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Abstract
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Chapter 4

Extrusion-Based Oilseed Processing Methods

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Introduction

Oilseeds occupy an important place in global agriculture by providing vegetable oils and high-protein meals for food, feed, and industrial uses. The leading oilseed crops by volume of world production are soybean, cottonseed, peanut, sunflower, rapeseed (canola), copra (coconut), and palm. The combined world production of these major oilseed crops in 2001–2002 was 324 million metric tons (MT) (1). Soybeans constitute the largest share of the world oilseed supply, accounting for 57% of global production in 2001–2002. The United States, Brazil, Argentina, People's Republic of China, and India dominate world soybean production. Together, these countries account for approximately 90% of the world soybean crop. Production of other oilseed crops is widely distributed throughout the world.

The oil content of oilseeds varies considerably among crop species, cultivars within species, and the agroclimatic conditions under which they are grown. The approximate oil contents of soybean, cottonseed, peanut, sunflower, rapeseed, copra, and palm kernel are 20%, 23%, 45%, 40%, 35%, 67%, and 50%, respectively (2). The economic exploitation of oilseeds begins with the primary process of separating oil and protein meal. The technology of oil separation has evolved with the progressive development of oilseed production from a subsistence agricultural practice to an extensive commercial agricultural enterprise. During the same period, the technology of oil separation has progressed from primitive manual methods to mechanical methods and to chemical methods using organic solvents. Today, solvent extraction using hexanes is the method of choice for large-scale oil extraction from oilseeds.

However, agriculture is becoming an increasingly competitive enterprise on a global basis, dictating the need to add value close to the crop production point for survival in the marketplace. New awareness of the nexus between diet and health on the one hand and food and environmental safety on the other has created opportunities for food processing without the use of chemicals. These circumstances have stimulated development of a new approach to oilseed processing by using mechanical means based on extrusion technology as an alternative to the use of organic solvents.

Historical Development of the Separation of Oil from Seeds

Oil is the storehouse of energy for the seed embryo's natural function of germinating into a new plant. Oil occurs in specific sites at the subcellular level within the seed tissue. For example, in soybeans the oil and protein are packed within the palisade cells of the cotyledon in spherosomes and protein bodies, respectively (3). Therefore, the ability to extract oil from the seed depends on disruption of the cellular structure within which the oil is naturally protected. The degree of rupture of the cell walls and spherosome membranes is one of the critical factors determining the efficiency of oil extraction by all methods.

Mechanical and Hydraulic Devices

In the early period of development, heat was used to condition oilseeds for extraction. Heat conditioning dries the seed and denatures the protein and reduces the viscosity of the oil. The first author of this chapter has witnessed seed being prepared by the crushing of oilseed using mortar and pestle followed by steaming in open vessels. The steamed mass was packed while hot into sock-shaped baskets of intricately woven cane. The basket was held inside the borehole of a large log. The oil was pressed out by driving a wedge between the basket and the side of the borehole. The next development in oilseed extraction technology was hydraulic pressing devices. High-oil–bearing seeds were dry heated in open pans or in steam-jacketed vessels. The material was then pressed in perforated baskets by gradually applying hydraulic pressure. Both of these methods were batch systems and labor intensive.

Screw Presses

The next development occurred around 1908 with the development of continuous screw pressing, a practice that is still widely prevalent outside the United States. The screw press consists of a flighted screw rotating within a slotted barrel. It is also often referred to as an "expeller" in the industry, but this is actually a trademarked term used to denote a specific manufacturer's screw presses. The barrel is of fixed diameter and the root diameter of the screw increases from the feed end to discharge end. This design achieves increasing pressure by compensating for volume reduction due to product compaction, thereby achieving oil removal through the slotted barrel while retaining the partially defatted solid mass within the barrel. In addition, throttle devices at the end of the barrel, called chokes, are available on some presses to enhance pressure buildup. For a detailed discussion of the engineering and technology of continuous screw presses the reader is referred to Bockisch (4).

Continuous screw presses have been used in two ways in oilseed extraction for over 80 years. The first is full-press operation, where the oilseed, after heat conditioning, is pressed one or more times through the same press or through several presses installed in series. In these cases, the screw press is the sole means of extraction.

This method is typically practiced when the objective is to achieve 5–6% residual oil content in the meal. In the second case, the screw press is used in a prepress operation mode to extract high-oil–bearing seeds (>30% oil), as is the typical case with sunflower seed. The seed is pressed to remove part of the oil, and the partially defatted material (16–18% residual oil content) is taken for solvent extraction to recover the remaining oil, resulting in <1.5% residual oil content.

Solvent Extraction

Solvent extraction is by far the most widely used method to extract oil from soybeans. Soybeans are prepared by cleaning, drying, tempering, cracking, dehulling, conditioning, and flaking. The flakes are extracted using an organic solvent, usually a petroleum distillate high in *n*-hexane (5). The advantage of this process is high extraction efficiency, with the residual oil in the meal potentially reduced to 1–2%. Solvent extraction is well suited for extremely large-scale operations with the associated economies of scale. Solvent extraction plants with capacities ranging from 100 to 5,000 MT/day are in existence. As the cultivation of soybeans expanded tremendously over the past half-century, solvent extraction technology was able to handle the ever-increasing crop volume. Detailed information on the theory and practice of solvent extraction has been presented by Woerfel (5) and Johnson and Lusas (6).

Extruder Applications

Traditional Extruders Used in the Food and Feed Industries

Extruders are mechanical devices in which a feed material is transported by a screw rotating within a closed barrel under varying conditions of heat, shear, and pressure and then discharged through die openings in the optimal geometry for the desired product. These machines are used in processing food (e.g., snack foods and breakfast cereals), feed (e.g., pet food), and industrial products (e.g., plastics). Extruders vary widely in design, function, capabilities, and cost. A comprehensive treatise on extruders and their applications in the food and feed industries is provided by Riaz (7).

Expanders Used in Oilseed Preparation for Solvent Extraction

Two types of extruders have found applications in the oilseed processing industry. The first type is the class of extruders called expanders. The general design of the expander consists of an unsegmented barrel housing a worm screw with interrupted flights. This design, derived from screw presses, was invented in 1963 (8). Commercial exploitation of the expander was first achieved in Brazil and later by Anderson International of Cleveland, Ohio. Specific applications to oilseed processing have been described by Williams (9,10). Expanders are provided with needle valves at the flight interruptions to inject water or steam into the product stream (usually flakes). The expander converts flaked materials into porous collets that are much denser than flaked oilseeds and allow more material in the fixed-volume solvent extractor. This transformation increases the throughput capacity and efficiency of subsequent solvent extraction by enabling increased bed depth, better contact between solvent and oil, more complete solvent drainage, and more cell disruption, thereby increasing plant capacity. Interrupted-flight expanders are used ahead of solvent extractors in many soybean-processing plants.

The original design for expanders was not capable of forming collets from high-oil–bearing seeds. This was due to the accumulation of oil within the closed barrel, causing slippage and unsteady mass flow. A new design called the Hivex® Expander, which married an expander to a screw press, was developed by Anderson International to remove part of the oil from the expander barrel. This is achieved by providing a slotted barrel section forming a drainage cage at the discharge end of the expander. Excess oil drains from this section, and the meal with reduced oil content proceeds to the die end of the machine, where a collet is formed.

It has been reported that expanders are also used to process full-energy (full-fat) soybeans. This refers to cooking whole soybeans after cracking to deactivate the antinutritional factors. These cooked full-fat soybeans are then used as livestock feed.

Dry Extruders Used in Oilseed Processing for Feed Applications

Dry extruders were developed by Triple “F”, Inc., Des Moines, Iowa, in the 1960s. The original purpose was to provide a simple means whereby farmers that raise both soybeans and livestock could heat-process soybeans on the farm for use in their own livestock rations. In fact, the first models of dry extruders were driven by the power takeoffs of farm tractors. Dry extruders derive their name from the fact that they generate all heat of cooking internally by friction and dissipation of mechanical energy rather than from an external heating source such as steam. For this reason, they are referred to as autogenous extruders. These are high-shear extruders running at screw speeds of about 600 rpm. They fit the needs of small-scale processing operations in remote places where utilities, such as steam sources, may not be readily available.

Cooking soybeans in dry extruders results in full-energy soybeans because all of the original fat is present. Full-energy soybeans have the advantage of being not only a good source of protein (approximately 38%) but also a generous source of metabolizable energy from the oil (approximately 18%). Proper heat processing denatures protein and inactivates natural soybean protease inhibitors (trypsin inhibitors), thereby maximizing the qualities of protein and energy in soybeans as reflected in the productivity of farm animals to which full-energy soybeans are fed. As farmers realized significantly superior efficiencies of extruded full-energy soybeans for poultry and livestock production, animal scientists initiated considerable research efforts to determine the nutritional characteristics of the product. Work of

Stillborn *et al.* (11) and Waldroup and Hazen (12) established the efficacy of dry-extruded full-energy soybeans for poultry. Studies carried out by Marty and Chavez (13), Smith *et al.* (14), and Hollis (15) established similar benefits in swine production. The use of full-energy soybeans in dairy rations was investigated by Smith *et al.* (16) and Socha (17). These studies established two important advantages for dry-extruded soybeans. First, the nutritional superiority of extruded full-energy soybeans over solvent-extracted soybean meal was validated. Second, the feed efficiency of the product points to inherent effects of the extrusion process that render the protein and energy more available to the consuming animals.

Because soybean oil continues to be a valuable product, the use of full-energy soybeans in poultry and livestock feeding has not become widespread in the United States. However, use of full-energy soybeans in livestock rations is growing in other countries, where different economic situations prevail.

Extrusion in Mechanical Processing of Oilseeds

Favorable Environment for Accepting New Technologies

Oilseed crushers are facing a delicate balance between control of hexane emissions and containment of energy costs. The 1990 Clean Air Act caused much concern regarding hexane emissions. *n*-Hexane, the main component of the distillate fraction known as "hexanes," is one of 189 hazardous air pollutants listed in the Clean Air Act, and hexane is regulated as both a criteria pollutant and a hazardous air pollutant. The emission limit for hexane as a criteria pollutant is 45 MT/yr (49.6 tons/yr) and as a hazardous air pollutant is 4.5 MT/yr (4.9 tons/yr). Exceeding either limit requires a federal operating permit and an annual fee based on the level of hexane consumption. About 25 years ago hexane loss was of the order of 10 L/MT; today it is about 1 L/MT. For solvent extraction plants, it is less expensive to use more heat energy than to invest in more efficient equipment. Increasing heat may affect meal quality, however.

The application of extrusion technology in oilseed extraction has received considerable attention during the past 15 years. Much of the development has taken place in the soybean-processing industry. A number of factors contributing to the development can be identified. Soybeans have become increasingly important as a food source in meeting acute nutritional needs around the world, especially in developing countries. For many countries where the soybean industry is still small, the large-scale, capital-intensive technology of solvent extraction is not readily applicable. Therefore, U.S. institutions connected with federal food and nutrition aid programs have focused on alternative methods to process soybeans. In some countries, soybean production is practiced on small farms over widely scattered areas. The infrastructure for collecting, handling, and transporting seed to a central processing facility is unavailable and impractical. Under these circumstances, new technologies for small-scale operations on a decentralized basis became a necessity.

In the United States, the farm economy has been under considerable pressure with diminishing returns from production and trade of raw agricultural commodities, including soybeans. Adding value by processing in rural areas has attracted the interests of investors and farmers' groups. New processing technology that is compatible with the needs of small enterprises at the rural level became an urgent need.

Soybeans were traditionally considered as a source of edible oil and high-protein meal for animal feed. In recent times, much scientific evidence has been accumulated in regard to the beneficial effects of soybeans on cardiovascular health, bone health, relief of postmenopausal symptoms, and even certain cancers. The U.S. Food and Drug Administration now allows health claims on food products that contain at least 6.25 g of soy protein per serving. There has also been a new awakening on the part of consumers with respect to health, natural, and organic foods. With the advent of transgenic soybeans (genetically modified organisms, or GMOs) to achieve resistance to certain herbicides, demands for certifiable identity-preserved, non-GMO soybeans and their oil and protein products for food and feed have grown, especially in Europe and Japan. There is also increasing producer and consumer interest in specialty oils from soybeans bred by traditional methods for unique traits. Low-linolenic soybeans (<1% linolenic acid) developed at Iowa State University are one example. This oil does not require partial hydrogenation, with attendant production of *trans* fatty acids, to achieve good oxidative stability. *Trans* fatty acids will soon have to be labeled as fat. More information about low-linolenic oil may be found on the Internet at http://www.notrans.iastate.edu.

Large-scale solvent extraction plants find it, in most cases, technically and economically infeasible to preserve the identity of specialty soybeans during processing. Their scale is usually far too great for the available supply and demand for these numerous specialty products. Typical soybean solvent extraction facilities have crushing capacities exceeding 3,000 MT/d; some are as large as 5,000 MT/d. The high capital costs to control hexane and meet environmental emission and safety requirements require these plants to have large capacities in order to be competitive. Therefore, technologies to process soybeans without using solvents and in a manner consistent with identity preservation have become necessary. Processing without solvents is also an attractive proposition based on environmental considerations because of increasing pressures to reduce emissions of organic compounds. Due to the foregoing favorable factors, extrusion-based soybean-processing technologies emerged as a viable option.

The Importance of Heating Soybeans

Any technology designed to process soybeans into feed or food products must meet several basic requirements. Soybeans must be heat processed for a number of reasons. They contain protease inhibitors, most importantly trypsin and chymotrypsin inhibitors. Feeding unheated soybeans to certain farm animals results in poor digestibility of the protein. This is manifested in poor growth rates and low feed efficiency. In extreme cases, trypsin inhibitors can cause hypertrophy of the pancreas. Hence, heat inactivation of these proteases is essential before using the meal in feed markets. Denatured proteins are also more easily digested. In addition, soybeans contain three isozymes of lipoxygenase. When the soybean seed tissue is disrupted during processing, these enzymes readily react with unsaturated fatty acids present in oil and catalyze the formation of a large number of undesirable reaction products. Some of these compounds are responsible for the beany and painty flavors often associated with soybean products. Rapid heat inactivation of these enzymes once the seed tissue is disrupted is essential for soy protein products to have good flavor, particularly for use in human food products. The enzyme urease is also present in soybeans. This enzyme breaks down urea to liberate ammonia. Urease is a significant problem in feeding ruminants where urea may be used as an ingredient in rations, because the animal may develop a toxic reaction due to the rapid conversion of the urea to ammonia. The activity of this enzyme is used as a basis for rapid testing to determine the degree of heat treatment to which soy protein products have been exposed. Extrusion is an efficient process for heating soybeans to achieve the above-mentioned objectives.

It is also necessary to disrupt the cellular structure of oil-bearing tissues to liberate the oil from the subcellular compartmentalization. The shearing action of the extrusion system efficiently disrupts cell tissues.

Dry Extruders Coupled with Expellers for Mechanical Oil Extraction

Nelson *et al.* in 1987 (18) reported the use of dry extrusion as an aid to mechanical expelling of soybeans. They reported that when coarsely ground soybeans were processed in a dry extruder, the material discharged was in a semi-fluid state when the extrusion temperature was about 121–135°C. They pressed the hot extrudate in a hydraulic press as well as several pilot-plant models of continuous screw presses. When the extrudate was pressed immediately after exiting the extruder, it was possible to easily and efficiently press out the oil. However, upon cooling, the extrudate turned into a dry meal. Pressing at this stage resulted in drastic reduction of oil yield.

Under the conditions of their experiments, the authors reported 71.8% extraction of oil in a single pass through the extruder and screw press system. The residual oil content in resulting press cake was 5.8–9.7%. Another significant finding was that the throughput capacity of one of the presses tested was 125–135 kg/h of extrudate, compared with the manufacturer's rated capacity of 39 kg/h for pressing whole soybeans. Nelson *et al.* postulated that increased throughput capacity was due to the functions of grinding, heating, and release of oil by the extruder before entry into the screw press. In an effort to produce low-fat soy flour suitable for human consumption, they proceeded to extrude and press dehulled soybeans. The trypsin inhibitor activity in raw soybeans was reduced by 91% due to the heat exposure during the extruding and screw-pressing operations. As would be expected, the protein dispersibility index (PDI) was reduced from 88% in the raw material to 13% in the flour. The flour contained 6.6% residual oil and 50% protein on a dry matter basis (0% moisture). The sensory quality of the flour was excellent, with bland flavor and light color.

Due to the reduced oil content in the press cake, it was possible and feasible to grind the press cake into flour using simple hammer-milling systems. Because of the high fat content, grinding whole soybeans is quite difficult and requires sophisticated and expensive milling systems.

It was also reported that the oil had desirable quality characteristics. The AOM (active oxygen method) stability was 15 h, the same as the National Soybean Processors Association (NSPA) specification for refined, bleached, deodorized oil. The unsaponifiable matter content was 1.08%, compared with the NSPA specifications of 1.6% and 1.5% for prime crude oil and once-refined soybean oil, respectively.

The work of Nelson *et al.* (18) laid the foundation for developing an alternative process for soybean processing by nonsolvent means using the extruder and screw press concept.

New Developments in Mechanical Processing

Nelson and his colleagues collaborated with Insta-Pro International (West Des Moines, Iowa), the manufacturer of dry extruders, to scale up the extruding and screw-pressing process. The process became known in the trade as Express Systems®, a registered name of Insta-Pro International. Among academicians this process is often referred to in the scientific literature as extruding-expelling (EE).

Extruding-Expelling System

A dry extruder with a nominal capacity of 1.0 MT/h was coupled with a large screw press. A cutaway view of a typical dry extruder is shown in Fig. 4.1.

The extruder screw is assembled on a central keyed shaft using several screw segments. The root diameter of the screw is constant. The pitch of the screw segments is variable so that the screw assembly can be configured to exert more or less shear depending on the material being processed and the shear desired. Shear locks, also called steam locks, are placed between the screw segments. These are discs that have a straight face on one side and are beveled on the other side with radial grooves. The shear locks are installed with the beveled side facing the feed end of the extruder. These locks are made in different diameters and land lengths. They impose restrictions in the path of the material being processed and thus generate mixing and shearing. The clearance between the land of the shear lock and the internal surface of the barrel can be changed by choosing shear locks with certain diameters. The larger-diameter shear locks provide a tight screw configuration resulting in high shearing rates. The screw assembly is held in place by a nose bullet with reverse threads screwed into the end of the shaft.

The barrel is assembled in segments over the screw. The barrel segments are secured with clamps. Unlike most other extruders, the barrel segments in the dry extruder

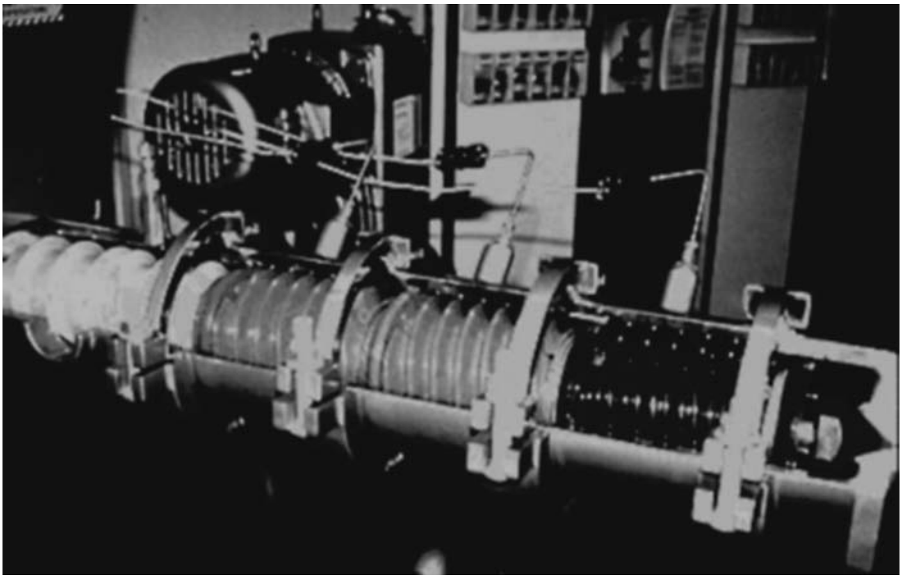

Figure 4.1. Cutaway view of a typical dry extruder.

are not jacketed because all heat of cooking is generated internally by friction. This reduces manufacturing costs. The internal surface of the barrel is rifled to promote mixing and shearing. The discharge end of the extruder is connected to an end cap, which accepts dies of the desired size and shape. The die, also called the nose cone, is threaded into the end cap. Its inner face is bored in a conical shape to complement the geometry of the nose bullet. The die can be moved toward or away from the nose bullet while the extruder is operating. The processing temperature profile is controlled by selecting the screw segments, shear locks, and dies appropriate to the material being processed. A tight configuration is required to process soybeans because the oil in the beans acts as a lubricant. The die can be moved back and forth to achieve minor adjustments to the process temperature profile while the machine is operating.

Extruding

Whole or dehulled soybeans at normal field moisture content (9–13%) are fed continuously to the extruder. The extruder operates at screw speeds of approximately 600 rpm. During passage through the barrel, the material is sheared, compressed, and heated. Heat is generated purely by the dissipation of mechanical energy. The temperature and pressure increase gradually, reach a peak at the die, and drop drastically upon exiting the die. The average residence time of the material within the extruder barrel is less than 30 s. The temperature profile can be varied as desired by making equipment changes. The highest temperature at the die end is adjusted to 160°C when the processed soybean meal is to be used as an end product, such as for direct feeding to farm animals. Under these conditions the nutritional value of the meal is maximized for poultry and swine.

In addition to maximizing the nutritional value of protein, the extrusion process enhances the pressing out of oil during the subsequent screw-pressing operation. As stated before, oil is confined in subcellular structures within the soybean cotyledon. The oil must be liberated from the subcellular structures in order to be extracted. Shearing forces exerted by the dry extrusion system disrupt the cellular structure. Upon exiting the die, the material is suddenly released to the atmospheric pressure environment. This sudden decompression results in explosive disruption of the cell tissue. Figure 4.2 shows the cellular structure of the soybean cotyledon in native form. The tightly packed palisade cells separated by cell walls are readily recognizable. Figure 4.3 shows the material after extrusion. The cellular structure is no longer visible.

The material is transformed by the extrusion process into a homogeneous matrix in which the oil is free and therefore readily pressed out. The reduction in moisture content of the extrudate due to flash evaporation also enhances the screw press's efficiency in removing the oil.

Screw Pressing

The extrudate exiting the extruder is in a semifluid and frothy state while the oil is free within the matrix. Upon cooling, the oil is absorbed back into the protein matrix

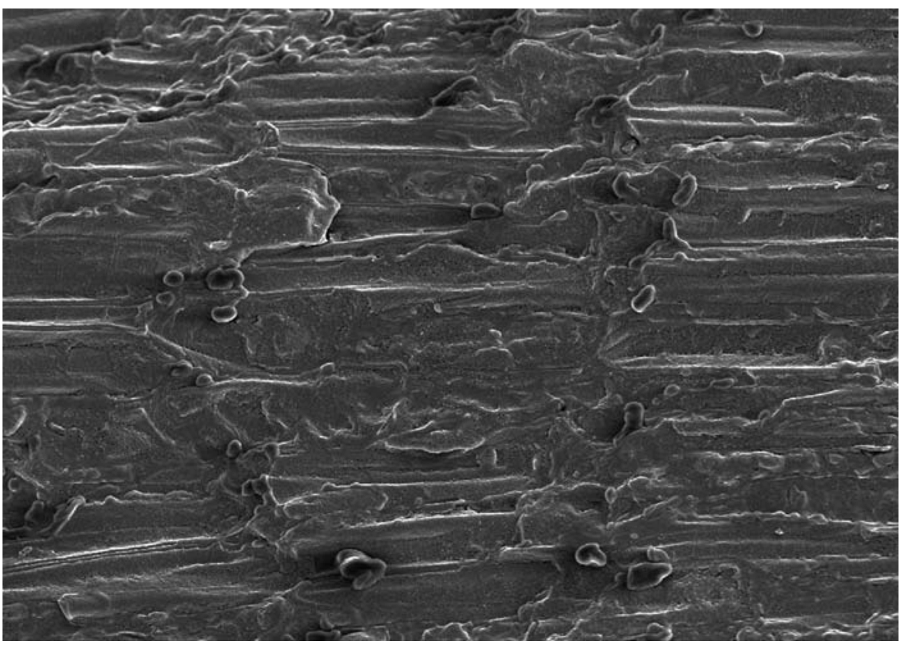

Figure 4.2. Cellular structure of the soybean cotyledon in native form.

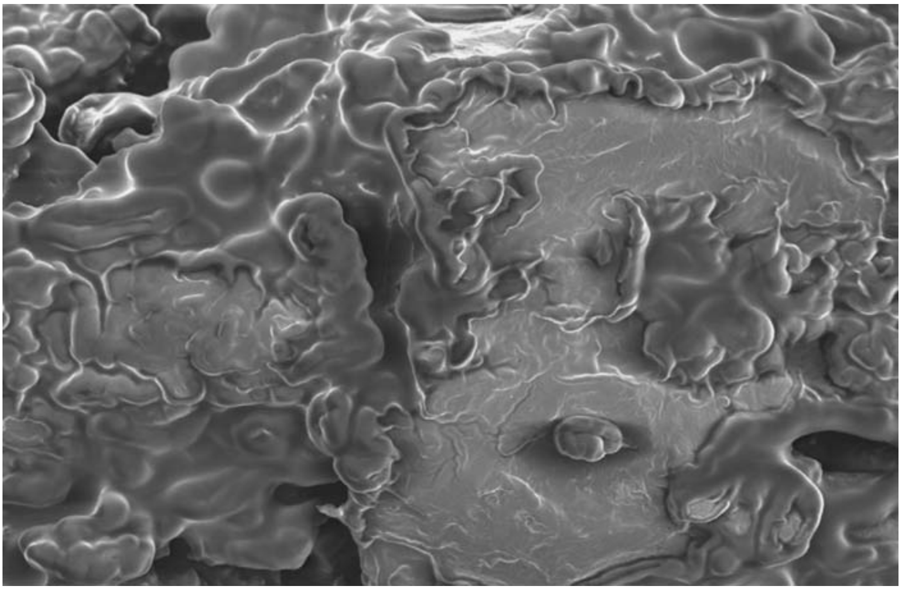

Figure 4.3. The soybean material after extrusion.

and the material becomes a dry and mealy mass. In order to extract the oil, the extrudate must be pressed immediately after extruding. There is progressive loss of oil extraction efficiency upon cooling of the extrudate.

The soybean extrudate is conveyed immediately and continuously into a screw press, where the oil is pressed out. Screw presses have been used for a long time to press oil from cooked and uncooked oilseeds; however, the configuration of the pressing worms in conventional screw presses is designed to press whole or cracked oilseed material, not extruded material. The physical properties of the soybean extrudate coming out of the extruder are very different from those of cracked or whole oilseeds. The particle size of extrudate is much smaller and the bulk density of the material is lower compared with whole or cracked oilseed. Therefore, the pressing worm designed to extract whole or cracked oilseed will not perform well with soybean extrudate. It must be modified to provide more aggressive transport and the higher compression demanded by extruded material. With the proper combination of extruder and screw press, soybean and cottonseed extrudates are pressed in one pass through the press. A schematic diagram of a typical Insta-Pro International extruder and screw-press system is shown in Fig. 4.4, and a plan view of an Anderson International extruder and screw-press system is shown in Fig. 4.5.

It must be realized that both the oil and meal coming out of the extruder-expeller system are at elevated temperature depending on the processing parameters. Both the meal and oil must be cooled to near room temperature before they are sent to storage.

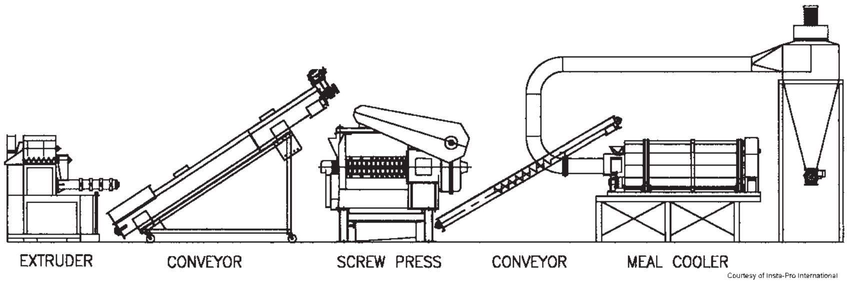

Figure 4.4. Schematic of an extruder–screw press system.

The protein-rich meal that comes out of the press in the form of press cake is declumped by using a roller mill and is passed through a meal cooler. A simple meal cooler design consists of a slowly rotating inclined drum through which a stream of ambient air is drawn at a controlled rate. The meal tumbles as it travels down the inclined drum while air is drawn countercurrent to the path of the meal. The air picks up heat from the meal and passes into a cyclone separator, where entrapped fine material is recovered and the warm air is exhausted.

The oil stream exiting the screw press carries small quantities of protein meal particles known as foots. The coarse particles are removed by passing the oil through continuous screening or settling basins. In large-scale operations, decanter centrifuges may also be used to separate the foots on a continuous basis. The foots can be recycled to the extruder to reclaim oil and meal. The presence of any foots in the oil imparts a cloudy appearance and also forms sediments in storage tanks. The oil stream must be cooled before being placed into storage in order to maintain oil quality. Plate heat exchangers or tubular heat exchangers using water as cooling medium may be used for this purpose.

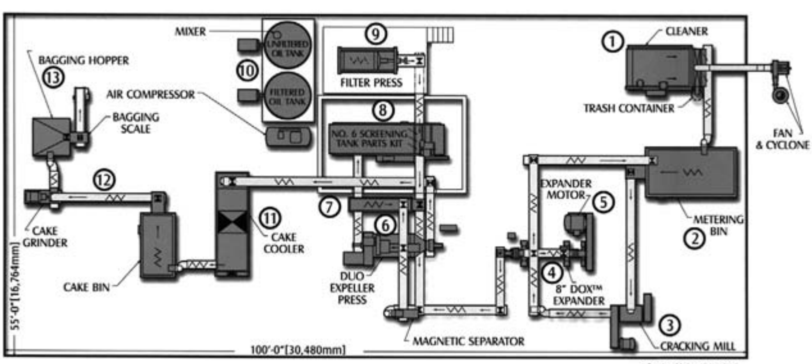

Figure 4.5. Typical plan view of an extruder–screw press system.

Application to High-Oil–Bearing Materials

The original focus of the extruder-expeller system for oilseed extraction was on low-oil–bearing seeds, such as soybeans and cottonseed, in which the oil content is 18–20%. In this case, extrusion cooking of the oilseed and a single pass of the extrudate through the screw press was established as the standard processing procedure. However, this did not work well for oilseeds with higher oil contents. High oil contents (>25%) resulted in oiling off of the material within the extruder barrel, which led to slippage and surging of the product. In extreme cases, complete cessation of the passage of material through the extruder barrel and backflow of product may result. Two approaches have been adopted to circumvent this problem. In one method a screw press is placed before the extruder-expeller system. The first screw press serves as a cold-pressing device for partial oil extraction. The press cake with reduced oil content is then passed into the extruder-expeller system as previously described.

As mentioned earlier, Anderson International has developed a special expander, called the Hivex® Expander, for partial defatting of high-oil–bearing seeds. This is a hybrid of a conventional expander and a screw press. The barrel consists of a closed section toward the feed end. The barrel section toward the discharge end is designed as a drainage cage, much like the cage of a screw press. The feed material is cooked in the first section, and excess oil from high-oil–bearing seeds is drained as it passes the drainage cage.

Performance of Extruding-Expelling Systems

Extraction Efficiency. Nelson *et al.* (18) reported that 73.7% of the oil in soybeans was extracted in their pilot-scale extruder–screw press operation. The residual oil content in the press cake was 5.3–7.8%. Under commercial processing conditions, the residual oil content in soybean meal was 6–9% when the oil content in the soybeans was 18–22%. The residual oil content in cottonseed meal was 6–8% when the oil content in cottonseed was 20–22% (Table 4.1).

TABLE 4.1
Extruding-Expelling Soybeans and Cottonseed[a]

Oilseed	Oil in seed (%)	Protein in seed (%)	Oil extraction efficiency (%)	Extruding temperature (ºC)	Oil in meal (%)	Protein in meal (%)
Soybean	18–22	36–40	65–67	150–160	6–9	42–46
Cottonseed	20–22	20–22	65–70	110–120	6–8	26–30

[a]All values used for oil content are expressed in average ranges. Actual content varies due to differences in varieties and growing conditions. Operator management also influences the quality of the end product.

Table 4.2 shows data from commercial-scale processing of canola and sunflower seed. The canola and sunflower seed was prepressed and then processed by the extruding-expelling method. For canola having 35–40% oil content, the residual oil content in meal was 8–11%. In the case of sunflower seed with 35–45% oil content, the residual oil content in meal was 10–13%. It should be noted that the process temperatures used in the extruder for processing cottonseed, canola, and sunflower seed were lower than in the case of processing soybeans. This is because canola and sunflower seed do not contain the protease inhibitors that are present in soybeans.

Feeding Value of Protein Meal. The protein-rich meal produced by the extruding-expelling system contains more residual oil than does solvent-extracted meal (typically less than 1.5%). Although the extraction efficiency is lower, it has been shown that the extruded-expelled soybean meal has advantages over the solvent-extracted counterpart in terms of feed value to farm animals.

A number of U.S. universities have conducted studies on the qualities and compositions of soybean meal and oil produced by the extruder-expeller system. Wang and Johnson (19) surveyed 13 extruding-expelling plants, 8 solvent extraction plants, and 1 traditional screw press plant over a one-year period with sampling at each plant every four months (Table 4.3). Comparisons of oil quality are discussed in a separate chapter. This discussion focuses on meal quality.

Extruded-expelled meal typically had lower moisture content than either solvent-extracted or screw-pressed meal because most extrusion-expelling plants do not normally add back moisture, although the meal could be remoistened if such practices became important. The residual oil contents of both extruded-expelled meals are higher than for solvent-extracted meal, but that oil contributes valuable metabolizable energy to the diet. Because of the higher oil contents, the protein contents of both extruded-expelled and screw-pressed meals are lower. Most extruding-expelling and screw-pressing plants do not dehull their beans as do solvent-extraction plants, but a few do and dehulling increases protein content. Extruded-expelled meal has protein solubility in potassium hydroxide similar to solvent-extracted meal, and this solubility is much higher than for screw-pressed meal. Low solubilities may indicate excessive heat treatment. Protein dispersibility indices (PDIs) of most extruded-expelled meals

TABLE 4.2
Prepressing and Extruding-Expelling Canola and Sunflower Seed[a]

Oilseed	Oil in seed (%)	Protein in seed (%)	Oil extraction efficiency (%)	Extruding temperature (ºC)	Oil in meal (%)	Protein in meal (%)
Canola	35–40	22–26	72–75	120–125	8–11	32–37
Sunflower	35–45	16–22	72–75	115–125	10–13	22–27

[a]All values used for oil content are expressed in average ranges. Actual content varies due to differences in varieties and growing conditions. Operator management also influences the quality of the end product.

TABLE 4.3
Quality Characteristics of Soybean Meals Recovered in Commercial Practice by Different Oil Extraction Processes

	Processing method		
Property	Extruding-expelling	Solvent extraction	Screw pressing
Moisture (% as is)	6.9	11.7	11.0
Oil (%)[a]	7.2	1.2	5.6
Protein (%)[a]	42.5	48.8	43.2
Urease (ΔpH)	0.07	0.04	0.03
KOH solubility (%)	88.1	89.1	61.6
PDI (%)	18.1	44.5	10.6
Rumen bypass (%)	37.6	36.0	48.1
Color (Hunter L)	65.8	69.1	51.5
Trypsin inhibitor (mg/g)	5.52	5.46	0.30
Trypsin inhibitor (TIU/g)	12,250	5,275	2,000

[a]At 12% moisture basis.

and screw-pressed meals were lower than for solvent-extracted meals. The rumen bypass values were the same for extruded-expelled meals as for solvent-extracted meal, but not as high as for screw-pressed meal.

Woolworth *et al.* (20) compared the nutritional quality of extruded-expelled soybean meal and solvent-extracted soybean meal using a swine model. They concluded that the apparent ileal digestibility of crude protein and lysine were greater in the extruded-expelled soybean meal compared with conventionally processed soybean meal. Likewise, the digestible energy and metabolizable energy values were higher for extruded-expelled soybean meal. They further indicated that the nutritional parameters were unaffected by the presence or absence of soybean hulls. Based on these findings, the authors proceeded to calculate price matrices to determine the price that can be paid for the extruded-expelled product based on the price of solvent-extracted meal with added oil (Table 4.4). It was shown that over the entire price range used for solvent-extracted meal and added soybean oil, the extruded-expelled soybean meal had higher intrinsic value.

Zhang *et al.* (21) studied the effect of extruding-expelling on the nutritional qualities of conventional soybean meal and Kunitz-trypsin-inhibitor–free soybean meal in chicken rations. They reported that extruded-expelled soybean meal had a true metabolizable energy value of 3,265 kcal/kg dry matter. Aldrich and Merchan (22) studied the effect of extrusion temperature on protein digestion by ruminants. They reported that increasing the extruder temperature from 104 to 160°C resulted in a linear decrease in *in situ* degradation of soybean protein. Raw soybean protein degraded rapidly (84.1%) compared with extruded soybeans at 160°C (30.4%). In other words, soybeans extruded at 160°C had a bypass protein value of 69.6%. The amino acid digestibility as measured by precision feeding to cecectomized roosters was reported to average 90% for the extruded treatments.

TABLE 4.4
Price Matrix for Extruded-Expelled Soybean Meal without Hulls When Compared to Soybean Meal on an As-Fed Basis: $/Ton

Fat price ($/lb)	Soybean meal (46.5% CP) price ($/ton)					
	150	170	190	210	230	250
0.15	181	202	224	246	268	290
0.20	192	213	235	257	279	300
0.25	202	224	246	268	289	311
0.30	213	235	257	279	300	322
0.35	224	246	268	289	311	333

Source: Courtesy J.C. Woolworth, Kansas State University, 1998.

Food Product Applications

The greatest significance of extruding-expelling is that this system provides a relatively simple means to produce soy flour with remarkably superior flavor compared with other products on the market. The main reason for the good flavor is attributed to the fact that the lipoxygenase enzymes responsible for off-flavor development are deactivated in the extrusion process before they have a chance to catalyze the oxidation of unsaturated fatty acids. A favorable environment for lipoxygenase-catalyzed reactions is avoided. Furthermore, the extrusion cooking parameters can be adjusted *so as* to impart a pleasant nutty flavor to the meal if such is desired.

By carefully controlling the process, the functional properties of soy flour produced by this process can be greatly influenced (23–25). The PDI can be controlled in the range of 14–70. Products with excellent water-holding, emulsification capacity, and fat-binding properties can be produced. PDI values >40 appear to be key to achieving good functional properties. Up to 30% of soy flour made by extruding-expelling has been successfully incorporated into unleavened bakery and pasta products. The soy flour has found acceptance in confectionery products as well. For instance, it has been shown that 25% of milk solids (Khoa) used in making Gulab Jamun (a popular Indian sweet preparation) can be replaced with extruded-expelled soy flour without affecting the physical or sensory properties of the finished product. As for nutrition, it has been reported that the flour contains approximately 48% protein, 6% fat, 14% dietary fiber, and 4,000 μg/g of total isoflavones.

Extruded-expelled soy flour with a PDI of 35 or higher has been successfully reprocessed into texturized soy protein (TSP) using dry extruders and twin-screw extruders (26,27). Conventional TSP is manufactured from defatted white flakes and flour having PDI in the range of 70 and residual oil content of less than 1.5%. Crowe and Johnson (26) were the first to demonstrate that excellent meat extenders could be produced using twin-screw extrusion to texturize extruded-expelled soy flour. Dry extruders are capable of generating much higher shearing rates, are capable of texturizing extruded-expelled soy flour, and are used in several commercial TSP plants. Higher energy input would be required to texturize lower-PDI soy flour in the presence of higher contents of residual oil. The TSP products produced from extruded-expelled flour are characterized by more open and porous texture and lower bulk density compared with the traditional counterparts made from defatted soy flour. Because of the open texture, TSP made from extruded-expelled soy flour rehydrates faster and has greater water-holding capacity than do the traditional products of higher density. Crowe and Johnson (26) have shown that TSP prepared from extruded-expelled soy flour can be used at levels up to 19% in ground beef patties without adversely affecting the texture or flavor of cooked hamburgers. Higher PDI and lower residual oil content of extruded-expelled flours favor high-quality TSP. Extruded-expelled soy flour and TSP made from this extruded-expelled soy flour are already finding their places in domestic and some overseas markets.

Future Prospects

The future for the extruding-expelling process seems to be bright as a means of processing identity-preserved oilseeds into specialty oils and meals. The low cost of constructing plants and the reduced safety issues are additional advantages. There are now over 150 extruding-expelling plants around the world and over 65 plants in the United States and Canada, with most processing soybeans. As soybean producers recognize opportunities for adding value to their crops and as consumers recognize the enhanced properties of soy products and health advantages of increased soy protein consumption, the extruding-expelling process will likely become more widely used.

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