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Drying Kinetics Model of Fermented Soybean Meal Using Hot Air-Drying

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Abstract

The aim of this research was to model the hot air-drying (HAD) of fermented soybean meal (FSBM) containing probiotic *Enterococcus faecium*. The HAD was performed to reduce the moisture content of the FSBM. The effects of drying temperature on cell viability and moisture content were investigated. Moisture content decreased rapidly with increasing drying temperature. This probiotic strain's cell viability slightly decreased at drying temperatures lower than 50°C and was greatly decreased at 55°C. Four mathematical models were applied to describe its drying kinetics, revealing that the Page model was the best fit for characterizing the drying kinetics during drying of FSBM, with a coefficient of determination (*R*2) of 0.9996. Moreover, the Page model provided the lowest root mean square error (*RSME*) and chi-square (*X*2) and the highest modeling efficiency.

Keywords : Drying Kinetics; Soybean Meal; Hot Air-Drying; *Enterococcus faecium*; Probiotic

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1. Introduction

The word, "probiotic," means "for life," and it is currently used to indicate living microorganisms associated with useful effects in humans and animals. Probiotics are extensively claimed to improve intestinal health, enhance the immune response, reduce serum cholesterol, and prevent cancer, produce bacteriocin, inhibit pathogens, and balance the digestive system [1], [2] Probiotics have also been used in animal feed to improve the gastrointestinal (GI) health of animals [3] Numerous of microorganisms that include bacteria and yeast are considered potential probiotics; *e.g.*, *Bifidobacterium longum*, *Lactobacillus rhamnosus, Lactobacillus plantarum, Lactobacillus casei*, *Enterococcus feacium*, and *Saccharomyces boulardii* [4].

Enterococci are gram-positive, facultative, anaerobic spherical bacteria that comprise a portion of the natural flora in the GI tracts of humans and animal. Enterococci are very robust because they can tolerate and stop the growth of undesired microorganisms in the GI tract [5]only two (Enterococcus faecalis and Enterococcus faecium. About 50 enterococcal species are currently accepted, including the most clinically pertinent such as *Enterococcus faecalis* and *E. faecium* [6]. At present, animal feeds containing probiotics are widely used to promote the immunity to and growth of pathogens in animals [7]. The literature suggests the benefits of using *Enterococcus* as a probiotic, especially *E. faecium*, because of its potential for inhibiting the growth of pathogens [8], [9]. In addition, *E. faecium* can produce enterocin and provide inhibitory activity against many bacteria [10].

Solid state fermentation (SSF) is a useful, simple process of interest in prebiotic production and probiotic cultivation [11]. Low-cost and inexpensive raw materials from agriculture or agroindustry like cassava, bagasse, and palm kernel, corncob, wheat bran, and rice bran residues are increasingly and widely used in SSF [12], [13]. Soybean meal (SBM) especially is applied due to its nutritional qualities. SBM contains protein, amino acids, oligosaccharides, Vitamin B, Vitamin E, and minerals [14], which promote the growth of microorganisms [15]. SBM is the most common protein source supplement used in animal feed manufacturing. SMB contains approximately 40-48% crude protein, the quantity being affected by hull removal and oil extraction. Moreover, the protein in SBM is preferred over other sources because it contains a sufficient amount of essential amino acids required by livestock [15].

In producing animal feed containing probiotics, the viability of the probiotic in the final product is very important. A viable probiotic microorganism content of 6-7 log CFU/g is suggested because

that level still exhibits probiotic characteristics following commercial production and survives the passage through a host GI tract [16]. To maintain high quality in animal feed containing probiotics, the viability of the probiotic in the product should remain high. Therefore, after fermentation, the moisture content in fermented SBM (FSBM) must be reduced to depress probiotic growth and extend viable probiotic shelf life in the final animal feed product. Reducing the moisture content also makes transportation from factory to farm and storage of the probiotic product easier and more convenient. At present, there are several processes for drying the product, including evaporation, fluidized bed drying, freeze drying, and spray drying [17], [18]. However, the cost of animal feed production should be considered. The hot air-drying process (HADP) is a simple, low-cost process for decreasing moisture content and has been used to remove water from many kinds of agricultural crops [19], [20]microwave and combined microwave–hot-air dehydration. Three microwave levels (210, 300, 560 W. The aim of this study was to study the drying of FSBM using a simple HADP. In addition, mathematical models were used to simulate the removal of moisture content in FSBM under different drying temperatures.

2. Research Methodology

2.1 Microorganism and maintenance

E. faecium A028 (DDBJ accession number: LC350006) was isolated from the GI tracts of healthy chickens, its in vitro probiotics properties were evaluated, and the strain used was identified by 16S rDNA sequencing in our previous research [21]. The strain was cultured aseptically in MRS (de Man, Rogosa and Sharpe) (Sisco Research Laboratories SRL, India) broth at 41±1°C (New Brunswick, Germany) for 24 h. Then, 800 μl of the cultured strain was supplemented with 200 μl of 80% glycerol (Univar, USA) and kept at -80±1°C (New Brunswick, Germany) as a stock culture.

2.2 Hot air-drying process

The SBM obtained from Thai Vegetable Oil Public Company Limited (TVO) was sterilized at 121°C for 15 min and then gently mixed with sterilized 5 %w/v molasses solution (the weight of SMB to the volume of molasses solution at 1:1). The starter of *E. faecium* cultured in MRS broth (for 18 h) was aseptically transferred to SMB containing molasses, mixed, and incubated at 41±1°C for 8 h.

A 2.0 kg of FSBM was gently spread on drying trays in a single layer (approximate tray loading capacity 6.8 kg/m^2; 0.45 m wide and 0.65 m long) (Contherm, New Zealand) and dried at 45, 50, and 55°C with air velocity of 0.4 m/s. FSBM aliquots were drawn for measuring moisture content and drying kinetics at 2 h intervals. The FSBM was dried continuously until the moisture content was lower than 10%.

2.3 Mathematical modeling of the drying process

Drying models were used to fit an experimental drying curve to describe the drying process of FSBM under different temperatures. The moisture ratio of FSBM during HADP was expressed using the following equation (1) [22] :

$$MR=\frac{M_t-M_e}{M_0-M_e} \quad (1)$$

Where MR is the moisture ratio (dimensionless); M_0, M_t, and M_e are initial moisture content (gwater/gdry basis), moisture content at drying time (t; hour), and equilibrium moisture content (gwater/gdry basis), respectively. The values of M_e are considered relatively small compared to M_0 or M_t. Thus, equation (1) can be revised into a simpler term, equation (2) [22] :

$$MR = \frac{M_t}{M_0} \quad (2)$$

Experimental drying curves with different temperatures were fitted to published mathematical drying models (equations (3) to (6)) [23]. The Solver function of Microsoft Excel 2010 using the least squares technique was employed to analyze the curve fitting data.

Lewis, $MR = \exp(-kt)$ (3)

Page, $MR = \exp(-kt^n)$ (4)

Parabolic, $MR = a + bt + ct^2$ (5)

Henderson and Pabis,

$MR = a\cdot\exp(-kt)$ (6)

The drying models were tested with the coefficient of determination (R^2), sum of squares for error (SSE), root mean square error ($RMSE$), modeling efficiency (EF), and chi-square (X^2) in equations (7) to (11).

$$R^2 = 1-\left[\frac{\sum_{i=1}^{N}\left(MR_{pre;i}-MR_{exp;i}\right)^2}{\sum_{i=1}^{N}\left(MR_{pre;i}-MR_{exp,ave}\right)^2}\right] \quad (7)$$

$$SSE = \frac{\sum_{i=1}^{N}\left(MR_{exp;i}-MR_{pre;i}\right)^2}{N} \quad (8)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre;i}-MR_{exp;i}\right)^2\right]^{1/2} \quad (9)$$

$$EF = \frac{\sum_{i=1}^{N}\left(MR_{exp;i}-MR_{exp;ave}\right)^2-\sum_{i=1}^{N}\left(MR_{pre;i}-MR_{exp;i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp;i}-MR_{exp,ave}\right)^2} \quad (10)$$

$$X^2 = \frac{\sum_{i=1}^{N}\left(MR_{pre;i}-MR_{exp;i}\right)^2}{N-n} \quad (11)$$

where $MR_{exp;i}$ is the ith experimental MR, $MR_{pre;i}$ is the ith predicted MR, $MR_{exp;ave}$ is the average experimental MR, and N and n are the numbers of observation and constant.

2.4 Analysis

Cell viability was experimentally measured by the serial plate dilution method using MRS agar following the method of [24]. The serial dilutions of each FSBM were plated in duplicate and the plates were incubated at 41±1°C

for 48 h. The results were reported as logarithm of colony forming units per gram (log CFU/g) and expressed as the cell survival (%) in equation (12).

$$\text{Cell survival} = \left(\frac{\text{log CFU/g at drying time}}{\text{Initial log CFU/g}}\right) \times 100 \quad (12)$$

The moisture content of the FSMB during the hot-air drying process was expressed as wet basis moisture content. The FSBM was dried at 105±1°C for 3 h and the dry weight then determined [25].

3. Results and Discussion

3.1 Growth of *E. faecium* in solid state fermentation with soybean meal

The probiotic bacterium *E. faecium* was cultured in SBM mixed with molasses by SSF. The SSF was carried out in SBM by 5% molasses and a 1:1 SBM-to-water ratio. The cell viability of probiotic strain was increased to 9.82 log CFU/g for 8 h of cultivation (**Fig. 1**).

3.2 Effect of temperature of the hot air-drying process on moisture content and cell survival of probiotic

The FSBM was gently distributed over a tray and placed in a hot air oven. The moisture content of the FSBM during the HADP is presented in **Fig. 2**. At the first tenth hour, the moisture content in the FSBM decreased from about 57% to 48% (Dry basis) under all drying temperatures. Afterward, the moisture content decreased continuously with drying time. At 45°C, the moisture content slowly dropped to 9.80% (dry basis) at 36 h and then rapidly decreased to below 10% (Dry basis) at 50°C and 55°C at the 26 h and 22 h periods, respectively.

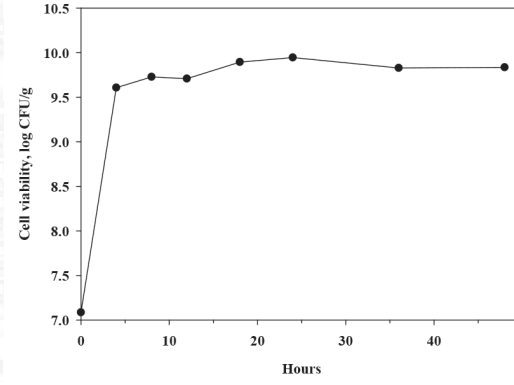

Fig. 1 Growth of *E. faecium* A028 in SBM by SSF

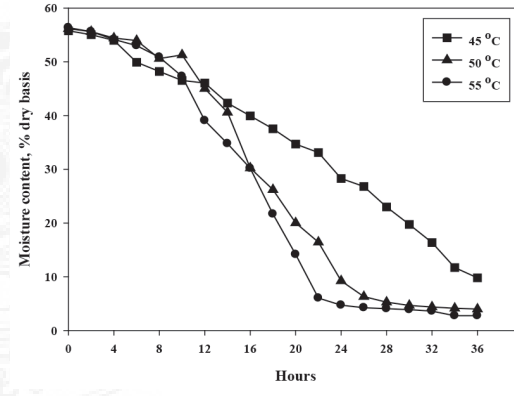

Fig. 2 The moisture content variation as a function of drying time

The survival of *E. faecium* A028 during the HADP at various temperatures was pronounced (**Fig. 3**). The initial viable cell number of *E. faecium* A028 was 10.04 log CFU/g. More than

98.34%of the probiotic strain survived when the SBM was dried at 45°C for 36 h, while survival decreased to 96.41% and 86.35% at 50°C and 55°C at 36 h, respectively. Moreover, the specific death rates at 45°C, 50°C and 55°C were 0.003 1/h, 0.022 1/h and 0.159 1/h, respectively. The specific death rate of *E. faecium* A028 was greatly increased when the drying temperature was raised to 55°C. At 55°C, the survival rate of the probiotic strain dropped dramatically after 18 h of drying.

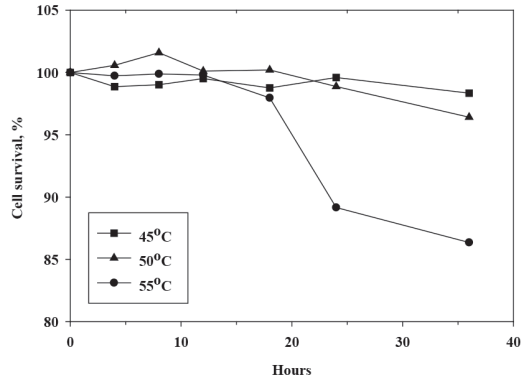

Fig. 3 Survival of *E. faecium* during the HADP

HADP is the conventional process used in lowering the moisture content of wet materials [26] and was used to dry the FSBM under different drying temperatures in this study. Our results noted that the drying rate of FSBM was definitely affected by temperature and the length of the HADP. At a high drying temperature, the drying rate is faster due to the water molecules being highly induced [27], [28]40 and 50°C with water activity ranging from 5% to 90%. The sorption isotherms of C. reticulata leaves decreased with increase in temperature at constant relative humidity. An hysteresis effect was observed. The experimental data of sorption were fitted by six models (Modified Henderson, Modified Chung-Pfost, Modified Oswin, Modified Halsey, GAB and Modified BET. When the drying temperature increases, water molecules inside the material move faster and increase the distance between molecules, indirectly decreasing the attractive forces between molecules. Thus, increasing the drying temperature increases the removal of moisture from the material.

Animal feed containing probiotics is widely used for increasing immunity and growth in animals [29]. The initial viable cell number in animal feed is strongly suggested to be at least 6 log CFU/g due to a decrease in viability when passing through the animal's GI tract [30]. The current study found that the drying temperature had an important effect on the survival of *E. faecium* in FSBM, especially at high temperatures. It has been reported that the temperature and exposure time of the drying process plays the main role in the viability of probiotics [30]. The cell membrane and probiotic proteins were the main constituents that were denatured during this process [31]. Therefore, the heating time in the drying process should be as short as possible to avoid lowering

probiotic viability in the final product. This study found that the viability of *E. faecium* A028 was over 8.50 log CFU/g after drying at 55°C for 36 h of drying, which was higher than the recommended value in animal feed [30]. In addition, cell viability slightly decreased to 9.93 log CFU/g and 9.61 log CFU/g at 45°C and 50°C of 36 h of drying, respectively. Due to the optimal growth temperature of *E. faecium* was 41°C and could tolerant the high temperature (45°C to 50°C) [21]. However, cell survival was dramatically decreased to 8.67 log CFU/g at 55°C for 36 h of drying. Hence, thermal drying processes of FSBM containing probiotic should be appropriately heated to receive the desired level of bacterial viability.

3.3 Mathematical modeling of the drying process

The moisture content data were converted to *MR*s. The *MR* during HADP was investigated as a function of drying time (*M*0 and *M*e were 56.10±0.30% and 2.75±0.01%, respectively). The experimental *MR* was fitted to four mathematical models (Lewis, Page, Parabolic, and Henderson and Pabis) and coefficients of determination (R^2) were estimated. The constants and coefficients of different mathematical model regressions were statistically analyzed (**Table 1**). Statistical parameters are listed in **Table 2**. The highest R^2 and *EF* values and the lowest *SSE*, *RMSE*, and X^2 values in the models were used to indicate the most suitable mathematical model for describing the hot air-drying behavior of FSBM.

R^2, *SSE*, *RMSE*, X^2, and *EF* values ranged from 0.9908 to 0.9999, 0.0001 to 0.0247, 0.0126 to 0.1572, 0.0001 to 0.0260, and 0.9910 to 0.9999, respectively (**Tables 1 and 2**). The Page model provided the highest R^2 (□ 0.999) and *EF* and the lowest *RMSE* and X^2 values, indicating that the Page model is the best fit of FSBM during the HADP. The drying characteristics, experimental data, and mathematical model predicted data are presented in **Fig. 4A-D**. The predicted *MR* of the Page model was in good agreement with the experimental values throughout drying, whereas the predicted values of the other models were more divergent from their experimental values.

Mathematical modeling has been widely used to study the drying behavior of high water-containing materials to discover and investigate the most suitable operating conditions during drying [32]. In this study, the experimental *MR* was fitted with Lewis, Page, Parabolic, and Henderson and Pabis empirical models. Among these models, Page more closely fit the experimental *MR* values at all three drying temperature levels. This model well describes the isothermal drying kinetics of FSBM. Statistically, the Page model was the best curve fitting model for understanding the dehydration of FSBM in this study (R^2 = 0.9996). Ruiz *et al* (2008), studied the behavior of corn

and amaranth grains at different drying temperatures (initial moisture content of approximately 30%-80%) [33]. Borah *et al* (2015), applied the Page model to predict the decrease in *MR* values in the drying process of turmeric using a solar conduction dryer [23]. It was suggested that the relative humidity (RH) has an important influence on the rate of water vapor transportation from the material surface to the air and effects the M_e. The high RH in low air velocity hot air oven decreases the drying rate at the initial period. Furthermore, the M_t of material is decreased to equal the M_e at the final period of the drying process [34] These rationales, the *M*t profile of FSBM was shown as the sigmoid curve which was controlled by the component *n* of the Page model. Thereby, the Page model presented the best fit when a simulation was done in this study. However, the suitability of a mathematical model for simulating the removal of *MR* is also dependent on several factors such the physical structure of the material, chemical treatment, drying temperature, and drying process [33].

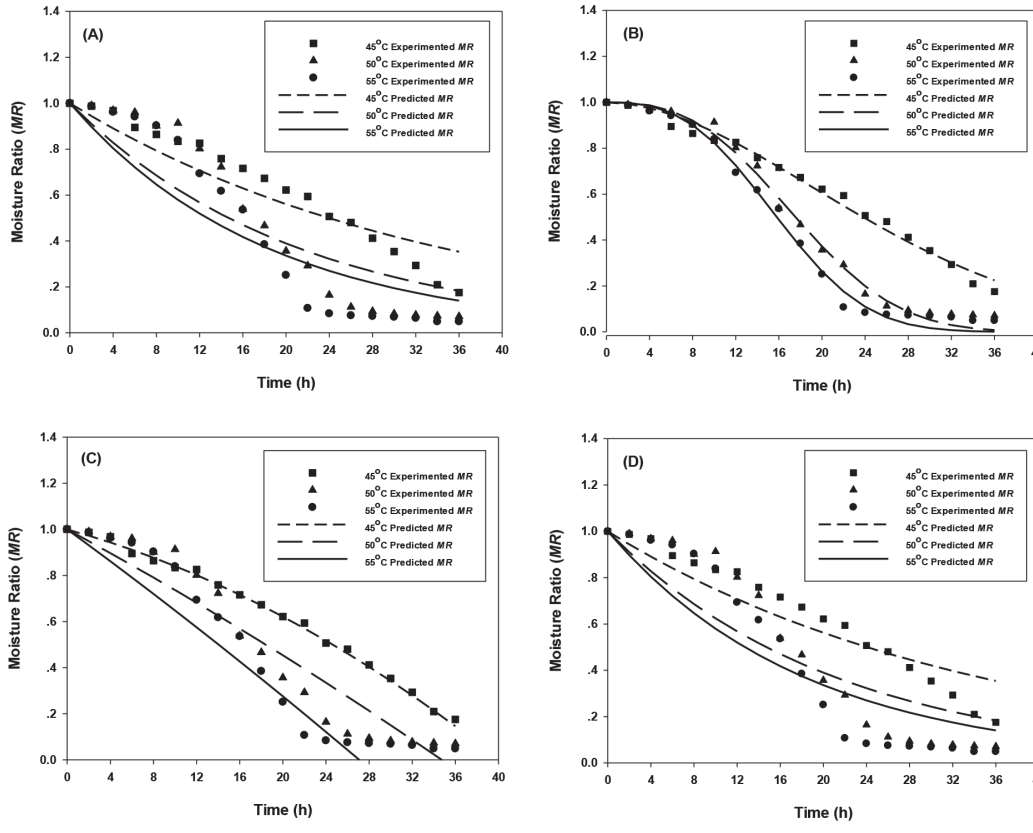

Fig. 4 Experimental MR and predicted MR of FSBM during the HADP. (A) Lewis model; (B) Page model; (C) Parabolic model; (D) Henderson and Pabis model

Table 1 Drying constant and coefficients of mathematical models for FSBM with different drying temperatures

Model	T (°C)	Constants			
Lewis	45	k = 0.0288	R^2 = 0.9969		
	50	k = 0.0471	R^2 = 0.9908		
	55	k = 0.0545	R^2 = 0.9919		
Page	45	k = 0.0019	n = 1.8577	R^2 = 0.9996	
	50	k = 0.0003	n = 2.7010	R^2 = 0.9996	
	55	k = 0.0003	n = 2.7826	R^2 = 0.9996	
Parabolic	45	a = 1.0000	b = -0.0129	c = -0.0003	R^2 = 0.9999
	50	a = 1.0000	b = -0.0253	c = -0.0001	R^2 = 0.9963
	55	a = 1.0000	b = -0.0342	c = -0.0001	R^2 = 0.9961
Henderson and Pabis	45	k = 0.0288	a = 1.0000	R^2 = 0.9969	
	50	k = 0.0471	a = 1.0000	R^2 = 0.9909	
	55	k = 0.0545	a = 1.0000	R^2 = 0.9919	

Table 2 Statistical parameters for hot air-drying mathematical modeling with different drying temperatures

Model	T (°C)	SSE	RMSE	X^2	EF
Lewis	45	0.0075	0.0864	0.0070	0.9969
	50	0.0247	0.1572	0.0260	0.9910
	55	0.0241	0.1552	0.0250	0.9920
Page	45	0.0009	0.0292	0.0009	0.9996
	50	0.0011	0.0326	0.0011	0.9996
	55	0.0012	0.0341	0.0012	0.9996
Parabolic	45	0.0002	0.0128	0.0002	0.9999
	50	0.0101	0.1007	0.0107	0.9963
	55	0.0119	0.1090	0.0125	0.9961
Henderson and Pabis	45	0.0074	0.0865	0.0079	0.9969
	50	0.0247	0.1573	0.0261	0.9911
	55	0.0241	0.1553	0.0255	0.9921

4. Conclusion

FSBM was dried with a simple HADP using a hot air oven. The drying temperature was evaluated and revealed that the moisture content of FSBM was rapidly reduced with an increase in drying temperature. The cell viability of the probiotic strain was slightly decreased at 45°C, and when the FSBM was dried at 55°C cell viability dropped greatly. Comparing coefficient and statistical models, the Page model obtained the highest R^2 and *EF* values and lowest *SSE*, *RMSE,* and X^2 values. This model was selected to characterize the drying process of FSBM under different temperatures. Drying temperatures affected the removal of moisture during HADP.

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