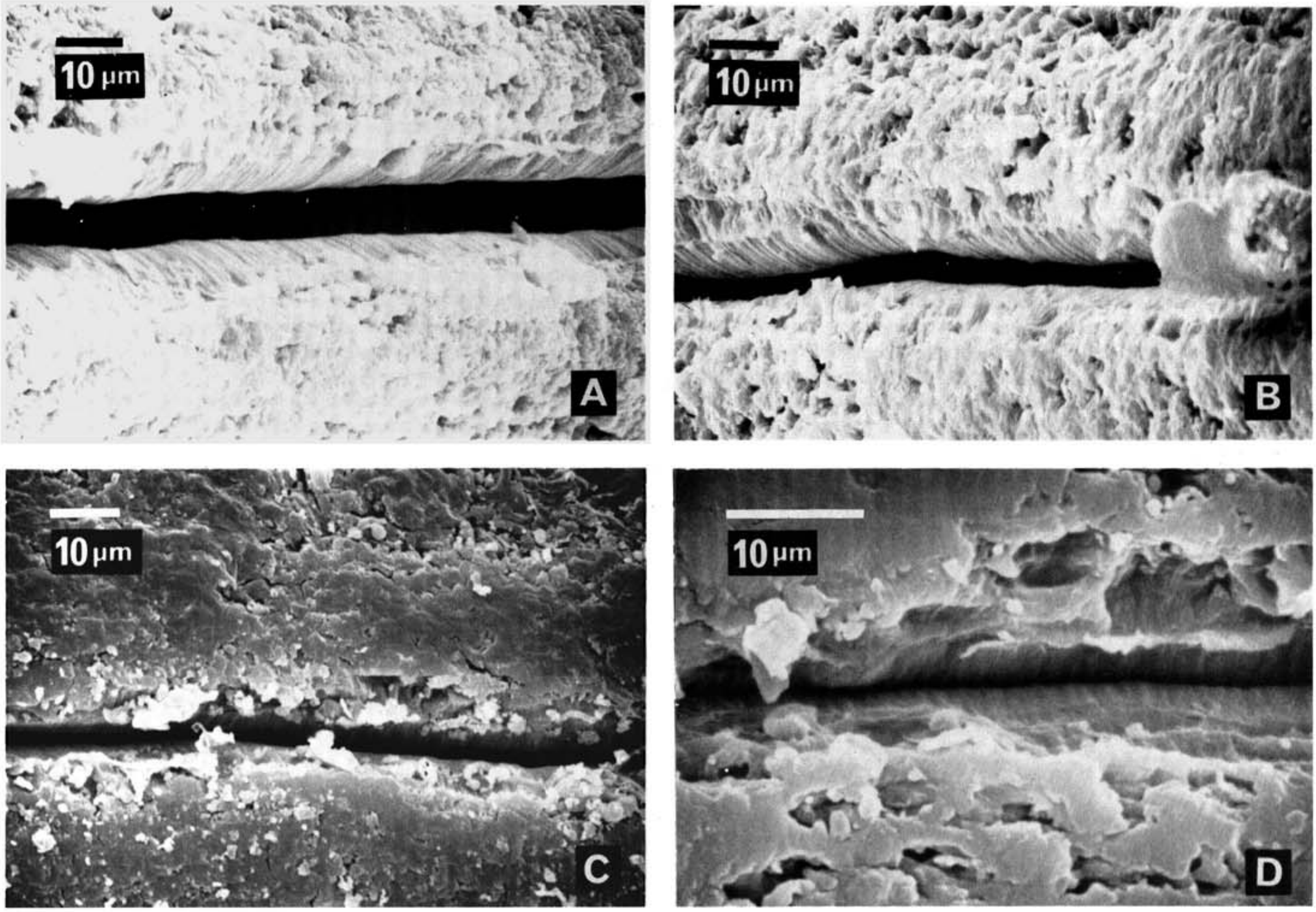

Fig. 4. Micrographs of the hilum openings. **A–C,** moisture contents of 24, 14, and 12%, respectively; **D,** closed hilum opening of a hard lentil of 12% moisture content after 10 hr of soaking at 22°C.

TABLE II
Effective Moisture Diffusivity (D_{eff}) in Lentils, and the Relative Mean Square Errors (RMS) for Curve Fitting Using Equation 3

Temperature (°C)	Initial Moisture (%)	D_{eff} (m^2/hr)	RMS (%)
22	24	1.14×10^{-8}	0.73
	22	1.10×10^{-8}	0.78
	19	0.76×10^{-8}	1.82
	16	0.68×10^{-8}	1.89
12	24	0.63×10^{-8}	0.98
	22	0.34×10^{-8}	0.79
	19	0.27×10^{-8}	0.82
	16	0.25×10^{-8}	1.31

DISCUSSION

The theoretical curves from Equation 3 follow closely the moisture absorption data for the lentils of 16, 19, 22, and 24% initial moisture contents in an environment of 12 and 22°C (Figs. 2 and 3). The corresponding RMS range from 0.73 to 1.89% (Table II). This suggests that the assumption of moisture migration through lentil seedcoat applies to the lentils of 16–24% initial moisture contents. However, Equation 3 was not applicable to lentils of 12% initial moisture content. Thus, the seedcoat was not the main route for water to enter lentils of 12% moisture content. Most moisture must have entered the lentils through the hilum opening. This is in agreement with the observations made in drying tests with lentils (Tang and Sokhansanj 1993b).

The effective moisture diffusivity in lentils increased with initial lentil moisture content and temperature (Table II). Moisture diffusivity D_{eff} in Equation 3 reflects the resistance of a composite material consisting of the seedcoat and the cotyledons. The values of D_{eff} in Table II are significantly smaller than those of the moisture diffusivity of the cotyledons: 3.6×10^{-8} m^2/hr at 22°C and 2.3×10^{-8} m^2/hr at 12°C (Tang and Sokhansanj 1993b). Thus, the seedcoat provides greater resistance to moisture migration than do the cotyledons. Changes in seedcoat properties may significantly affect moisture absorption rates by lentils.

Increased rates of moisture uptake in lentils with increasing initial moisture contents during moisture absorption and water imbibition tests may be attributed to increased widths of lentil hilum openings (Fig. 4) and increased moisture permeabilities in the seedcoats. The waxy cuticle layer that exists on the surfaces of legumes (Arechavaleta-Medina and Snyder 1981, Yaklich et al 1984) serves as the prime barrier to water migration through the seedcoat (Bukovac et al 1981). Because the waxed lentils of 16% initial moisture content imbibed water readily (Table I) and moisture migrated mainly through the seedcoat of the lentils of 16–24% initial moisture contents (Figs. 2 and 3), pores and fissures must exist in the cuticle layer to allow moisture to migrate through the seedcoat of these lentils. The sizes of cuticle pores and fissures should affect the permeability of the seedcoat. As lentils are hygroscopic, the surface area of a lentil changes as lentil moisture content varies. Tang and Sokhansanj (1993a) were able to relate the seedcoat surface area to lentil moisture content:

$$S = 2\pi\,(a_o^2 + h_o^2)\,e^{0.0062(M - M_O)} \qquad (5)$$

where, S is the surface area at moisture content M; a_o and h_o are the radius and half thickness, respectively, of a lens-shaped lentil at a reference moisture content M_o. From Equation 5, percent change in lentil surface area can be calculated as:

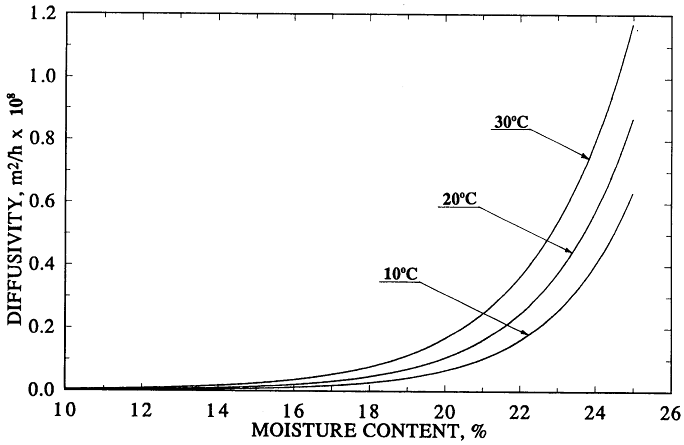

Fig. 5. Relationship among the moisture diffusivity in the seedcoat of Laird lentils, moisture content, and three temperatures calculated using Equation 7.

$$\frac{S_o - S}{S_o}, \% = [1 - e^{0.0062(M - M_o)}]\,100\% \qquad (6)$$

where S_o stands for the surface area at moisture content M_o. According to Equation 6, a 10% increase in moisture content will result in a 6% increase in seed surface area. As the cuticle layer is not hygroscopic, its area remains constant. Increased seed surface area will result in larger pores and fissures and, thus, greater permeability of the seedcoat.

A quantitative relationship among the moisture diffusivity in the seedcoat of Laird lentils, moisture content, and temperature was reported by Tang and Sokhansanj (1993b):

$$D = 63.2e^{-(9741.4/T)}\, e^{[-0.549 + (284.5/T)]M} \qquad (7)$$

where D is the moisture diffusivity in the seedcoat in m^2/hr; T is the absolute temperature in K; and M is lentil moisture content. Equation 7, as illustrated in Figure 5 for 10, 20, and 30°C, predicted a dramatic increase in the diffusivity of lentil seedcoat as lentil moisture content increased. This may explain the observation that moisture migrated mainly through the seedcoat of the lentils of 16–24% initial moisture contents (Figs. 2 and 3). Tang (1991) reported that waxing the hilum and micropyle did not significantly change the rate of water uptake during soaking when lentil moisture content was greater than 16%. Because the seedcoats of lentils of 16–24% were permeable to water, hardshell lentils were not expected at these moisture contents. In fact, Jones (1928) reported that seed impermeability was rarely encountered among *Vicia villosa* seeds at moisture contents exceeding 14%.

The diffusivities in the seedcoat of lentils at 12% moisture content were estimated to be 1.7×10^{-11} m^2/hr at 10°C and 7.4×10^{-11} m^2/hr at 30°C (Fig. 5). These values are so low that moisture entered the lentils mainly through the narrow hilum openings, resulting in much lower absorption and imbibition rates in the lentils of 12% initial moisture content, as compared to the lentils of 16–24% initial moisture contents (Figs. 2 and 3, and Table I). During water imbibition tests, water entry into the lentils of 12% initial moisture content indeed started at the hilum region. Similar observations were reported by Heil et al (1992) with dry pinto beans. Varriano-Marston and Jackson (1981) concluded that the hilum is the rate-limiting barrier in water imbibition of dry black beans.

As pictured in Figure 4D, the hila of a small number of lentils at 12% moisture content were closed even after 10 hr of soaking. The seedcoat of some lentils might also be less permeable than the others in the lentil population, because of more wax or cutin deposits in the cuticle layer. The concurrence of an impermeable seedcoat and closed hilum opening in lentils of 12% initial moisture content resulted in 5% hardshell lentils at 22°C and 9% hardshell lentils after 10 hr of imbibition time at 12°C (Table I). Jones (1928) and Hyde (1954) found that hardshell legumes occurred only at <14% moisture content. But once the waxy cuticle layer was removed by either chemical or mechanical means, hardshell soybeans imbibe water rapidly (Arechavaleta-Medina and Snyder 1981).

TABLE III
Weight (mg) of 130 Hardshell and Control Lentils

Lentil Type	Sample[a]	Mean	Standard Deviation	Minimum	Maximum
Hardshell	Des	61.0	13.8	24	90
	S1	67.7	13.5	33	94
	S2	69.6	14.2	26	91
Control	Des	70.3	11.4	39	95
	S1	71.2	8.5	43	87
	S2	73.4	10.1	40	93

[a]S1 and S2 = lentils from swathed plants, Des = lentils from chemically desiccated plants.

Figure 5 illustrates that the moisture diffusivity in the seedcoat increases with increasing temperature. This may explain the larger effective moisture diffusivity D_{eff} in the lentils at 22°C as compared to the lentils at 12°C (Table II). It may also explain the lower percent of hardshell seeds in the lentils soaked at 22°C vs. 12°C (Table I). Thus, increasing soaking temperature will increase the permeability of the seedcoat and help reduce the percentage of hardshell lentils.

It is not clear why the hila of certain lentils at 12% moisture content were closed (Fig. 4D) while the other lentils at the same moisture content were open (Fig. 4C). It may depend upon the maturity of each individual lentil and the width of the hilum opening at the time of harvest. Weight analysis on lentils indicated that the mean weights of hardshell lentils were significantly ($P < 0.02$) smaller than those of the control lentils (Table III). There was also a larger number of small hardshell lentils in the chemically desiccated lentils than there was in lentils swathed before harvest. Arechavaleta-Medina and Snyder (1981) reported that hardshell soybeans tended to be smaller than normal soybeans.

CONCLUSIONS

The initial moisture contents of lentils played a major role in moisture uptake during water imbibition and moisture absorption. Increasing lentil moisture content resulted in more permeable seedcoats and greater moisture uptake rates. Moisture migrated mainly through the seedcoat at lentil moisture contents of 16–24%. Because of hygroscopic shrinkage, reducing moisture content resulted in a decrease in the permeability of the seedcoat and narrowing of the hilum opening. At 12% moisture content, moisture entered lentils mainly through the hilum opening. The impermeable seedcoat and concurrent closing of the hilum opening (favored at low lentil moisture contents) resulted in hardshell lentils. Increasing soaking temperature increased the permeability of the seedcoat and, therefore, reduced the percentage of hardshell lentils.

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