DRYING CHARACTERISTICS OF SOYBEAN (*GLYCINE MAX*) USING CONTINUOUS DRYING AND INTERMITTENT DRYING

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ABSTRACT
The effects of drying temperature by continuous and intermittent drying on the drying characteristics of soybean was determined in this study. Among the thin layer drying models, the Midilli-Kucuk model showed the best fit (R^2>0.99) to describe the drying of soybean. At 300 min of the effective drying time, the moisture content of continuous drying at 35, 40, and 45ºC were 9.38 (±0.00), 8.69 (±0.17), and 7.70% (±0.48), respectively; while the moisture content of intermittent drying at 35, 40, and 45ºC were 8.28 (±0.21), 7.31 (±0.41), and 6.97% (±0.07), respectively. The image analysis method for detection of the crack in soybean demonstrated that at the target moisture content (7.7%), cracked grain ratios with intermittent drying at 35, 40, and 45ºC were reduced by 52.08, 27.59, and 18.24%, respectively. With the effective drying time, the activation energy for intermittent drying (9.33kJ/mol) was significantly lower than that value for continuous drying (21.23kJ/mol).

Keywords: intermittent drying, image analysis, thin-layer drying models, soybean

1. INTRODUCTION

Soybean (Glycine max) is one of the most important food resources in Asian countries, due to high protein and oil content. Traditionally, soybeans are processed and served in many ways including tofu, soybean paste, and soybean sauce (Kwon 1972). The moisture content of soybean is an important factor for controlling the quality during storage and processing. Since the 20 to 25% post-harvest moisture content is unsuitable for long term storage, solar or hot air drying is used to reduce the moisture content in soybeans (Rafiee 2009, Soponronnarit et al. 2001). Solar drying is traditionally used due to its low cost of energy consumption. However, solar drying has several drawbacks including weather dependence that makes it difficult to control the soybean quality; low heat and mass transfer rate that causes a longer drying time and outdoor conditions that carry a risk of contamination by microorganisms and insects (Doymaz 2006). The hot air drying method has advantages of short drying time and low labor cost. However, hot air drying has a fast drying rate due to high heat and mass transfer rate, which causes thermal damage to the soybeans. The best-known thermal damages include cracking or breaking of soybeans (Soponronnarit et al. 2001, Wiriyaumpaiwong et al. 2003). Cracking or breaking of soybean is mainly due to the tension on the skin of soybeans associated with an abrupt or a steep moisture gradient from the surface to the center of beans (Hirunlabh et al. 1992). Therefore, it is necessary to develop a drying method to minimize the amount of thermal damage to soybeans by controlling the moisture gradient associated with a hot air drying. A few studies have focused on minimizing the thermal degradation of soybeans during hot air drying (Lee and Lee 2009, Niamnuy et al. 2012); however, an alternate drying method for reducing the amount of thermal damage in soybeans has not been proposed to data.
Intermittent drying (ID), also called cyclic drying, is a novel method to minimize the moisture gradient of the product during drying (Kumar et al. 2014). In ID, samples are removed from the dryer for a certain time interval to allow central to peripheral diffusion of moisture; subsequently, the samples are returned to the dryer. The repeated periodic drying process reduces thermal damage by controlling the products' diffusion rate and producing a less steep moisture gradient. ID is commercially applied to several agricultural products, including soybeans. Few studies have been reported to demonstrate the effect of drying air condition and intermittency on the moisture changes of soybean during intermittent drying (Defendi et al. 2017, Zhu et al. 2016). However, the thermal degradation of soybeans during ID remain still unknown. Most commercial scale ID processes are based on trial-and-error or operators' experience.
Drying process is one of the most complex unit operation, because in most, heat, mass, and momentum transfer phenomena are simultaneously connected (Kudra and Mujumdar 2002, Yilbas et al. 2003). Due to the complexity of developing an analytical or a numerical

model to interpret the drying process, many empirical models have been developed (Baker 1997, Marinos-Kouris and Maroulis 1995). Thin layer model, a well-known empirical model for drying, has been practically used to design the drying process based on the experimentally-derived drying curves (Moon et al. 2014, Rafiee 2009). Since there are no empirical models to characterize an ID method for soybeans, it is useful to construct a mathematical model to describe the drying behavior of ID for soybeans based on the thin-layer drying model.
The purposes of this study were 1) to analyze the drying characteristics of soybean according to a continuous hot air drying and an intermittent hot air drying method, 2) to compare the change in quality of soybean according to continuous drying (CD) and ID, and 3) to develop a model to describe the drying behavior of ID for soybean based on the thin-layer model.

2. MATERIALS AND METHODS

2.1. Material

Soybeans were donated from National Institute of Crop Science, Department of Functional Crop (Miryang, Kyungsangbuk-do, S. Korea). The initial moisture content of soybeans was adjusted to 22.0% (± 0.8) immediately after harvesting (Overhults et al. 1973, Soponronnarit et al. 2001). All samples were vacuum packed and stored at room temperature during the experiment.

2.2. Drying process

A tray dryer (width × depth × height = 550 × 520 × 600 mm, Dong Yang Science Co., Seoul, S. Korea) was used for the CD and the ID. The target moisture content for this study was set at 7.7 % because the moisture content measured from the cracked beans was 7.7%. Soybeans (25 g (± 0.7)) were placed in the center of the dryer throughout the drying process to minimize the effect of temperature gradient in the dryer on the drying rate. The drying temperature was varied at 35, 40, and 45 °C, and the inlet air velocity was fixed at 3.0 m/s. Drying time was 600 min, and the weight of the soybean was measured every 30 min. For the CD, the drying time was 600 min (without interruption); and, for the ID, soybean was dried for 30 min in the dryer followed by diffusion of the moisture for 30 min in the desiccator, repeatedly during the 600 min time period.

2.3. Detection of cracked bean with image analysis

The quality of soybean during the drying process was evaluated by the ratio (%) of cracked bean at the target moisture content of 7.7% after continuous and intermittent drying at 35, 40, and 45 °C, respectively. Image analysis was used to detect the cracks of soybeans. The image analysis procedures for this study included (1) image acquisition, (2) image segmentation, (3) thresholding, (4) filtering, and (5) image analysis (Fig. 1).

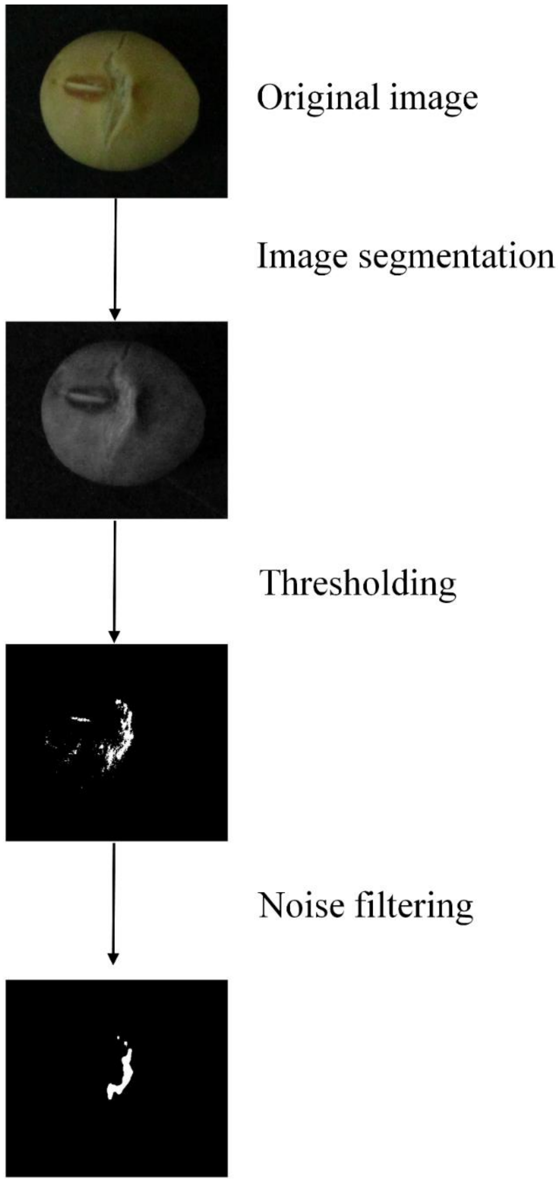

Figure 1: The Overall Procedure for Image Analysis of Soybean.

A digital single-lens reflex camera (DSLR-500D, Canon Inc., Tokyo, Japan) with a lens (EF-S 18-55 mm *f*/3.5-5.6, Canon Inc., Tokyo, Japan) was placed vertically over the sample at a distance of 18 cm. The image of the sample was acquired using a camera with a resolution of 2.1 million pixels. Image acquisition was replicated 10 times with shaking for 3 s. The image processing tool in MATLAB (Mathworks® Inc., Natick, MA, USA) was used for analysis of the structural features of the soybeans. Threshold-based segmentation was a particularly effective technique for imaging solid objects on a contrasting background. After image segmentation, the threshold was obtained from histogram of the image (not shown). With the optimal threshold, all pixels at or above the threshold level were assigned to white color and all pixels below the threshold level were assigned to black color. After applying this process, the hilar fissures and the crack of soybeans were extracted with white

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color. A median filter is a non-linear filtering technique that allows the edges to be preserved while filtering out unwanted noise (Du and Sun 2004). It replaces the output pixels with the median of the adjacent pixel values instead of a weighted sum of those values. In this study, the median filter was applied to remove the hilar fissures from the soybean images after applying the thresholding technique. The cracked bean ratio was estimated from the maximum detected edge ratio of 10 replicates.

2.4. Thin-layer drying model and drying rate

Four different thin-layer drying models were applied to evaluate the drying behavior of soybeans. The thin-layer drying models used in this study were presented in Table 1. These drying models have been used in many food products (Herderson and Pabis 1961, Lewis 1921, Midilli et al. 2002, Page 1949).

The moisture ratio and the drying rate were calculated as the follows:

$$MR = \frac{M-M_e}{M_i-M_e} \tag{1}$$

where MR is the moisture content, M is the moisture content according to the drying time (g/g d.b.), M_e is an equilibrium moisture content (g/g d.b.), and M_i is the initial moisture content.

Table 1: Thin Layer Models Used to Describe the Drying Kinetics of Soybean.

Model no.	Model name	Model equation	References
1	Newton	$\mathrm{MR} = e^{-kt}$	Lewis (1921)
2	Page	$\mathrm{MR} = e^{-kt^n}$	Page (1949)
3	Henderson and Pabis	$\mathrm{MR} = ae^{-kt}$	Henderson and Pabis (1961)
4	Midilli-Kucuk equation	$\mathrm{MR} = \mathrm{a}e^{-kt^n} + bt$	Midilli et al. (2002)

The drying rates at initial stages of drying, during drying, and at the final stage of drying were calculated according to Guine and Fernandes (2006):

at $t = t_0$,

$$\frac{dM}{dt} = \frac{M_i - M_0}{t_1 - t_0} \tag{2}$$

at $t = t_i \ (i = 1, 2, \ldots, n-1)$,

$$\frac{dM}{dt} = \frac{M_{i+1} - M_{i-1}}{t_{i+1} - t_{i-1}} \tag{3}$$

at $t = t_n$,

$$\frac{dM}{dt} = \frac{M_n - M_{n-1}}{t_n - t_{n-1}} \tag{4}$$

2.5. Effective moisture diffusivity and activation energy

The effective moisture diffusivity (D_{eff}), which is affected by the porosity, moisture content, composition, temperature a material, provides useful information to understand the mechanism of moisture movement during drying process. The D_{eff} at given moisture content can be estimated using the "methods of slope" technique from the solution of Fick's second law equation (Karathanos et al. 1990, Marinos-Kouris and Maroulis 1995, Zogzas et al. 1996).). For Fick's second law of diffusion,

$$\frac{\partial M}{\partial t} = \frac{1}{r}\left[\frac{\partial}{\partial r}\left(D_{\text{eff}} r \frac{\partial M}{\partial r}\right) + \frac{\partial}{\partial z}\left(D_{\text{eff}} r \frac{\partial M}{\partial z}\right)\right] \tag{5}$$

For a sphere,

$$MR = \frac{M-M_e}{M_i-M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2} \times exp\left(-n^2\frac{\pi^2 D_{\text{eff}}}{r^2}t\right) \tag{6}$$

where D_{eff} is the effective moisture diffusivity (m^2/s), and r is the spherical radius (m).

When the drying time is long enough, the solutions are simplified by eliminating the second term:

$$MR = \frac{M-M_e}{M_i-M_e} = \frac{6}{\pi^2} exp\left(-\frac{\pi^2 D_{\text{eff}}}{r^2}t\right) \tag{7}$$

The simplified solution can be written in a logarithmic form as follows:

$$\ln MR = A - B \times t \tag{8}$$

where B is $\pi^2 D_{eff}/r^2$ for a sphere.

The temperature dependence of the D_{eff} is generally expressed as the Arrhenius-type relationship as follows:

$$D_{eff} = D_0 exp\left(\frac{E_a}{RT}\right) \tag{9}$$

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{RT} \tag{10}$$

where D_0 is the pre-exponential/frequency factor of the Arrhenius equation (m^2/s); E_a is the activation energy (kJ/mol); R is the universal gas constant (kJ/mol K) and T is the absolute temperature (K). In this study, the effective moisture diffusivity and the activation energy for intermittent drying were calculated from the effective drying time (i.e., the time that soybeans are dried in the drying chamber).

3. RESULT AND DISCUSSION

3.1. Drying kinetics

CD and ID were conducted with different drying temperatures (35, 40, and 45 ºC) to investigate the effect of drying temperature on the drying kinetics. Drying temperature significantly affected the rate of moisture reduction in both CD (Fig. 2A) and ID (Fig. 2B). The higher drying temperature showed the faster moisture reduction rate for both drying methods. However, the moisture content at the same drying time showed a difference between CD and ID (Table 2). The moisture content of ID after 300 min of the effective drying time (duration within the drying chamber), was lower than that of CD regardless of drying temperatures. The moisture contents of CD at 35, 40, and 45 ºC were 9.38

(± 0.00), 8.69 (± 0.17), and 7.70% (± 0.48), respectively; and those of ID were 8.28 (± 0.21), 7.31 (± 0.41), and 6.97% (± 0.07), respectively. The rates of moisture reduction from ID were significantly faster than those of CD for all drying temperatures.

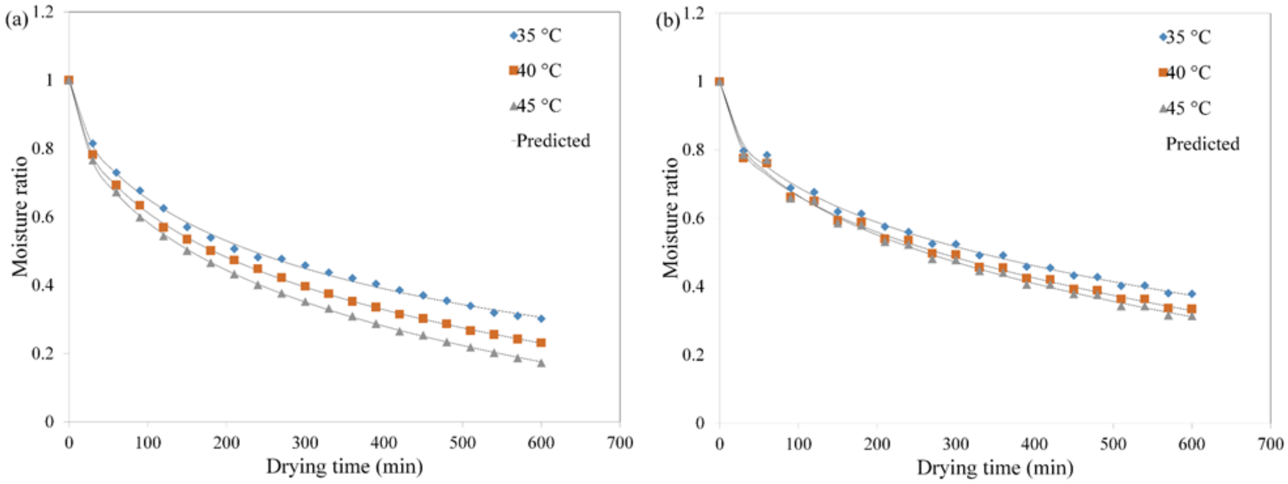

Figure 2: Changes of Moisture Ratio of the Soybean Upon the Drying Temperature Using (a) Continuous Drying and (b) Intermittent Drying.

The faster rate of moisture reduction observed from ID is mainly due to the moisture diffusion from the center to the surface during the rest period. Since the rest period allows moisture transfer solely by concentration difference, the effective drying time applied in the drying chamber was eventually reduced. This result implied that the drying method and the drying temperature significantly influenced the moisture reduction rate of soybeans. Thus, ID may help reduce the energy consumption required for soybean drying. ID has been applied to the various bio-products because of these advantages (Chua and Chou 2005, Hemati et al. 1992, Putranto et al. 2011b). Putranto et al. (2011a) have described reducing energy consumption in depth.

Table 2: Moisture Content of Soybean at Different Effective Drying Time and Temperature.

Drying method	**Temperature (°C)**	**Effective drying time (min)**	**Moisture content (%)**
Continuous drying	35	90	13.86±0.09
		180	11.04±0.11
		300	9.38±0.00
	40	90	13.88±0.14
		180	10.98±0.17
		300	8.69±0.17
	45	90	13.07±0.45
		180	10.18±0.48
		300	7.70±0.48
Intermittent drying	35	90	13.46±0.17
		180	10.69±0.17
		300	8.28±0.21
	40	90	12.88±0.31
		180	9.91±0.38
		300	7.31±0.41
	45	90	12..88±0.03
		180	9.81±0.03
		300	6.97±0.07

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3.2. Thin-layer drying model

Thin-layer drying model is a well-known semi-empirical model to predict the moisture changes during drying. Although many studies have used the thin-layer models to describe the drying behavior of food and biomaterials, the thin-layer model has not been used to characterize the drying behavior of soybean using ID. Four thin-layer models were applied to characterize the drying behavior of soybeans using CD and ID. The Midilli-Kucuk model was the most suitable model among the four models based on the R^2 (> 0.9942), RMSE (< 0.0147), and SSE (< 0.0037); while the minimum R^2 of Newton, Page, and Henderson and Pabis model showed 0.7726, 0.9933, and 0.9251, respectively. The Midilli-Kucuk model well described the moisture changes of soybean during drying for ID and CD (Fig. 2). As energy efficiency is highly dependent on the effective drying time (i.e., the time that soybeans were dried in the drying chamber), the effective drying time to achieve the target moisture content was calculated based on the Midilli-Kucuk equation and the model parameters induced in this study. The effective drying time to achieve the target moisture content for CD and ID were 479 min and 322 min at 35 °C, 358 min and 264 min at 40 °C, and 315 min and 262 at 45 °C, respectively. The effective drying times of ID at different drying temperature were shorter than those of CD due to moisture diffusion during the rest period of ID.

3.3. Drying rate and quality evaluation of soybean

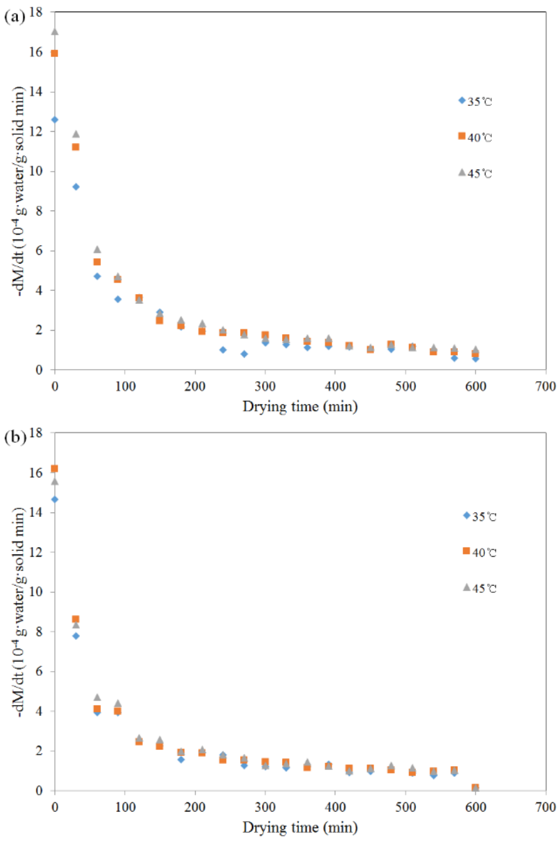

Figure 3: Effect of Drying Temperature on the Changes of Drying Rate Using (a) Continuous Drying and (b) Intermittent Drying.

Changes of the drying rate of soybeans calculated by Eq. 2-4 based on the moisture changes during CD and ID were compared (Fig. 3). Constant rate period was not observed for all drying temperatures in CD and ID, and the drying rate showed continuous decrease as the drying time increased. Because the ratio of the surface area to the volume of soybean is very large, the moisture content on the surface decreases much more rapidly than at the center of a soybean as the drying begins, hence, the falling rate period was presented from the initial stage of drying. The constant rate period may be short or absent in drying of biomaterials, and is dependent on the ratio of surface area to volume or the structure of the biomaterial. Moon et al. (2014) reported that there was no constant rate period in drying sea cucumbers using hot air drying and far infrared drying. The structure of biomaterial is very diverse according to species. Some biomaterials may have a relatively uniform structure, such as a meat, but some biomaterials contain different structure layers for example soybeans or sea cucumbers. When the structure of the dried layers near the surface differs from that near the center, the drying rate may have a gradient in the material. Because the layers near the surface cannot provide a constant supply of water, the drying rate is dominated by the diffusion of moisture from the inside to the outside that consequently causes the drying rate gradient (Chua and Chou 2005, Johnson et al. 1998, Moon et al. 2014, Srikiatden and Roberts 2006).

In the initial stage of drying, the drying rate of ID was lower than that of CD due to the rest period of ID. However, the drying rate of ID was higher than CD with repeated rest and drying periods. Generally, the concentration difference inside a soybean rather than near its surface is the major driving force for the falling rate period. In the early stage, the resistance to drying is predominantly near the surface, but, as the drying time progresses, the moisture diffusion inside of a bean mainly governs the drying rate (Chua and Chou 2005, Hemati et al. 1992, Putranto et al. 2011b). The higher drying rate of ID than CD was due to moisture diffusion in the soy bean during the rest period, which decreased drying resistance near the surface of the bean as the drying time increased. After 360 min of drying, the drying rate of ID showed no significant difference from that of CD at all drying temperatures ($p<0.05$). The fast drying rate is one of the practical operation conditions of the drying process; however, the fast drying rate obtained from the high drying temperature may cause degradation of soybean quality and thermal damages, such as cracked beans. Therefore, the design of drying process of soybean should consider the effect of drying temperature and drying rate on the quality of soybeans (Karathanos et al. 1990, Sangkram and Noomhorm 2002, Soponronnarit et al. 2001, Wiriyaumpaiwong 2003).

The results of the cracked bean ratio from image analysis were compared with the cracked grain ratio determined manually by the expert group (Fig. 4). No significant differences were observed between two results. Thus, the results demonstrated that the proposed image analysis method was applicable for high accuracy measures of cracked beans ratio. The quality changes of soybean on CD and ID were evaluated as the ratio of cracked beans at the target moisture content of 7.7% (Fig. 4).

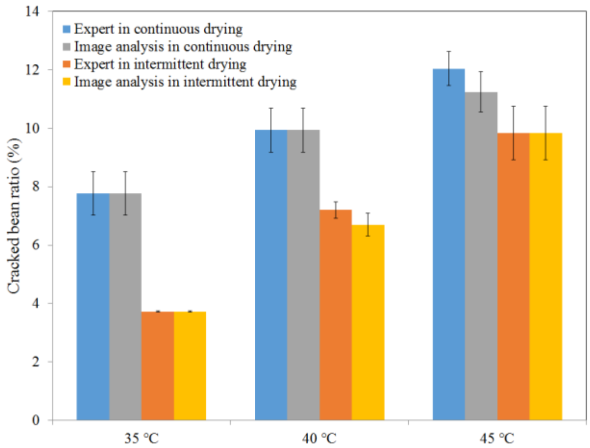

Figure 4: Effect of Drying Temperature on the Cracked Grain Ratio at the Target Moisture Content of 7.7%.

Regardless of drying methods, the cracked bean ratio increased as the drying temperature increased. This is because the high drying temperature has more possibility to cause the moisture gradient in the soybean, creating tension between the surface and the center of the bean that initiates the cracking (Hirunlabh et al. 1992). However, the cracked bean ratios of ID treated samples were much lower, as compared to CD treated samples, possibly due to less abrupt moisture gradient from surface to center, due to diffusion of moisture during the rest period of ID. As the drying temperatures were reduced, the difference of the cracked bean ratios between CD and ID were increased. At 45 °C, the difference was 18.24%, but at 35%, the difference increased to 52.08%, suggestive of a synergistic effect of drying temperature and ID on the thermal damage of soybeans. Our results clearly demonstrated that the drying temperature and the diffusion time, i.e., the time required to move the moisture from around the center to the surface, are important factors to maintain the quality of soybeans after drying.

3.4. Effective moisture diffusivity and activation energy

The values of D_{eff} were calculated by the semi-log relations expressed in Eq. (8). Regardless of the drying methods, the semi-log relation was well fit and showed that the D_{eff} values varied in the range of 3.81×10^{-11} m^2/s to 6.10×10^{-11} m^2/s and 5.68×10^{-11} m^2/s to 6.98×10^{-11} m^2/s for CD and ID, respectively (Table 3). These values were in the range of most food or bioproducts (Zogzas et al. 1996). The D_{eff} values for CD were significantly higher than those for CD at the same temperature. Hence, the ID was more efficient drying method for soybean than the CD. The activation energy (E_a) of soybean being dried was estimated using the Arrhenius relation expressed in Eq. (9) (Fig. 5). The E_a values for CD and ID were 21.23 and 9.33 kJ/mol, respectively.

Table 3: The Effective Moisture Diffusivity Estimated During Continuous Drying and Intermittent Drying of Soybean.

Drying method	**Temperature (°C)**	**Effective moisture diffusivity (10^{-11} m^2/s)**	R^2
Continuous drying	35	3.81	0.9766
	40	4.75	0.9902
	45	6.10	0.9954
Intermittent drying	35	5.68	0.9922
	40	6.31	0.9959
	45	6.98	0.9963

The physical meaning of the E_a is interpreted as the amount of energy required to transfer moisture through the samples being dried. In this study, the activation energy for ID was significantly lower than that for CD, which indicated that the samples being dried with ID required significantly less energy than those dried with CD.

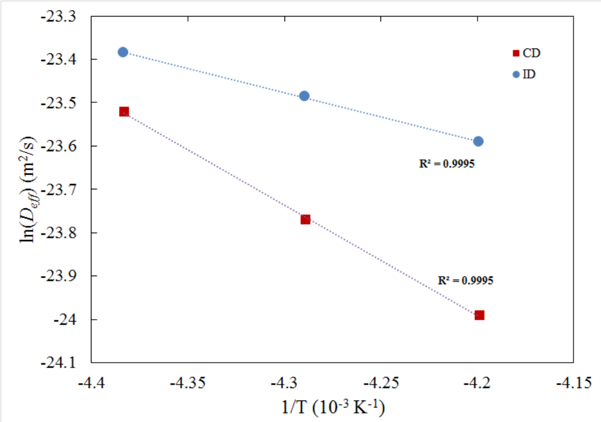

Figure 5: Comparison of the Activation Energy of Samples Dried by Continuous Drying (CD) and Intermittent Drying (ID).

4. CONCLUSION

The continuous drying and intermittent drying were applied to investigate the drying characteristics of soybean with 22.0% (±0.8) initial moisture content. To describe the drying kinetics of soybean, the Midilli-Kucuk model showed the best fit (R^2>0.99) among the thin layer models. At 300 min of the effective drying time, the moisture content of continuous drying at 35, 40, and 45ºC were 9.38 (±0.00), 8.69 (±0.17), and 7.70% (±0.48), respectively; while the moisture content of intermittent drying at 35, 40, and 45ºC were 8.28 (±0.21), 7.31 (±0.41), and 6.97% (±0.07), respectively. The image analysis method for detection of the crack in soybean demonstrated that at the target moisture content of 7.7%, cracked grain ratios with intermittent drying at 35, 40, and 45ºC were reduced by 52.08, 27.59, and 18.24%, respectively. Based on the diffusion model, the D_{eff}

values were estimated, and the varied in the range of 3.81 × 10-11 m2/s to 6.10 × 10-11 m2/s and 5.68 × 10-11 m2/s to 6.98 × 10-11 m2/s for CD and ID, respectively. These values were in the range of most food or bioproducts. The activation energy for intermittent drying (9.33 kJ/mol) was significantly lower than that value for continuous drying (21.23kJ/mol), which indicated that the samples being dried with ID required significantly less energy than those dried with CD. The empirical models developed in this study can provide useful information in selecting an optimum condition of intermittent drying to minimize thermal degradation of soybeans.

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