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Controlling the physical and structural properties of soybean powder by the instant controlled pressure drop technology

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Abstract

To achieve the powder quality required by customers for different uses, a new method for producing the soybean powder has been proposed. Soybeans were processed by the instant controlled pressure drop technology (DIC is its French acronym - Détente Instantanée Contrôlée) before being pulverized. The physical and structural properties of soybean powder were controlled through investigating the effects of steam pressure and processing time of the DIC by using the Response Surface Methodology (RSM). The results show that the properties of soybean powder were affected more by steam pressure than by processing time. An increase in the porosity (10.3%), interstitial air volume (36%), compressibility (14.5%); a decrease in the Sauter mean diameter (17.7%), tapped density (15%), and bulk density (17%) were observed after DIC treatment. The modification of soybean grain structure after DIC treatment enhanced the drying kinetics and made the subsequent grinding easier and this implied a significant reduction in energy consumption.

Keywords: DIC treatment, Autovaporisation, Soybean, Powder properties

1. Introduction

The Chinese have been cultivating soybeans for more than 5000 years and have considered them as one of the five sacred crops along with wheat, millet, barley, and rice. In the past, they were used mainly for animal feed and soil enrichment (a natural nitrogen-fixing cover). Today, soybeans are present in many modern foods such as natto, soy sauce, miso, and tempeh [1].

Soybeans are used both as food and as a good source of medicine. Soybeans are the world's leading source of protein and oil. Over 60% of the world's oilseed production belongs to soybeans [2]. The protein content of soybeans is the highest of any cereal or legume (about 35 to 40%). Besides, they contain significant amounts of fat (15 to 20%), carbohydrates (30%), vitamins, minerals, and dietary fiber [3]. Phytochemicals present in soybeans can prevent and treat many chronic diseases.

As the trend of vegetarianism develops, soybeans play a more prominent role in the global food industry. Soybean-based foods are also increasingly diverse, including traditional soy foods, soy ingredients, second-generation soy foods, and foods where soy is used as a functional ingredient [4].

For convenience in processing, soybeans are usually powdered or isolated. The structural parameters of powder such as the porosity, pore volume, mean pore diameter, particle size, and particle size distribution are closely related to functional properties [5]. The physical properties of powder such as the bulk density, compressibility, filling rate, cohesiveness are important parameters for packaging, handling, transportation, and storage. Depending on the needs of the customers and manufacturers, these physical and structural properties of soybean powder need to be controlled and improved. For example, powder with a higher bulk density is desirable for easier transportation, packaging, and storage. In order to achieve a high specific surface area of the powder, the manufacturers always need to produce powders with smaller particle sizes.

Soybean powder on the market today is mainly produced by two methods: spray-drying and grinding after conventional convection drying. The spray-drying technique shows many advantages such as the direct transformation of liquid materials into the dry powder form, a high degree of automation, and a short drying time.

The physical, structural, functional properties of spray-dried soymilk powder were investigated by Nguyen et al. [6]. Osthoff et al [7] also reported on the morphological and chemical properties of spray-dried soymilk powder. Improvement of powder quality through changes in soymilk preparation prior to drying has been studied [8]. Using fluidized bed agglomeration to alter the particle size of soymilk powder was also performed by Jinapong et al [9]. The influence of operational parameters on the volumetric heat transfer coefficient in spray-drying of soymilk powder was also investigated by Nguyen et al. [10].

In some cases, the cost for production as well as the initial investment become a barrier to the application of spray-drying for low-value products like soybeans [11]. The higher price of spray-dried products in the market makes it less competitive than other products. Meanwhile, a method that is easier to operate and less expensive than spray-drying is to grind soybeans after conventional hot air drying. Full-fat soy flour used in the food formulations is mainly manufactured by the conventional grinding process [4]. The problem with conventional ground powders is caused by their more compact structure. The functional properties of powders are severely affected by such a structure [12]. Controlling and improving the physical and structural properties of the ground soybean powder becomes an issue that needs to be studied in order to meet customer requirements in terms of final product quality.

The Détente Instantanée Contrôlée (DIC) technology (instant controlled pressure drop) is considered a very effective technique to modify the structure of foods [13]. This has been proven through many studies carried out on the different products such as green coffee beans [14], dried onion [15], skim milk powder [16], dried cassava [17] and gum arabic [18].

This research aims to introduce the DIC technology into the production process of soybean powder by the conventional grinding in order to improve and control the properties of the final product (density, filling rate, porosity, compressibility, interstitial air volume, cohesiveness, particle size). Controlling these properties will meet the different needs of consumers in terms of product quality. The effects of process variables, i.e., processing time and steam pressure in the DIC reactor on the drying kinetics and physical properties of the final product were also investigated to be able to predict, evaluate and optimize operational parameters when required.

2. Materials and methods

Materials were selected and processed in the DIC reactor according to the experimental design. The obtained powder product was then analyzed according to the methods described below.

2.1 Materials and preparation

Soybean seeds purchased at the local markets have been cleaned before processing. Each experiment in this study was carried out with approximately 400 g of soybeans. Soybean seeds were soaked in water for 24 h at room temperature (19-22°C) and then manually peeled. The peeled soybeans were pre-dried at 35-40°C in a hot-air dryer to a moisture content of about 9.5% dry basis. Then, soybeans were treated by DIC according to the experimental plan. After the DIC treatment, soybeans were dried at 60°C until the moisture content was about 5% dry basis. The dried soybeans were pulverized using a mill Retsch-Grindomix GM 200 at 5000 rpm for 5 min. The dry powder was stored in an airtight bag for characterization analysis.

The DIC reactor (Figure 1). High pressure steam was introduced into a process vessel where the soybean samples were treated for a predetermined time. To be able to perform an instantaneous pressure drop, the DIC reactor used a large vacuum tank and a vacuum pump capable of achieving and maintaining a vacuum of 5 ± 0.1 kPa. The connection between the process vessel and the vacuum tank was ensured by a large-diameter instantaneous valve which can be opened within 0.2 sec.

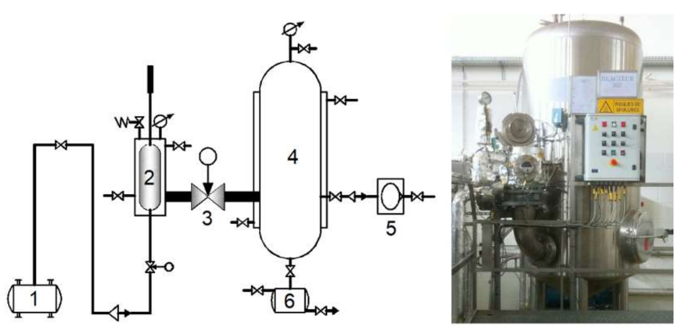

Figure 1 The DIC reactor: 1) steam generator, 2) process vessel, 3) instantaneous valve, 4) vacuum tank, 5) vacuum pump, and 6) condenser.

2.2 Design of experiments

In this work, the central composite experimental design was used to investigate the effect of the operational parameters of the DIC reactor on the different response parameters. The processing time (t) and the steam pressure (p) in the DIC reactor were the two operational parameters studied, while the other parameters such as the initial water content of soybeans (9.5% dry basis) were kept constant. Preliminary trials were performed to determine the ranges of these operational parameters. The experimental plan with 4 factorial points, 4 axial points, and 5 central points was established (Table 1).

Table 1 Experimental (EXP) plan for soybeans.

Points	Coded level of variables		Actual level of variables	
	x_1	x_2	Steam pressure (MPa)	Procesing time (s)
EXP 1	0	0	0.45	70
EXP 2	1.4142	0	0.70	70
EXP 3	0	1.4142	0.45	120
EXP 4	0	0	0.45	70
EXP 5	1	1	0.63	105
EXP 6	1	-1	0.63	35
EXP 7	0	0	0.45	70
EXP 8	-1	-1	0.27	35
EXP 9	-1	1	0.27	105
EXP 10	0	0	0.45	70
EXP 11	-1.4142	0	0.20	70
EXP 12	0	-1.4142	0.45	20
EXP 13	0	0	0.45	70

The x_1, x_2 signify the coded variables that correspond to the actual parameters that are being considered. x represents the coded level of variables.

By using nonlinear regression, the experimental results were analyzed to obtain the following quadratic polynomial:

$$Y = c_0 + c_1 \times P + c_2 \times t + c_{11} \times P^2 + c_{12} \times P \times t + c_{22} \times t^2 \quad (1)$$

2.3 Statistical analysis

The software Statgraphics Centurion XV (Manugistics Inc., USA) was used for the statistical analysis and determination of the constants of the regression equation (c_o, c_1, c_2, c_{11}, c_{12}, and c_{22}). The fit of the regression equations to the experimental data was given by the determination coefficient (R^2). The coefficient of variation (CV) indicates the dispersion of the experimental data and is calculated as the ratio of the standard deviation to the mean. The experiment has a high precision if the CV is below 10%. When the CV is between 10 and 20%, the experiment precision is good. The experiment with the CV from 20 to 30% is considered to have low precision. Finally, the experiment has a very low precision if the CV greater than 30 % [19].

2.4 Powder properties analysis

The soybean powder sample (100 mL) was gently introduced into a graduated cylinder of 250 mL. The mass of this sample was measured, and the mass-volume ratio was calculated to obtain the bulk density (ρ_b) (kg/m^3). This graduated cylinder containing the powder sample was then tapped 1000 times using Autotap Quantachrome (USA). The final volume of the powder sample was recorded in order to determine the tapped density (ρ_t) (kg/m^3). The particle density (ρ_p) (kg/m^3) was measured with a helium pycnometer (AccuPyc 1330, USA) at 25°C. The moisture analyzer Sartorius MA30 (Germany) was used to measure the moisture content of soybean samples (% db).

The compressibility (COMP) expressed in percentage (%) was determined by the CARR formula [20] as follows:

$$\text{COMP}\ (\%) = 1 - \frac{\rho_b}{\rho_t} \quad (2)$$

The filling rate (FR) was calculated from the tapped density and the particle density as shown below:

$$\text{FR} = \frac{\rho_t}{\rho_p} \quad (3)$$

The porosity (ε) was determined by the following formula [12]:

(4)

$$\varepsilon = 1 - \frac{\rho_b}{\rho_p}$$

The interstitial air volume(Vai) (expressed in cm^3) was calculated according to the NIRO method [21]:

$$V_{ai} = 10^5 \left(\frac{1}{\rho_t} - \frac{1}{\rho_p} \right) \quad (5)$$

The cohesiveness of a particulate system was evaluated through the Hausner ratio (HR) which was calculated from the tapped density and the bulk density as follows [20]:

$$HR = \frac{\rho_t}{\rho_b} \quad (6)$$

The particle size distribution was determined as follows: Approximately 100 g of soybean powder sample was placed in a vertical vibrating sieving system (ANALYSETTE 3 PRO Fritsch, Germany). This system consists of sieves 40, 50, 71, 100, 140, 200, 280, 400, 560, 600, 800 µm. After an operating time of 5 min with an amplitude of 2.5 mm, the amount of powder in the sieves was weighed using a precision balance (Sartorius CP2202S, Germany) with an accuracy of 0.01 g.

The Sauter mean diameter (SMD) was calculated using the following formula [22]:

$$SMD = \frac{100}{\sum \frac{f_i}{d_i}} \quad (7)$$

where d_i and f_i are the mean diameter and mass percent of powder in the particle measurement class i.

3. Results and discussion

All properties of soybean powder were calculated for 13 points according to the experimental plan and presented in Table 2.

Table 2 Properties of soybean powder according to experimental plan.

Points	ρ_b (kg/m^3)	ρ_t (kg/m^3)	ρ_p (kg/m^3)	FR	COMP (%)	HR	ε	V_{ai} (cm^3)	SMD (µm)
Control	490.3	684.8	1267.1	0.540	28.40	1.397	0.613	67.11	213.4
EXP 1	408.7	601.0	1262.9	0.476	32.00	1.471	0.676	87.20	208.8
EXP 2	408.0	592.2	1255.6	0.472	31.10	1.451	0.675	89.23	175.6
EXP 3	449.2	623.9	1258.9	0.496	28.00	1.389	0.643	80.85	187.4
EXP 4	425.9	615.5	1262.8	0.487	30.80	1.445	0.663	83.29	210.2
EXP 5	427.2	585.2	1256.7	0.466	27.00	1.370	0.660	91.31	180.0
EXP 6	427.1	597.3	1261.1	0.474	28.50	1.399	0.661	88.11	189.5
EXP 7	419.9	599.9	1266.0	0.474	30.00	1.429	0.668	87.72	209.2
EXP 8	426.4	618.0	1273.8	0.485	31.00	1.449	0.665	83.31	208.3
EXP 9	462.3	651.1	1273.4	0.511	29.00	1.408	0.637	75.05	220.6
EXP 10	411.7	609.9	1264.0	0.483	32.50	1.481	0.674	84.84	207.8
EXP 11	456.0	651.4	1273.8	0.511	30.00	1.429	0.642	75.00	227.4
EXP 12	453.6	623.1	1272.9	0.489	27.20	1.374	0.644	81.94	219.9
EXP 13	417.8	605.5	1265.1	0.479	31.00	1.449	0.670	86.11	205.7
Average	430.3	613.38	1265.2	0.485	29.85	1.426	0.660	84.15	203.9

The regression equations representing the relationship of these properties to the processing time (t) and steam pressure (p) were obtained with an R^2 in the range from 0.70 to 0.92 (Table 3). This indicates that knowing the processing time and steam pressure in the DIC reactor will allow an accurate estimate of the soybean powder properties. The CV from 0.51 to 7.84 shows that the experiment had a high precision.

Table 3 Regression equations for the properties of soybean powder.

Property	c_o	c_1	c_2	c_{11}	c_{12}	c_{22}	R^2 value	Adjusted R^2	CV value
ρ_b	498.448	-148.139	-1.02092	195.618	-1.43198	0.0126477	0.85	0.75	4.35
ρ_t	656.288	-145.964	0.207653	169.228	-1.81158	0.0049	0.92	0.86	3.33
ρ_p	1290.38	-42.4049	-0.13901	16.2401	-0.159998	0.000886	0.92	0.87	0.51
FR	0.507424	-0.0942756	2.23434E-04	0.123197	-1.3599E-03	3.47999E-06	0.90	0.82	2.91
COMP	23.4191	8.18208	0.193185	-12.9601	0.02	-0.001504	0.70	0.50	5.95
HR	1.29659	0.172776	0.0038465	-0.274002	4.80004E-04	-3.025E-05	0.70	0.49	2.51
ε	0.612962	0.105114	7.68672E-04	-0.149198	1.07999E-03	-9.73E-06	0.85	0.74	2.08
V_{ai}	75.0742	31.1311	-0.0565989	-37.8961	0.458394	-1.236E-03	0.91	0.84	5.97
SMD	194.872	86.5414	0.584345	-132.918	-0.86819	-2.4717E-03	0.89	0.81	7.84

CV: Coefficient of Variation.

3.1 Bulk density (ρ_b)

Table 2 shows that, compared with the untreated powder, the bulk density of all samples decreased after DIC treatment. An average reduction of 12.24% was recorded. The largest reduction of about 17% occurred for the soybean sample treated at 0.7 MPa and 70 sec. This reduction is due to the fact that many voids have been created inside the soybeans under the influence of DIC treatment [23]. In the DIC reactor, the instant release of saturated steam toward a vacuum will stimulate the autovaporization of water, which causes the vapor expansion inside the product and may also lead to cell wall rupture [24].

Figure 2A illustrates the effect of two operational parameters on the bulk density of soybean powder. This figure shows that initially as the processing time and steam pressure increased, the bulk density decreased and reached its minimum at the processing time of 78 sec and pressure of 0.66 MPa. Then, if the processing time was extended to more than 78 sec, the bulk density would increase.

This behavior may be due to chemical modifications such as protein denaturation and conversion of insoluble fibers into soluble fibers. The native protein has a lower bulk density than denatured one [25]. Similarly, the soluble fibers have a higher bulk density than the insoluble one, which in turn contributes to an increase in the bulk density e.g., Dalgetty and Baik [26] observed that hulls and soluble fibers exhibited higher densities than did insoluble fibers. Besides, the fragile and porous structure of soybeans after the DIC treatment promotes the formation of many fine particles after pulverization. The fine particles will fill the space between the larger particles and create a new arrangement of the powder.

3.2 Tapped density (ρt)

The soybean powder lost a part of its volume after mechanically tapping. In this study, the tapped density of powder after DIC treatment varied from 585.2 kg/m^3 to 651.4 kg/m^3 and that of untreated powder was 684.8 kg/m^3 (Table 2). These values show that the tapped density of soybean powder decreased after the DIC processing stage. The average reduction was 10.43% and the soybean sample treated at 0.63 MPa and 105 sec showed a maximum reduction of 15%.

The effect of processing time and steam pressure on the tapped density is shown in Figure 2B. The processing time had very little effect. Meanwhile, the tapped density was significantly affected by the steam pressure. When the pressure increased from 0.2 MPa to 0.7 MPa, the tapped density of soybean powder decreased from 651.4 kg/m^3 to 585.2 kg/m^3 the steam pressure is directly proportional to the temperature of saturated steam. The higher the steam temperature (at a given pressure), the more vapour is generated by autovaporization because the temperature difference of the material before and after pressure-drop is a determining factor in the amount of generated vapour. This leads to a higher structural expansion of the soybean. Rochova et al. [27] found the pores with radius of between 5 and 50 μm in the soybean treated with the steam DIC process and the number of large pores grew considerably compared to raw soybean (even 30-fold in the case of pore radius about 10 μm). Kamal et al. [28] also observed a similar trend for coffee beans. This behavior shows the relation between the tapped density and each the bulk density, porosity, and the volume of interstitial air.

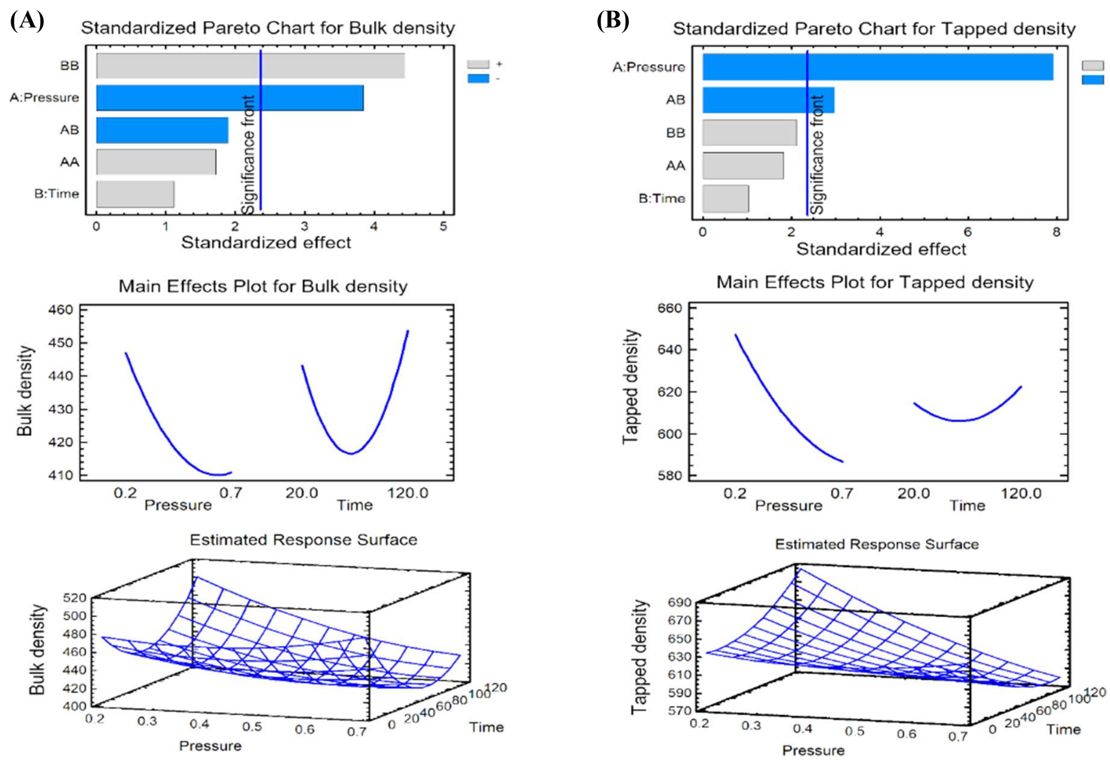

Figure 2 Effect of processing time (s) and steam pressure (MPa) on: (A) the bulk density (kg/m^3); (B) the tapped density (kg/m^3).

3.3 Partical density (ρ_p)

The particle density of soybean powder did not change significantly after one treatment period in the DIC reactor. The particle density of untreated soybean was 1267.1 kg/m^3 and it was reduced to 1265.2 kg/m^3 (average value) after the DIC treatment (Table 2). It means that a very slight reduction of 0.15% was recorded. Such a reduction could be caused by the measurement error.

Regarding the effect of operational conditions, (Figure 3A) shows that the impact of processing time was negligible. Increasing the steam pressure in the DIC reactor also only reduced the particle density of soybean powder to a maximum of 1.4%.

In fact, the particle density, also known as true density, does not consider the pore volume inside the particle and depends only on the chemical composition of the particle material. Soybeans, after processing in the DIC reactor at high pressure/high temperature, may have a slight change in their chemical composition. Some studies have also shown that soybeans can lose lipoxygenase and some volatile components (methanol, ethanal, and ethanol) after a thermal treatment process [29-31]. Besides, protein denaturation and fibers solubilization can also occur [25,26]. This explains the very little change in particle density of the soybean samples in this work.

3.4 Filling rate

Compared with the control sample, the filling rate of the DIC-treated soybean samples was slightly reduced from 0.540 to a mean value of 0.485 (Table 2). An average reduction was 10.3% and a minimum reduction of 5.4% was recorded for the soybean sample treated at 0.2 MPa and 70 sec.

Figure 3B illustrates the effect of processing time and steam pressure on the filling rate of the soybean powder. This figure shows that the filling rate decreased with increasing the steam pressure while the processing time insignificantly influenced the filling rate. In this study, a negligible change in particle density was observed. So, the behavior of the filling rate was similar to tapped density because it was calculated according to formula (3).

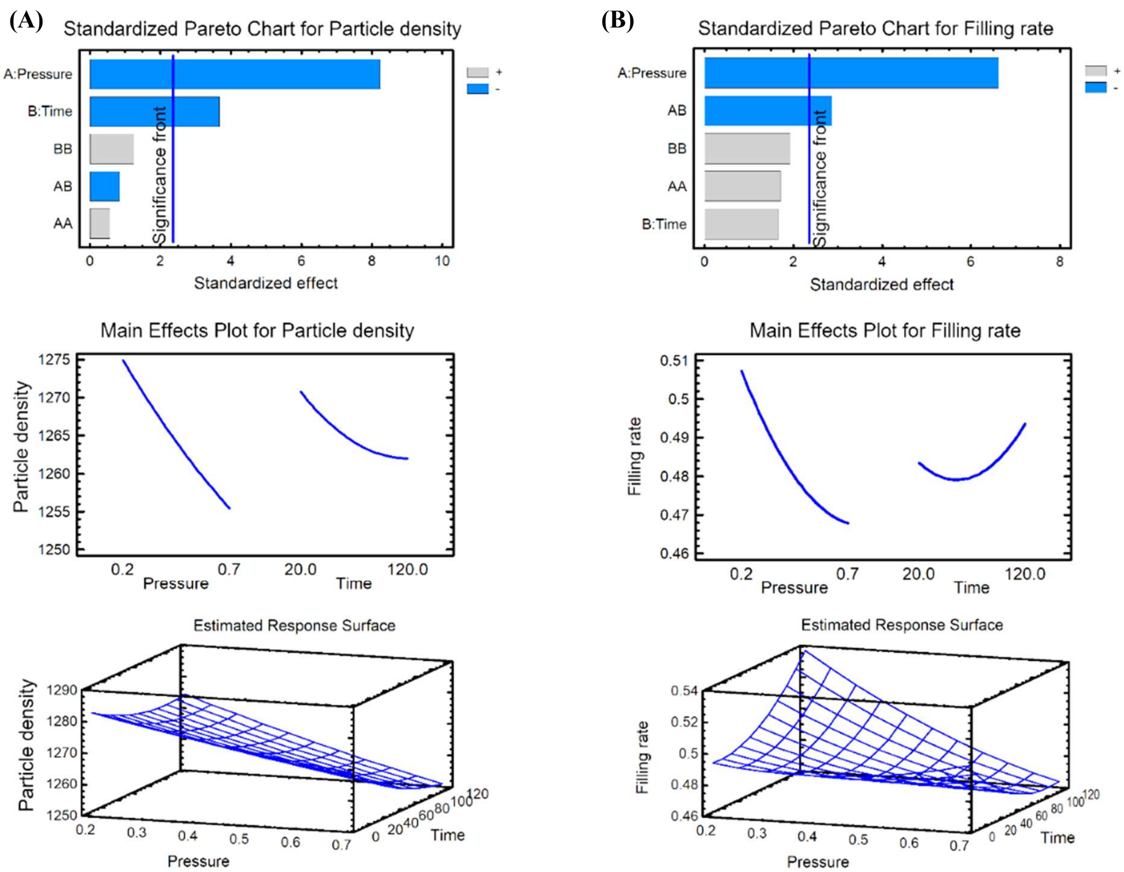

Figure 3 Effect of processing time (s) and steam pressure (MPa) on: (A) the particle density (kg/m^3); (B) the filling rate.

3.5 Compressibility

The compressibility of a powder (expressed as a percentage) indicates how much its volume decrease when compressed. The soybean samples treated in the DIC reactor tended to have higher compressibility than the control sample (Table 2). Generally, the compressibility of powder is inversely proportional to the particle size of samples. The DIC-treated samples showed a smaller particle size than those of untreated sample (Table 2). For example, the soybean sample treated at 0.45 MPa and 70 sec had a compressibility of 32.5% which was 14.5% higher than that of the control sample (28.4%). The average value of all samples was 29.85%. It means that an average increase of 5.12% was found. Kudo et al. [32] also observed a similar behavior for the granulated lactose.

Figure 4A shows that the effect of processing time on the compressibility of soybean powder was more pronounced than that of steam pressure. When increasing the processing time of soybean samples in the DIC reactor until about 67 sec, the compressibility of powder increased. However, if the processing time was extended beyond 67 sec, the compressibility tended to decrease. This tendency is due to the longer processing time which resulted in more fine particles appearing in the soybean powder after grinding.

3.6 Interstitial air volume

The interstitial air volume of the control sample was 67.11 cm^3 and that of the DIC-treated samples varied from 75 cm^3 to 91.31 cm^3 (Table 2), while this volume of spray-dried soymilk powder ranging from 73 to 103 cm^3 was reported by Nguyen et al. [6]. Thus, the DIC processing considerably increased the interstitial air volume by 12% to 36%. The largest increase of 36% belonged to the soybean sample treated at a pressure of 0.63 MPa and a time of 105 sec. The average increase of all 13 samples was 25.4%.

The processing time of DIC treatment had little effect on the interstitial air volume while increasing the steam pressure resulted in a marked increase in the interstitial air volume of the soybean powders (Figure 4B). This is because the effect of steam pressure during the DIC treatment swelled the soybean samples. After grinding into powder, the resulting particles had many spaces and cavities among them.

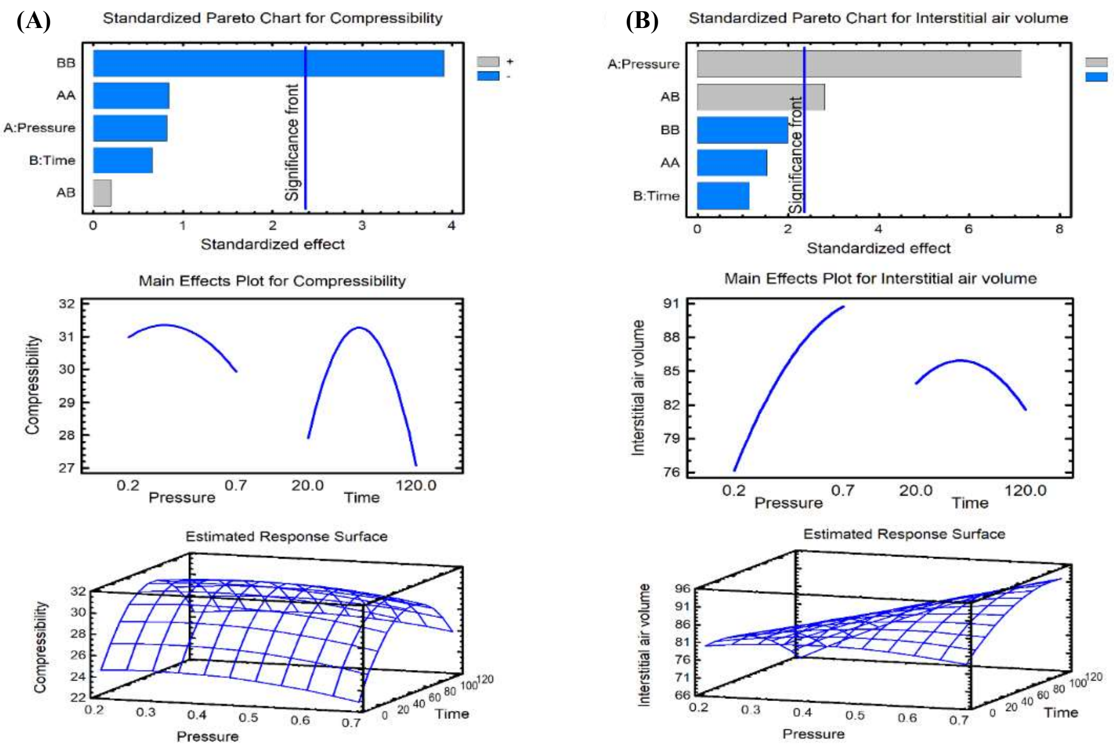

Figure 4 Effect of processing time (s) and steam pressure (MPa) on: (A) the compressibility (%); (B) the interstitial air volume (cm^3).

3.7 Porosity

The porosity of the food powder is normally in the range of 0.45 to 0.7 [12]. The porosity of the soybean samples treated by DIC in this study ranged from 0.637 to 0.676 as presented in Table 2. A slight increase in porosity compared with the control sample was observed. The average increase was 7.7%. The soybean sample treated at 0.45 MPa and 70 sec exhibited the highest porosity with a maximum increase of 10.3%.

Both the processing time and the steam pressure in the DIC reactor affected the porosity (Figure 5A). The porosity of soybean powder increased as these two operational parameters increased. However, when increasing the processing time to more than 74 sec, the porosity decreased.

3.8 Cohesiveness

The cohesiveness of soybean powder in this study was evaluated through the Hausner ratio (HR). The HR values of all powder samples including the samples treated by DIC and the control sample ranged from 1.370 to 1.481 as presented in Table 2. These values indicate that the soybean powder exhibited an intermediate and high cohesiveness [9]. The high-fat content (about 20%) in soybeans may have increased the cohesive forces between the particles and made the flowability of the powder very poor [33]. Table 2 also shows that the DIC-treated soybean samples had a higher HR value (about 2% on average) than the control sample. Similar to the compressibility, the smaller particle size of the DIC-treated samples is responsible for this trend. The soybean sample treated at 0.45 MPa and 70 sec showed a maximum increase of 6%. However, a few samples showed a negligible decrease in the HR value compared to before treatment. The moisture content of the DIC-treated samples was in the range 1.5 % to 5 % (db) and that of the control sample was 4.17 % (db). The HR value decreases as moisture content decreases. This is probably due to the decrease in the number of liquid bridges in the powder samples. Decreasing moisture content causes an decrease in the number of liquid bridges and increases the flowability of powders [34].

The effect of processing time on the cohesiveness of powder was stronger than the steam pressure in the DIC reactor (Figure 5B). Initially, the HR value increased when extending the processing time. Then, if soybean samples were processed longer than 67 sec, the HR value would be lower.

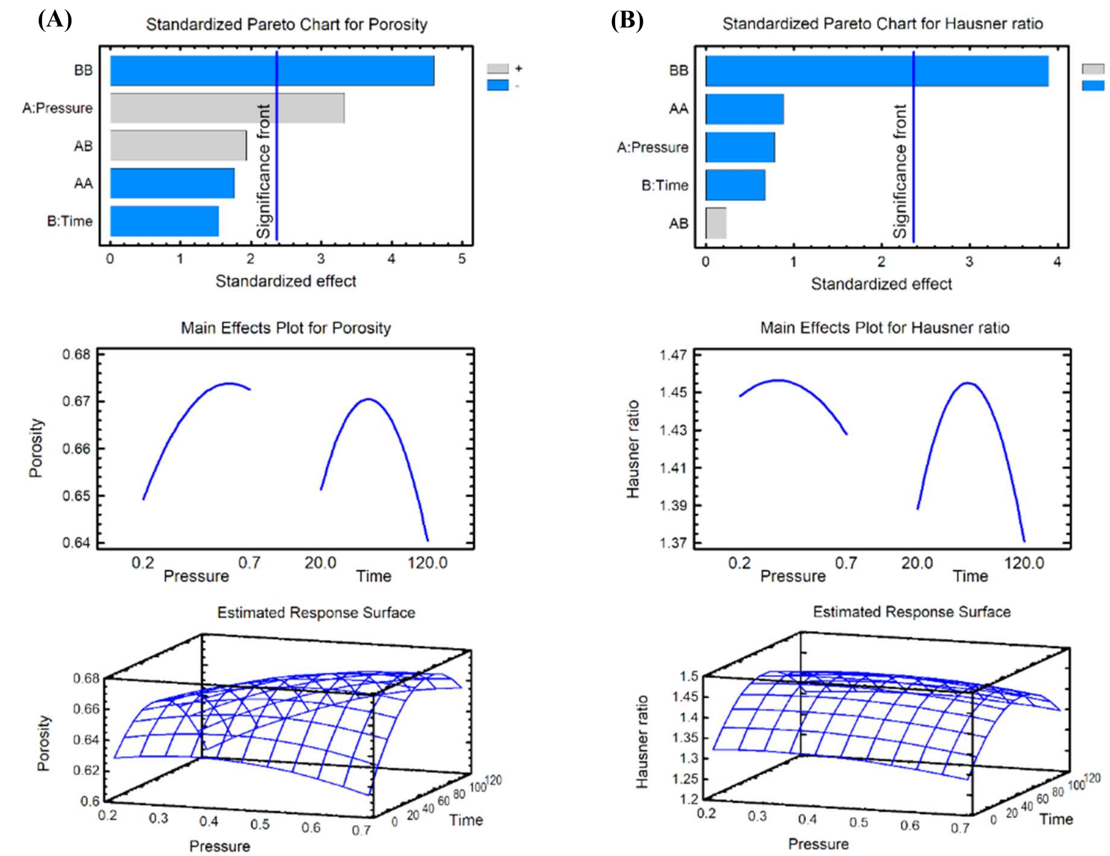

Figure 5 Effect of processing time (s) and steam pressure (MPa) on: (A) the porosity; (B) the cohesiveness.

3.9 Sauter mean diameter and particle size distribution

Figure 6A illustrates the particle size distribution of soybean powder obtained after grinding. The soybean samples became more porous due to the autovaporization of water inside the sample after pressure-drop in the DIC reactor, and the subsequent pulverization was easier than that of the control sample which had a denser texture. As a result, the number of particles smaller than 100 μm and larger than 400 μm in diameter was reduced.

The DIC-treated soybean samples exhibited a narrower size distribution with a more uniform particle size than the control sample. The particle size of 140 μm in diameter accounted for a large proportion. For example, the powder sample treated at 0.63 MPa and 150 sec contained up to 45% of particles with a diameter of 140 μm. Meanwhile, the control sample showed a larger particle size (15% of the particle amount in the range of 400 μm to 800 μm in diameter) and a broader particle size distribution.

In general, the Sauter mean diameter (SMD) of the DIC-treated powder samples was slightly reduced compared with the control sample (Table 2). The largest reduction of 17.7% occurred when the soybean sample was treated for 70 sec and with a steam pressure of 0.7 MPa. The average reduction for all 13 samples was 4.5%. Figure 6B shows that the processing time affected the Sauter mean diameter less than the steam pressure. The SMD value decreased with increasing these two operational parameters of the DIC reactor.

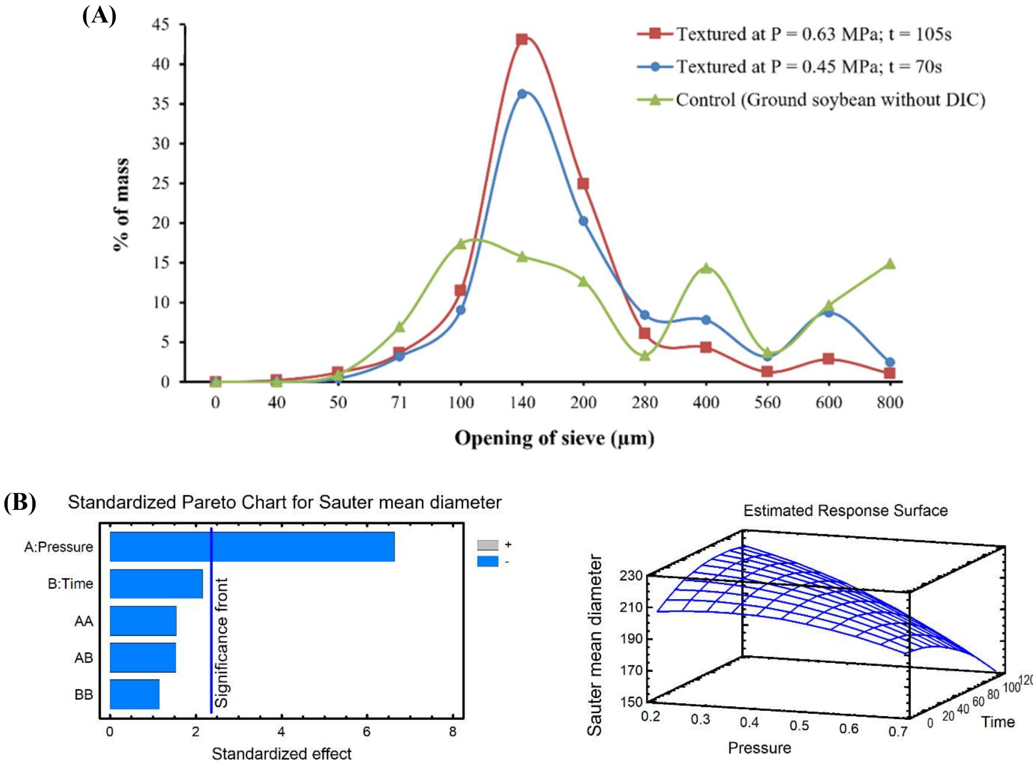

Figure 6 (A) Particle size distribution; (B) Effect of processing time (s) and steam pressure (MPa) on the Sauter mean diameter (µm).

3.10 Drying kinetics

The drying kinetics are illustrated in Figure 7 for both the control sample and the DIC-treated samples. The heat and mass transfer between the drying air and the soybean samples were reinforced due to the porous structure of soybeans after processing in the DIC reactor. The water evaporated from the DIC-treated samples faster than the control sample. For example, the soybean sample treated for 105 sec and with a steam pressure of 0.63 MPa reached a moisture content of 4.17% after only 25 min of drying. The drying time of the sample treated at 0.7 MPa and 70 sec was 40 min. Meanwhile, the control sample needed up to 240 min to reach this moisture content. Thus, the DIC processing significantly reduced the drying time of soybean samples. As a result, the energy consumption would also be reduced.

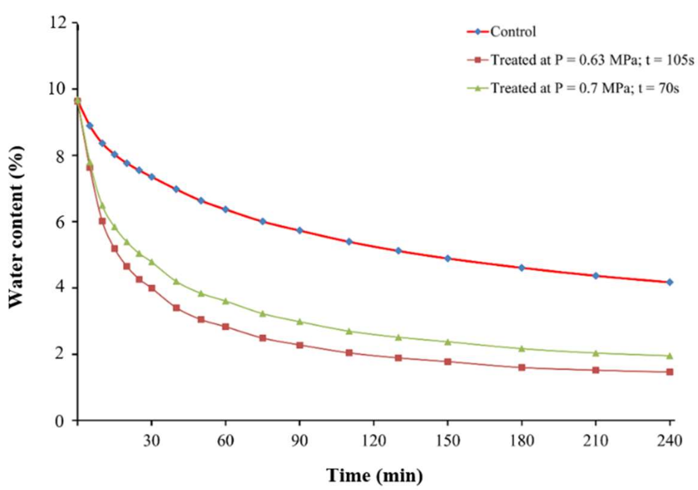

Figure 7 Drying kinetics of soybean at air temperature of 60°C.

4. Conclusion

Controlling the properties of soybean powder could be carried out through a conventional grinding process combined with a DIC processing stage. The steam pressure and processing time were two important operating parameters of the DIC reactor. Thanks to the Response Surface Methodology (RSM), the effects of these two operating parameters on the properties of soybean powder were investigated and the regression equations for the powder properties were found. These equations can be used to predict the physical and structural properties of soybean powder, evaluate the influence of the DIC operating parameters, and optimize them in terms of the product quality. The results show that the steam pressure had a stronger influence than the processing time. Raising the steam pressure in the DIC reactor increased the interstitial air volume and porosity of soybean powder, and decreased the bulk density, tapped density, filling rate, and particle size. Meanwhile, the compressibility, porosity, and cohesiveness of the powder were reduced when the processing time was extended. The DIC processing stage has given soybean a new structure with many internal voids. The obtained powders (which may be called expanded granule powders) were able to overcome the problems caused by the dense structure of conventional ground powders. When compared with the control sample, the properties of the DIC-treated soybean powder could be improved depending on the manufacturer's requirements. The drying kinetics study showed that the drying time was significantly reduced when the soybean samples were subjected to a treatment stage in the DIC reactor. This improves energy efficiency in the production process of soybean powder.

In addition to the physical and structural properties, the quality of soybean powder depends on many other factors such as its nutrition, smell, taste, color, etc. Thus, more extensive, and in-depth studies need to be carried out in future projects in order to better apply this technology at the industrial level.

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