Mechanical Oil Expression from Extruded Soybean Samples

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ABSTRACT: Soybean is generally recognized as a source of edible and industrial oil, and the deoiled meal is seen as a source of protein in animal feed. In recent years, however, more interest has been directed toward using soy meal as a protein source for human consumption. Extrusion-expelling of soybean provides an opportunity in this direction. The main focus of this study was to maximize the oil recovery from extruded soybean processed using three different kinds of extruders and processing conditions. These extruded samples were later pressed uniaxially in a specifically designed test-cell and the oil recovery was recorded over time. The effects of process variables, including applied pressure, pressing temperature and sample height, were investigated. Results indicated that over 90% of the available oil could be recovered from pressing of extruded soy samples. The information generated is likely to be useful in interpreting the effect of process variables and extruding equipment for pretreatment of soybean for subsequent mechanical oil expression.

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KEY WORDS: Edible soy meal, extruded soybean, extrusion-expelling, mechanical oil expression, soybean oil, uniaxial compression.

Soybeans have been thus far considered as a source for crude oil for edible and industrial purposes, and the protein-rich (>50%) meal is seen as a protein source for animal feed. In recent years, however, there has been increasing interest in utilization of soy meal as a protein source for human foods. This is in view of the easy and abundant availability of this quality protein at relatively low cost.

The main constraint in achieving this end has been the lack of an appropriate and efficient method for separating oil from soybean. Presently, the solvent extraction method is the most popular method for separation of oil from soybeans, mainly because of the method's high extraction efficiency (over 99%) as well as its capability to handle large quantities. The main drawback of the method is that, unless highly sophisticated equipment, proper hygienic conditions, and control of process parameters are maintained, the quality of the soy meal produced is not adequate for sustainable human consumption. This is in view of the traces of residual chemical solvents remaining in meals beyond levels acceptable for edible grades. Therefore, the low-fat (<5%), protein-rich (>50% protein) soy flour has to be processed mainly for animal feed.

Alternative oil-separating methods, such as mechanical oil expression, appear to have potential for producing chemical-free, edible-grade defatted soy flour suitable for human consumption (1). However, mechanical oil-expression equipment and processes presently available are not considered adequate for this purpose, as their oil extraction efficiency is quite low (<70% oil extraction). These need to be improved so that no more than 5% oil remains in the deoiled meal to make this process economically viable. Extrusion has been reported to be a promising pretreatment to mechanical expelling of soybean oil (1–3).

Extrusion cooking offers a convenient method for tissue disruption and heating in a slight fraction of time through a single-step operation. High-pressure, high-temperature extrusion through small openings converts raw oilseeds into cooked and partially inflated particles known as collets. The porous collets are larger, heavier and stronger, and handle better than traditionally prepared materials in mechanical screw presses. The high-temperature (125–135°C), short-duration (7–30 s) treatment contributes greatly to the retention of the nutritional value of the products while effectively inactivating oil-damaging enzymes before they adversely affect oil quality (1–2).

Nelson *et al.* (1) coupled dry extrusion with continuous screw pressing of soybean to extract oil. The coarsely ground whole soybean at 10–14% moisture content was extrusion cooked. The extrudate that emerged from the die in a hot semifluid state was immediately pressed in a continuous screw press. This approach was reported to greatly increase the oil recovery (up to 70% in a single pass) as well as the throughput of the expeller over the rated capacity. For the experimental conditions used, press cake with 50% protein, 6% residual oil, and 90% inactivation of trypsin inhibitor was obtained. Besides the edible low-fat soy meal, the oil obtained from the process had remarkable stability and improved flavor compared to solvent-extracted oil.

Isobe *et al.* (3) combined the extrusion and expelling operation by developing a twin-screw for oil extraction from

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oilseeds with a view to improve upon screw press performance. The dehulled sunflower seed without pretreatment (cooking or crushing) gave 93.6% oil recovery with the twin-screw press, in contrast to 20% oil recovery with the single-screw press. Besides this, the energy consumption for the overall process was much lower while the quality of oil and meal obtained was superior.

Some leading screw press manufacturers have initiated the development of modified extruders for cooking of oilseeds (2,4). Application of such equipment has so far been restricted to the solvent extraction technique for oilseeds, in which the oilseeds are converted to collets using extruders prior to their solvent extraction. Such an approach has been reported to enhance plant capacity and quality of oil and cake, and to reduce the solvent and energy requirements of these plants (2). Application of the extrusion-cooking technique to oilseeds prior to their mechanical pressing has remained isolated and, therefore, experimental data on these aspects have been lacking.

The research presented in this paper proposed to study the effect of method and equipment used for extrusion of the soybean samples prior to mechanical compression. In addition, during uniaxial compression of these extruded samples, some of the process variables such as pressing temperature (22, 60, and 90°C), applied pressure (20, 40, and 60 MPa), and initial sample height (8 and 16 mm) were included with a view to maximize oil recovery from these samples (5). The levels for these variables were selected based upon a review of the literature (6–8).

MATERIALS AND METHODS

Procurement of extruded soybean samples. Over half a dozen soybean processors in North America were approached to supply extruded soybean samples along with the details of the process followed for producing extruded soybean samples. From among these, three extruded soybean samples, each weighing about 15 kg, were procured for this study. These commercial samples were prepared using extrusion equipment manufactured by three different companies. The postharvest processing steps for each of these samples also varied, and are briefly described in the following section based on information provided by the soy processors. The samples will be referred to as samples A, B, and C to maintain anonymity.

Sample A. The soybeans were cleaned and dehulled using a high-temperature dehuller, followed by conditioning and then flaking. The flakes were then fed to the extruder (Model-10" DOX™ dry expander, Anderson International Corp., Cleveland, OH), where the samples attained a maximum temperature of about 150°C and the retention time was about 20 s. The extrudate exited in the form of expanded, porous, cylindrical-shaped pieces with an average diameter of 20 mm and a length of 50 to 100 mm. The sample was bright yellow in color.

Sample B. The soybeans (U.S. Grade 2) were cleaned, dehulled, conditioned, and flaked prior to feeding into a cone discharge expander (Model-Exp 250-10"; Group Tecnal, Rodovia Raposo Tavares, Ourinhos, Brazil). During the extrusion process, the samples were subjected to an average pressure of about 4 MPa, a maximum temperature of about 108°C, and a retention time of 120 s. The extrudate, which exited from the extruder in the form of chunks and cake, was air-cooled to about 65°C. The sample was in the form of small to large chunks and had a bright-light yellow color.

Sample C. Cleaned soybeans were fed into the extruder (Model-2000R; Insta-Pro Division of Triple "F" Inc., Des Moines, IA) where they were subjected to a maximum temperature of about 150°C. The total retention time inside the extruder was about 25 s. The heated extrudate exited from the extruder in granular powder form, having a moisture content of 7.5–8% (wet basis). On cooling, the sample had about 3–4% moisture content (wet basis). The sample was in the form of granular powder with a dark yellow color. The mixture had some pieces of broken soybeans of about one-sixth to one-eighth of the normal soybean kernel size.

Proximate analysis of the extruded soybean samples. A proximate analysis was performed on all three extruded soy samples following procedures of the American Association of Cereal Chemists (9). The moisture content of the sample was kept constant. To achieve this objective, all other samples were dried to a constant moisture level of 3.7% (for sample B), which was the lowest value among these samples. A hot air oven (Thelco, Model-28; Precision Scientific, Chicago, IL) set at 60°C was used for this purpose. To attain the desired moisture content of 3.7%, the samples were placed in the oven and were weighed every 10 min until the sample weight reached the desired value. The dried samples were then stored in air-tight glass bottles to maintain their moisture level until use.

Experimental setup. A specially designed compression-permeability test-cell was used to measure the oil recovery over time from different extruded soy samples compressed uniaxially under different constant loads. Figure 1 shows several views of the cell, its installation on the Instron machine, and details of the sample mounting components (described below). The test-cell was mounted through the threads provided in its base (Fig. 1a) to an Instron machine (Model 1137; Instron Corporation, Canton, MA) capable of applying compressive loads up to 150 kN (accuracy ±5% full scale) with cross-head speeds ranging from 0.05 to 500 mm/min (accuracy ±1% of set speed). The cylindrical block of the test cell has a 37.5 mm diameter × 100 mm deep bore through which a loading piston compresses an oilseed sample. The loading piston of the cell is provided with threads on one end, by means of which it connects to the cross head of the Instron machine. The other end of the piston is used to apply a compressive load to the extruded soy sample contained inside the cell. The loads can be held constant over time through holding the knob at a precalibrated mark on the graphical display provided on the Instron machine. The applied load on sample during compression can be read, to the nearest 1 kN, through the load display window provided on the machine control panel.

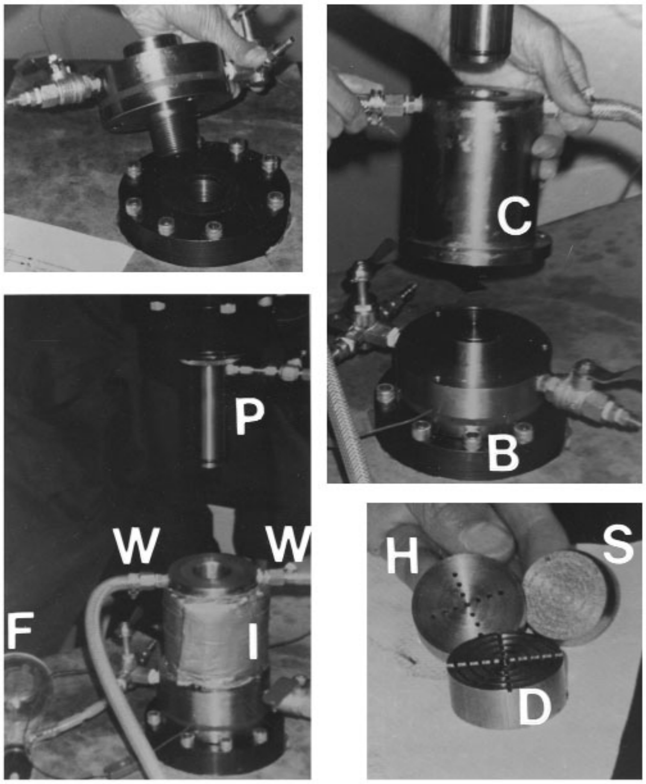

FIG. 1. Assembly of compression-permeability test-cell apparatus. From top left, clockwise: (a) Mounting test-cell base unit to Instron machine baseplate. (b) Assembling cylindrical main cell body C to base unit B. The valves to the oil extraction plumbing system are seen protruding from the base unit. The thermocouple wire can also be seen extending from the forward left side of the base. (c) Elements of the oilseed sample holder: porous stone S with holding cup H, and die with spiral groove D. (d) Completely installed test-cell with insulation I, hot-water circulating system inlet/outlet pipes W, collecting flask F, and loading piston P.

To maintain a constant test-cell temperature during the experiments, a thermostatically controlled hot water bath incubator (Model-M3; Lauda, Germany; temperature range −20°C–122°C) was used to continuously circulate water through channels provided in the periphery of the test-cell body. Glycol was added to the water, up to 70% by volume, to raise its boiling temperature to 110°C. Cell temperatures up to 90°C could then be achieved. The cell was insulated around its periphery using fiberglass covered with insulating tape. To minimize heat transfer to the base of the Instron machine through the test cell thread, a special insulating material, 6 mm thick, made of glass-epoxy laminate (Phenolite-natural grade-G-10, compressive strength-450 MPa, NVF Industries of Canada Ltd., Rexdale, ON, Canada) was used in the mounting plate. To measure the temperature of the cell, an ANSI Type-T thermocouple (Duplex insulated, Copper-Constantan; maximum temperature, 200°C; insulation, Neoflon FEP; AWG 24, accuracy ±0.1°C; Omega Engineering Inc., Stamford, CT) was placed on the top of the cell base and secured just below the sample using an epoxy adhesive. It is expected that at equilibrium the temperatures of the cell and sample approach the same value. The thermocouple was connected to a digital display thermocouple thermometer with 1°C resolution (Model-660; Omega Engineering Inc.).

When a sample is compressed, oil is extruded through a porous bronze stone (No. S1602B; Geotest Corporation, Evanston, IL) and a 20-mm thick die with a 4-mm transverse channel (Fig. 1c) into the collection system built into the base unit of the test-cell. The upper surface of the die has spiral grooves to facilitate smooth movement of oil expressed from the sample into the collection channels. The base of the test-cell is provided with a 4-mm diameter opening for flow of oil expressed from compressed, extruded soy samples. The upper end of the collection channel is connected to a one-way valve, while the lower exit is connected to a suction pump (Cenco Hyvac, Central Scientific Company, Chicago, IL) through a two-way valve (Fig. 1b). The second port of the two-way valve is connected to a flask for collecting expressed oil. For efficient collection of the expressed oil, a vacuum of 700 Torr (absolute) is applied through the two-way valve into the drainage channel. The second port of the valve is used to release the vacuum to flush out the smallest possible quantity of oil into the weighing flask. A digital top pan balance with a 0.001 g resolution (Model-GT480; OHAUS, Florham Park, NJ) was used to weigh the conical flask, which was tared prior to collection of the expressed oil. Pressing time was monitored using a digital stopwatch (0.01 s resolution).

Experimental procedure. The experiments involved uniaxially loading each type of extruded soybean for two different sample heights at selected temperatures and pressures (Table 1). To supplement the literature review (5–8), preliminary experiments were conducted to arrive at various levels of considered variables. The oil recovery tests were designed so that one level of each parameter was tested against every level of all other parameters.

TABLE 1
Variables and Experimental Design for Measurement of Oil Recovery from Three Extruded Soy Samples Pressed Under Uniaxial Compression

Variables	Levels
Extruded soy samples	3 (extruded through three different kinds of extruders)
Pressing temperature	3 (22, 60, 90°C)
Applied pressure	3 (20, 40, 60 MPa)
Sample heights	2 (8 and 16 mm, obtained using 10- and 20-g samples, respectively)
Moisture content	1 (3.75% wet basis)
Deformation rate	1 (20 mm/min)
Measurement intervals	6 (60, 120, 240, 420, 720, and 1200 s)
Replications	3
Experimental design	
Design	Randomized complete block design with three blocks (time)
Treatment design	$3^3 \times 2^1$ factorial
Response design	Repeated measures of oil recovery over time

The base of the test-cell was mounted on the Instron machine and the cylindrical top portion was attached to it using three equidistant screws (threadholes are visible in Fig. 1b). For each experiment, the die was placed into the cylinder bore, followed by the porous stone enclosed in a stainless steel holding cup (Fig. 1c), on top of which a filter paper (No. 4, Whatman International Ltd., Maidstone, Kent, United Kingdom) cut to the size of the diameter of the cylindrical bore was placed. The steel holder prevents lateral deformation of the porous stone when subjected to high loads. The purpose of the filter paper was to prevent entry of solids from the oilseed sample into the perforations of the porous stone. A weighed extruded-soy sample (10 or 20 g to obtain shallow and deep initial sample heights, respectively) was then poured into the bore of the test-cell onto the filter paper. A 5-mm thick, 37.5-mm diameter steel disk was then placed above the sample and just below the loading piston. The sample was loaded by the piston in one direction, vertically, for a uniaxial compression.

With the test apparatus assembled and the sample in place (Fig. 1d), a deformation rate of 20 mm/min was selected and the Instron cross-head drive was set for compression mode. This deformation rate is similar to those found in screw presses (10). The piston travel was stopped as soon as the load reached the desired value, after which the load was held constant for 1200 s. At time intervals of 60, 120, 240, 420, 720, and 1200 s the vacuum was released and the flask weighed to determine the oil yield. Prior to each weighing, the flask was disconnected from the suction line and placed on the top pan balance to record the increase in the weight of the flask. The oil recovery was calculated as the percentage ratio of the oil collected at the corresponding time to the original sample oil content.

The data generated were analyzed using the multivariate analysis of variance for repeated measures over time. In multivariate analysis, responses at each time are considered to be separate response variables. The General Linear Models (GLM) procedure available in SAS (11) was used for this purpose.

RESULTS AND DISCUSSION

Proximate analysis of samples. Results of the proximate analysis of the three extruded soy samples used in the present study are presented in Table 2. The values of total dietary fiber (TDF) in samples A (13.9%) and B (13.8%) are lower because dehulled soybean were used in preparation of these samples. When soybeans with hulls were used for extrusion, as in the case of sample C, the TDF content was much higher (16.6%).

The presence of hulls in sample C would produce a deoiled meal with much higher fiber content. Such meals would be more appropriate for lower digestible energy livestock rations such as maintenance feeds for mature poultry and pigs. The presence of hulls also appeared to affect the color of the extruded sample adversely. The sample C was much darker and had burnt brown spots in contrast to the bright-yellow color of samples A and B. This may be due to partial burning of hulls when subjected to high temperature (150°C for 20–30 s) during extrusion.

Uniaxial pressing of extruded soybean samples. The results of experiments on oil recovery from the extruded soy samples A, B, and C are classified on the basis of the effect of method of extrusion, applied pressure, pressing temperature, and sample height. These are presented in the following sections.

(i) Effect of method of extrusion. Among the three samples considered, the maximum oil recovery was obtained from the sample A for all the pressing conditions considered in the present study. The comparison of means of oil recovery from the three samples also indicated that sample A provided significantly higher levels of mean oil recovery at all six time intervals. This was followed by the values of oil recoveries for sample B.

The maximum oil rate of 90.6% was recovered when a pressure of 40 MPa was applied to sample A of shallow (8 mm) height at a pressing temperature of 90°C for 1200 s (Fig. 2). For sample B, the maximum oil recovery (80.4%) was obtained for the same pressing conditions, but in case of sample C, the maximum oil recovery was obtained when the pressure was 60 MPa rather than 40 MPa. However, the difference in the values obtained at these two pressures was not significant ($P < 0.05$). Hence, an applied pressure of 40 MPa, a pressing temperature of 90°C, and a shallow sample height (8 mm) was considered to be the optimal uniaxial pressing condition for oil expression from the extruded soybean samples.

The residence time inside a screw press is generally about 120 s (12). Therefore, the oil recoveries for the three extruded sample types at this time interval were compared. Of the total available oil, 61.6% was recovered from sample A at the end of 120 s of pressing. Under similar pressing conditions (7), when whole soybeans were pressed without any pretreatment, a negligible quantity of oil was recovered, while from soyflakes oil recoveries of 40.6 and 43.0% were obtained after 240 and 360 s of pressing, respectively. The significant improvement in oil recoveries from extruded soybean samples could be attributed to the rupture of the cell walls during pretreatment when a sample was passed through an extruder.

TABLE 2
Proximate Analysis of the Three Extruded Soybean Samples (expressed in % wet basis)[a]

Sample	Moisture content	Crude fat	Crude protein	Ash	Total dietary fiber	Other[b] constituents by difference
A	3.75 ± 0.08	21.42 ± 0.04	39.55 ± 0.18	4.65 ± 0.01	13.9	16.77
B	3.73 ± 0.08	22.13 ± 0.05	39.76 ± 0.15	4.72 ± 0.05	13.8	15.87
C	3.74 ± 0.09	20.63 ± 0.02	39.54 ± 0.10	4.67 ± 0.05	16.6	14.82

[a]Average of two replications, except for total dietary fiber values which are based on one determination.
[b]Other constituents include sugars, phytate, starch, polar lipids, and volatile matter.

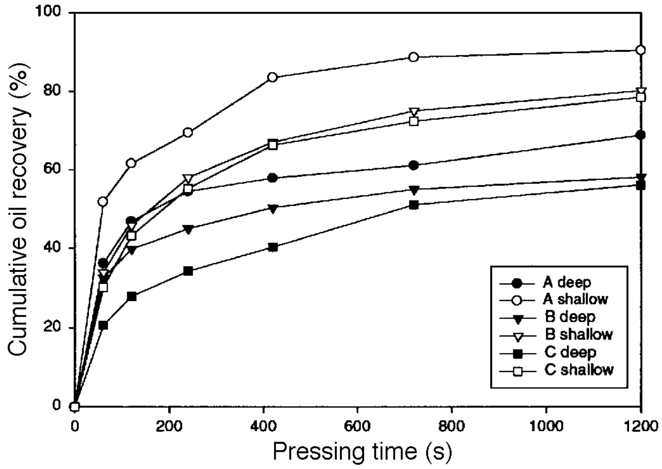

FIG. 2. Effect of sample heights (shallow and deep) and pressing time on oil recovery from three extruded soybean samples (A, B, and C) pressed at an optimized pressing condition of 40 MPa applied pressure and 90°C pressing temperature.

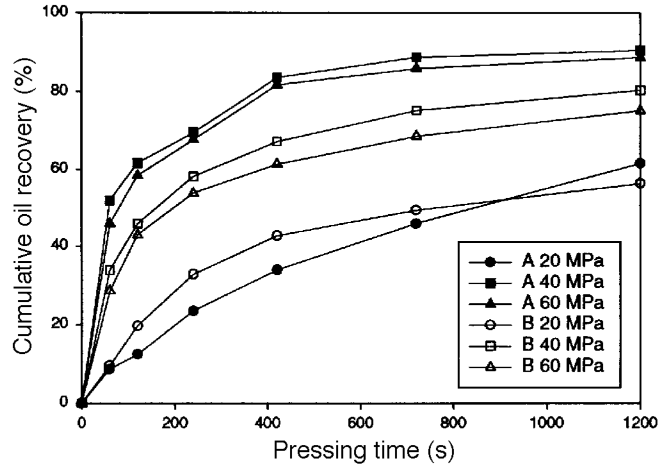

FIG. 3. Effect of applied pressures and pressing time on oil recovery from shallow (8 mm) extruded soybean samples (A and B) compressed at an optimized temperature of 90°C.

It is likely that if these extruded samples were pressed instantaneously, i.e., as soon as they exited from the extruder in hot semifluid condition, similar high levels of oil recovery could be attained in even shorter pressing times (5).

The comparison of means shows that, with respect to oil recovery, the three samples were significantly different ($P < 0.01$). This inference was supported when the means of oil yield based on t-tests and Least Significant Difference (LSD) at 5% significance level were compared. This indicated that equipment and preprocessing operations adopted during extrusion significantly affected oil recovery during subsequent mechanical pressing.

(ii) Effect of sample heights. The shallow samples (8 mm) yielded significantly ($P < 0.01$) higher oil recovery for the three samples when compared with deep samples (16 mm) (Fig. 2). A comparison of means of sample heights also indicates a significant difference between oil recoveries obtained from the two sample heights. This was found to be true for almost all the pressing conditions studied except for the oil recovery measured at time interval of 60 s, when the difference between the means was insignificant ($P = 0.38$). This trend of higher oil recovery from shallow samples would be in part because, in samples with shallower height, the compression is more uniform throughout the thickness of the sample. In addition, the drainage length for the oil is shorter. In the case of deep samples it appears that although the oil globules exited from the ruptured cell walls, they were entrapped by the solid particles. Similar findings have been reported for groundnut kernels (13), cottonseed (14), and soybeans (15).

(iii) Effect of applied pressures. There was a consistent increase in oil recovery when the applied pressure was increased from 20 to 40 MPa for all the experimental conditions and samples considered (Fig. 3). However, a further increase in applied pressure from 40 to 60 MPa seems to have a temperature-dependent effect on oil recovery. At temperatures up to 60°C, there was a consistent and significant increase in oil recovery as the applied pressure was increased from 40 to 60 MPa. At a temperature of 90°C, an increase in pressure from 40 to 60 MPa had a negative effect on oil recovery. When the means for three samples pressed at 40 MPa and 60 MPa and a temperature of 90°C were compared, the oil recoveries under 40 MPa applied were insignificantly higher ($P > 0.05$) than those of samples compressed at 60 MPa for most of the time intervals. These results indicate that excessive pressure does not necessarily have a positive influence on total oil recovery. A similar observation was made by Hamzat and Clarke (13) while pressing groundnuts. A more predominant temperature and pressure interaction at higher levels of these factors was observed. Such an interaction may be understood from the fact that increasing temperature decreases the viscosity of the flowing oil and thereby increases its flowability, while an increase in applied pressure has the opposite effect. Based on the results obtained, it seems that the optimal range of applied pressure for uniaxial compression of soybeans lies between 40 and 60 MPa. For purposes of this study a pressure of 40 MPa was considered to be an optimum.

(iv) Effect of pressing temperatures. An increase in pressing temperature increased oil recovery consistently for the three samples and all considered pressing conditions (Fig. 4). In all cases, a temperature of 90°C was found to maximize oil recovery. An increase beyond this temperature might have further enhanced the yield; however, in considering the reported adverse effects of temperatures above 100°C on the quality of expressed oil and deoiled cake (16), higher temperatures were not considered. The positive effect of temperature on oil recovery has also been reported for soybean flakes (7), cottonseed (14), cashew, and rapeseed (17). A comparison of means also indicates that the oil recoveries were significantly different ($P < 0.01$) at varying pressing temperatures. The interaction of temperature with other variables and their combinations were also significant.

The analysis of variance further indicates that there were no significant differences among the replicate experiments

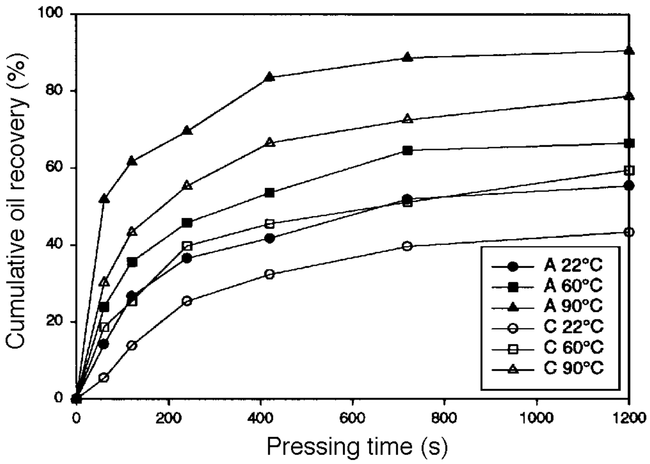

FIG. 4. Effect of pressing temperature and pressing time on oil recovery from shallow (8 mm) extruded soybean samples (A and C) compressed using an optimized pressure of 40 MPa.

conducted at different times. In addition to the significant effect of the main factors, the interaction between temperature and pressure (T × P), sample height and pressure (H × P), sample height and temperature (H × T), and other second- and third-order interactions were highly significant ($P < 0.01$). Similar significance of the main factors and interactions have been reported for soybean flakes and soybeans with hulls (7). The high significance of most of the factors was not surprising, as the examined independent variables and their levels were selected based on previous research (6–8).

The significant time effect could be due to the fact that the soybean is basically a hard-to-press oilseed with a low oil content. The movement of oil globules through the compressed cake while under high pressure is a continuous but slow process. While the increased pore pressure and the reduced viscosity (due to increased temperature) promote the movement of oil through the cake, compression of the solids in the cake reduces the porosity and restricts the flow of oil. The resulting discontinuity of pores makes the flow of oil through the cake a time-dependent process. When two oil globules are joined, they make a capillary and tend to flow through a tortuous path until they exit from the cake. An oil recovery of about 91% would appear to be the maximum possible oil that could be recovered through uniaxial pressing of these extruded samples as, during the last 480 s of pressing, only 1.8% oil was recovered. It has also been observed by earlier researchers (13,18–19) that there exists an upper limit on oil that can be recovered from a given oilseed by mechanical pressing.

The use of extrusion as a pretreatment was found to significantly enhance oil recovery from the soybean samples. Of the three types of extruded soy samples evaluated, sample A was found to give a maximum oil recovery of 90.6% after 1200 s of pressing. The "optimum" levels of pressing variables considered for all extruded soybean samples were: a shallow sample height (8 mm), a moderate applied pressure (40 MPa), and a high pressing temperature (90°C). The extrusion and pressing unit operations, sample height, applied pressure, temperature, pressing time, and second- and third-order interactions among these variables were found to significantly influence the oil recovery from the soybean samples.

Commercial application of extrusion-expelling technique. Mechanical expression of oil from soybeans at the commercial level has considerable potential, particularly in the developing countries where protein malnutrition is prevalent and oil extraction facilities are decentralized. In these countries, a much smaller quantity of soybean is available for processing at the rural level and, therefore, installation and operation of a solvent extraction plant is often not feasible. The development of a small-scale integrated extrusion-expelling unit, capable of extracting nearly 70% of the available oil, would provide an opportunity for production of edible grade, low-fat (<6%), protein-rich (>50%), excellent quality soy flour at much lower cost. Such flour could then be blended with local traditional popular foods for enhancement of their protein content.

India, which produces about 5 million tons of soybean annually, is a good example. About 85% of the soybean crop is currently used for oil extraction by the solvent extraction technique. The protein-rich meal produced using this process is considered unsuitable for food uses due to unacceptable levels of residual solvent and high microbial loads. The meal is therefore exported at a very nominal price to be later processed for animal feed. If this soybean were to be processed using mechanical means, an additional 1.5 million tons of edible grade, good quality protein would be available annually. This would go a long way in combating the protein-malnutrition prevalent in this country.

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