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EDIBLE SOYBEAN PROTEIN PRODUCTS*

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INTRODUCTION

In the U.S., soybean processors produce and market a variety of protein products that are used not as direct foods but primarily as ingredients by the food industry. Whole soybeans are converted directly into foods on only a small scale (estimated at 74 million lb in 1981), but this use has shown a rapid growth in the past 2 to 3 years. These direct food uses consist of traditional Oriental foods, including tofu, miso, and tempeh, that are discussed elsewhere in this volume.

The edible protein products available in the U.S. are conventionally classified according to protein content:

	Min. Protein, % (dry basis)
Grits and flours	40—50
Concentrates	70
Isolates	90

PRODUCT DEFINITIONS[1]

Grits and Flours

Soy grits are the screened, graded product obtained after expelling or extracting most of the oil from selected, sound, clean, dehulled soybeans; they are usually ground to conform to the following range of granulations in terms of majority percent through respective U.S. standard screens:

Coarse	No. 10 to No. 20
Medium	No. 20 to No. 50
Fine	No. 50 to No. 80

Soy flours are the screened, graded product obtained after expelling or extracting most of the oil from selected, sound, clean, dehulled soybeans, except that full-fat soy flours are not subjected to expelling or extraction and contain all of the oil originally present in the soybeans. Flours are ground finely enough to pass through a 100-mesh or smaller screen and are usually available in various grinds to meet specific requirements.

Full-fat soy flours are essentially dehulled, ground soybeans and contain all of the oil originally present in the raw soybeans; fat content usually is 18 to 20%.

Defatted soy flonrs are produced by the nearly complete removal of the oil from soybeans by the use of hexane; they usually contain about 1% fat.

Low-fat soy flours are produced either by partial removal of the oil from soybeans or by adding back soybean oil and/or lecithin to defatted soy flours to a specified level such as 5 to 6%.

High-fat soy flours are produced by adding back soybean oil and/or lecithin to defatted soy flours, usually in the range of 15%.

Lecithinated soy flours are a type of low- or high-fat flour in which lecithin is added, usually in the range of 15%.

* The mention of firm names or trade products does not imply that they are endorsed or recommended by the U.S. Department of Agriculture over other firms or similar products not mentioned.

Protein Concentrates

Protein concentrates are prepared from high-quality, sound, clean, dehnlled soybeans by removing most of the oil- and water-soluble nonprotein constituents (mainly sucrose, raffinose, and stachyose) and contain not less than 70% protein (N × 6.25) on a moisture-free basis.

Protein Isolates

Protein isolates are the major protein fraction of soybeans prepared from high-quality, sonnd, clean, dehulled soybeans by removing a preponderance of the nonprotein components (primarily the water-soluble sugars plus the water-insoluble polysaccharides) and contain not less than 90% protein (N × 6.25) on a moisture-free basis.

PROCESSING

Full-Fat Flours

The only major soybean processor that formerly prepared full-fat flour discontinued production in the U.S. several years ago. Full-fat flour is, however, being produced by a subsidiary company in England as outlined in Figure* 1.[2] Foreign material, such as sticks, weed seeds, and stones, are removed by a dry process — sifting and aspiration — and the beans are then washed to remove adhering dirt. Next, they are cooked, conditioned to a low moisture content (to facilitate dehulling), dehulled, ground, classified, and reground if necessary, and finally packed.

The cooking step inactivates enzymes and antinutritional factors, optimizes nutritional value, and develops a nutty, toasted flavor. For some applications, such as bread baking, it is desirable to have an enzyme-active flour, especially one in which lipoxygenase activity has been retained. Such flours are prepared by omitting the cooking step. Enzyme-active soy flours are used at levels of only 0.5 to 1.0% (based on weight of wheat flour); inactivation of enzymes and improvement of nutritional value are believed to occur during baking.

Defatted Grits and Flours

These products are made from hexane-defatted flakes. The initial processing steps in the preparation of defatted flakes for meal for animal feeds or for edible grits and flours are basically as outlined in the section entitled "Processing of Soybeans for Oil and Meal". However, preparation of products for human consumption requires more emphasis on sanitation than does manufacture of feeds — more thorough cleaning of the beans; control of bacteriological quality during processing; and prevention of bird, insect, and rodent infestation.[3] The desolventizer-toaster is used to process meal intended for feeds, but is not normally used for edible flakes. Instead, flakes leaving the extractor are desolventized by one of several alternate means, including flash desolventizing and vapor desolventizing-deodorizing.

Flash desolventizing[4,5] involves a closed loop consisting of a pneumatic-conveying desolventizing tube, a cyclone flake separator, a hexane recycle blower, and a hexane vapor superheater (Figure 2). Solvent-wet flakes (containing about 30% hexane) from the extractor feed continuously into the system and are fluidized in a rapidly moving hexane vapor. Flash evaporation of the hexane in the flakes occurs, leaving a residual solvent of about 1%. Hexane vapor and flakes are separated in the cyclone. Part of the hexane is removed by condensation and the remainder is recirculated through the superheater. The desolventized flakes proceed to a deodorizer that strips out the balance of the residual solvent plus other volatile compounds that may be present. Reten-

* Figures and tables are found at the end of the text.

tion time is only a few seconds; under ideal conditions, protein denaturation is minimal and protein solubility is high as measured by the Protein Dispersibility Index (PDI) or the Nitrogen Solubility Index (NSI).[6] High protein solubility is desired in flakes that are used to make enzyme-active flours and for flakes utilized for the preparation of isolates. However, for many food applications, it is preferred to cook or toast the flakes to varying degrees depending upon the intended end use. When desired, cooking can be done by taking flakes directly from the flash desolventizer (omitting the deodorizer shown in Figure 2) and treating them in a combination flake stripper and cooking system mounted one above the other (Figure 3).[5] The flakes enter the upper vessel, where live steam is injected to strip out residual solvent. When flakes with high PDI values are wanted, steam temperature and rate of injection are controlled to prevent condensation of moisture, and flakes with PDI values of 85 (a PDI of 90 is typical of an undenatured flake) are obtained. To prepare cooked flakes, steam is added in the upper chamber and allowed to condense; jacket temperature may be raised and retention time increased so that protein denaturation occurs while the flakes pass through the stripper and cooker units. By controlling operating conditions, it is possible to obtain flakes with PDI values ranging from 85 (essentially uncooked) to as low as 10 (fully cooked).

Vapor desolventizing-deodorizing involves some of the same physical principles as flash desolventizing, but the configuration of the equipment is different (Figure 4).[4] Solvent-wet flakes from the extractor are dropped into a steam of superheated hexane vapor, thereby flashing off the bulk of the solvent. Again, part of the hexane is superheated and recycled and part of it is condensed and removed. The flakes are conveyed to the opposite end of the desolventizer and dropped into a mixer section, where water may be added if desired. Next, the flakes pass to the deodorizer. Here, steam is utilized to strip out remaining solvent. The deodorizer can be operated between 1/2 and 2 atm. Under vacuum operation the stripping steam does not condense, with the result that little cooking occurs. At atmospheric pressure some of the steam condenses and, correspondingly, more cooking takes place. With increasing pressure, more of the steam condenses and thorough cooking results. Extent of cooking is determined by residence time, temperature, pressure, and moisture. By controlling these variables, it is possible to prepare flakes with PDI values ranging from 90 (uncooked) to 10 (fully cooked).

Protein Concentrates

Defatted flakes or flours are the starting materials used for production of soybean protein concentrates (Figure 5). The basic process involves extraction of the defatted meal under conditions where the bulk of the proteins are insoluble, but the sugars dissolve and are removed. Three different extraction solvents can be employed for this purpose (Figure 5).

Aqueous ethanol is the solvent used most extensively today. The proteins and polysaccharides are insoluble in this solvent; whereas sugars, ash, and minor constituents are extracted. After solvent removal, a concentrate (70% minimum protein content) is obtained.[7] A recent variation of the alcohol process consists of extraction of defatted flakes with hexane:ethanol to remove residual lipids prior to the aqueous alcohol treatment.[8]

Dilute acid of a concentration to give a flake-water pH of about 4.5 is a second solvent employed. This solvent adjusts the flakes to the isoelectric region, the condition of minimum solubility for soybean proteins (Figure 6). At this pH, only some of the minor proteins dissolve along with the sugars. After removal of the dilute acid extract, the protein-polysaccharide mixture is adjusted to neutrality and dried to yield a protein concentrate.[9]

Water is a third solvent that can be used.[10] This process was formerly practiced commercially but was discontinued several years ago. An important first step in employing water as an extraction solvent is a moist-heat treatment of the flakes to denature and insolublize the proteins. Subsequent washing with water then removes mainly the sugars, and a concentrate is obtained on drying the washed product. A variant of this process consists of cooking cracked, dehulled soybeans at 82 to 100°C and washing with fresh, hot water to remove the sugars. The product is then dried to yield a "full-fat" soybean concentrate that can be defatted to obtain a typical protein concentrate.[11]

Yields of protein concentrates by the three processes range from 60 to 70%, based on the weight of the starting defatted flakes or flours.

Protein Isolates

These are the most highly refined soybean protein products available.[1] They are made from undenatured, defatted flakes by extraction with dilute alkali (Figure 7). The slurry is centrifuged to remove the spent flakes and the resulting extract is then adjusted to pH 4.5, the isoelectric region (Figure 6) where most of the proteins coagulate and precipitate as a curd. After washing, the curd may be spray dried directly to yield an isoelectric protein or, more commonly, the curd is redispersed in water, adjusted to pH 6.8 to 7.2, and then spray dried. The resulting soy proteinate is more water-soluble than the isoelectric form and hence more readily incorporated into wet food systems. Yields of isolates are about 30% of the weight of the starting defatted flakes.

Textured Protein Products

Flours, concentrates, and isolates are normally powders, but they are also available in textured forms with fibrous, chewy properties characteristic of the muscle proteins of meats. The majority of the textured flours are made by thermoplastic extrusion.[12-14] In this process (Figure 8), defatted flour is mixed with water plus additives to form a dough, which is then fed to the extruder where the material is subjected to high temperature, pressure, and mechanical stress. On emerging through a die, the dough puffs and assumes a fibrous texture simulating certain meat products. Size and shape of the textured dough can be controlled at the extruder die. Protein concentrates can be textured by analogous processes and are available commercially. Another process used by one company to texturize soy flour is steam texturization. Soy flour is introduced into a rotary valve, subjected to a burst of high-pressure steam, and ejected through a gun barrel, thereby imparting texture.[15]

Protein isolates are available in two textured forms. In preparation of the first type (Figure 9), an isolate is prepared, mixed with alkali to form a "spinning dope", and then pumped through a spinnerette into a coagulating bath contaiuing acid and salt. Under these conditions, the alkali is neutralized and the protein is coagulated to produce tiny protein filaments that are gathered into bundles or "tows". The tows are washed, stretched, blended with fats, flavors, colors, and other additives, and finally fabricated into a variety of sizes and shapes of meat-like products.[16]

Textured soy protein isolates are also produced by a "dry-spinning" process in which isolate slurries are pumped through a heat exchanger under high pressure at temperatures in the range of 116 to 157°C. Fibers are obtained by expelling the heated slurries through a small circular or slot-type nozzle. The expelled fibrous isolate is cooled by dropping it through ambient air into a collecting vessel. Excess water is removed by centrifuging.[17]

PRODUCERS AND PRODUCTION ESTIMATES

Table 1 lists major producers of soy proteins and the general types of products they provide as ingredients to the food industry. Of the 14 concerns listed, 9 process soybeans into oil and defatted meal; the others are in related businesses of foods or food chemicals. Production estimates for the various protein products are found in Table 2.

COMPOSITION

Table 3 shows typical proximate analyses of soy flour, concentrates, and isolates. Mineral and trace element analyses for a laboratory-prepared, defatted soybean meal and examples of commercial products are listed iu Table 4. Analyses for a total of 87 elements that accounted for 95.5% of the sample were reported for the laboratory meal preparation.[20] Vitamin contents of soybean products are given in Table 5.

Table 6 shows amino acid analyses of commercial soybean protein samples. Approximately 30% of defatted soy flour consists of carbohydrates made up of water-insoluble polysaccharides and oligosaccharides. The amounts of the constituent sugars obtained on hydrolysis of the various carbohydrates are found in Table 7. The sugar alcohol, pinitol, is also present in soybeans.[25]

In common with other legumes, most of the proteins in soybeans are high in molecular weight; about 80% of the proteins have molecular weights of 100,000 or higher. In the ultracentrifuge (Figure 10), the water-extractable proteins of defatted soybean meal are resolved into four fractions with approximate sedimentation coefficients of 2S, 7S, 11S, and 15S. The sedimenting fractions are not homogeneous. Table 8 gives approximate distribution of the four sedimenting fractions. Protein components that have been isolated and characterized have molecular weights ranging from 8000 to 480,000, and many of them are enzymes that occur in small amounts. Two proteins, the 7S globulin (β-conglycinin) and the 11S globulin (glycinin), constitute the major proteins in soybeans. The 7S globulin constitutes about 60% of the total 7S fraction or 22% of the total protein (calculated from data in Table 8 and from results of Wolf and Sly).[43] As far as is known, the 11S fraction consists of a single protein, the 11S globulin, although there is evidence for genetic polymorphism of this protein.[44] The 7S and 11S globulins thus make up about 50% of the total proteins in soybeans.

The 11S and 15S protein fractions precipitate quantitatively when a water extract of defatted soybean flakes is adjusted to pH 4.6 (as in the preparation of isolates, Figure 7), whereas the 2S and 7S fractions precipitate only partially. Consequently, soybean protein isolates contain all four ultracentrifugal fractions, but with reduced amounts of the 2S and 7S fractions as compared to the starting water extract.[45,46]

NUTRITIONAL PROPERTIES

Antinutritional Factors

Since the report of Osborne and Mendel[47] in 1917 that rats grow poorly when fed raw soybean meal, a number of biologically active substances have been identified in soybeans (Table 9). Detailed reviews of this topic are available.[1,48]

Trypsin inhibitors are proteins with molecular weights ranging from 8000 to 21,500 (Table 8) and have received the most attention in nutritional studies of soybeans. Although they inhibit trypsin and chymotrypsin, important enzymes involved in digestion of proteins, the trypsin inhibitors exert a more indirect effect. Trypsin inhibitors accelerate protein synthesis and increase secretion of pancreatic enzymes into the intestine, which in turn cause pancreatic hypertrophy and loss of undigested pancreatic enzymes into the feces. Excessive loss of essential amino acids through the feces is believed responsible for inhibition of growth in young rats.[48]

About 40% of the growth-depressing and pancreatic hypertrophy effects of raw soybean protein are attributed to trypsin inhibitors. The remaining 60% of the effects are believed to be caused by the poor digestibility of the undenatured soybean proteins.[70] Trypsin inhibitors are inactivated and raw proteins are denatured by moist-heat treatment, or toasting, as it is commonly referred to. As time of moist heating increases, trypsin inhibitor activity decreases and protein efficiency ratio (PER) increases (Figure 11).[48]

Complete inactivation of trypsin inhibitors is not necessary to abolish pancreatic hypertrophy in rats. Feeding of commercial soy flour, protein concentrate, and soy protein isolate to rats for 285 days, about half of the rat's life span, revealed no pancreatic hypertrophy, and all organs were normal in size and appearance. The products tested had residual trypsin inhibitor activities 13 to 33% of that found for raw soy flour.[71]

Agglutinins in defatted soybean meal consist of several glycoproteins (mol wt = 110,000, Table 8) capable of agglutinating red blood cells.[49] Although once thought to be antinutritonal factors, soybean agglutinins now appear to have few, if any, growth-inhibiting properties.[50] The agglutinating activity is readily abolished by moist heat or by digestion with pepsin.[51]

Goitrogen activity in the form of goiters occurs in rats consuming high levels of raw soybean meal or isolated protein in the absence of added iodide.[52] A goitrogenic fraction isolated from raw soy flour appears to be an oligopeptide consisting of two or three amino acids, or to be a glycopeptide comprised of one or two amino acids plus a sugar.[53] Toasting decreases goitrogenicity of raw soy flour, but does not abolish it. However, the goitrogenicity of soybean protein products is overcome by adding small amounts of potassium iodide to the diet.[52]

Estrogens in soybeans consist of at least three isoflavones (Figure 12) plus a small amount of coumestrol. The isoflavones occur primarily as the glucosides — genistin, daidzin, and glycitein 7-β-glucoside — with smaller amounts of the corresponding aglycones (Table 10). Acetyl daidzin plus an unknown isoflavone were reported recently, but the amounts present in soybeans were not given.[74] The total isoflavone content is about 2600 ppm compared to only 0.05 ppm of coumestrol. Genistein and daidzein have estrogenicities only about 10^{-5} that of diethylstilbestrol. Coumestrol is about 35 times as active as the isoflavone aglycones, but is present at much lower levels (Table 10); hence, it is a minor source of estrogenicity. At a level of 0.5% of the diet, genistin and genistein inhibited growth of rats, but no effects were noted when the diet contained only 0.1% of the isoflavones.[55] Since soybeans contain only about 0.26% total isoflavones (equivalent to about 0.37% isoflavones for defatted flour), a practical diet containing 10% soy protein as defatted flour will contain only about 0.07% isoflavones.

Feeding of defatted soybean meal causes an increase in uterine weight in mice, but the minimum level of meal in the diet needed to give a response is not known. Feeding mice a total dose of 6 mg of genistein over 6 days doubles the uterine weight.[75] Apparent absence of reports on estrogenic responses in hnmans consuming soybean protein products suggests that there is no problem when practical levels of soy are ingested. Isoflavones remain active in commercially processed soybean meal; hence, they are stable to moist heat,[56] but are soluble in aqueous ethanol[54] and may be largely removed in the preparation of isolates.[57]

Allergen activity in soybeans is weak and has been isolated in crude form.[76] Incidence of allergenicity to soybeans is low. In a study of 1753 infants fed breast, soy, or cow's milk from birth to 6 months of age, only 0.5% developed an allergy towards soy, whereas 1.8% became allergic to cow's milk.[77] Overall incidence of allergies is estimated to be about 10% of the general population.[59] Although reported infrequently, sensitivity to soybean foods occurs and is often described for infants who are allergic to other foods such as cow's milk.[78] Most subjects that are sensitive to soybeans exhibit symptoms only after ingestion of soy foods, but a few individuals are sensitive to soybean dusts occurring at soybean processing plants and in food plants using soy flour.[60,79] Although weak, soybean allergen requires drastic heating to inactivate it; typical conditions are 127°C for 60 min[60] and 180°C for 30 min.[61] These conditions are generally considered to be more severe than those necessary to inactivate the other antinutritional factors, and lowering of nutritional value may result from such overprocessing.

Raffinose and stachyose plus sucrose are major soluble sugars in soybeans (Table 7). When ingested by humans, sucrose is hydrolyzed and absorbed, but lack of α-galactosidase activity in the small intestine leaves the raffinose and stachyose unhydrolyzed and hence unabsorbed. These sugars then pass into the large intestine where microbial fermentation converts them into CO_2 and H_2, the main components of flatus.[62,63] Production of flatus resulting from ingestion of soy products by humans is summarized in Table 11. Ingestion of defatted soy flour results in generation of a large volume of flatus as compared to the basal diet. A protein concentrate prepared from defatted flakes was lower in flatus production than the defatted flour, whereas a protein isolate and the water-insoluble residue obtained as a by-product in isolate preparation are both comparable to the basal diet. Whey solids, the other by-product obtained in isolate production, were a very active source of flatus. Likewise, the materials that are extracted from defatted flakes by 80% ethanol are high in generating flatus. The high content of raffinose and stachyose in the whey solids and alcohol extractives is believed to cause the high production of flatus.[64]

Since the oligosaccharides are water-soluble, they are removed in the preparation of concentrates and isolates. Their content in soybeans can be lowered by soaking in water[65,66] and by germination.[65,67] Fermentation can be used to reduce the oligosaccharide level in soy milk.[68,69]

Protein Quality

Quality characteristics of soybean proteins have been estimated by amino acid scoring based on amino acid analyses and by biological testing in experimental animals and in humans.[80]

Amino acid scores are a chemical approach to assessing protein quality. Table 12 lists the essential amino acid requirements as estimated for man and the rat and compares these values with amino acid contents obtained for soy protein products. The amino acid score is obtained by expressing the most limiting amino acid as a percentage of the requirement. Comparing soy proteins with the FAO/WHO amino acid pattern shows that their scores range from 71 (flour) to 86 (concentrate) based on the sulfur amino acids, which are first limiting. However, when the FNB reference pattern with its lower sulfur amino acid requirement is used, soy proteins score 96 to 100. By contrast, the rat amino acid pattern has a high requirement for methionine plus cystine (the lysine level is also high) and results in soy protein scores of only 50 to 60.

Biological assays, in various forms, have been utilized to evaluate the nutritional value of soy proteins,[80,84] but the most widely used procedure is the Protein Efficiency Ratio (PER) method. The PER assay is the official method currently recognized by the Food and Drug Administration for regulatory purposes[85] and is expressed as the weight gained per unit weight of protein consnmed by rats nnder standard conditions.[86] Representative values for commercial soy products are as follows:

Product	PER	Ref.
Flours		87
Raw	1.3	
Lightly toasted	1.6	
Fully toasted	2.2	

Concentrate	2.3	23
Isolate	1.1—1.2	24
Casein (reference)	2.5	

The PER values of flours show the effects of moist heat treatment as discussed earlier (Figure 11). None of the soy products have PER values equal to that of casein because of their low methionine content relative to the requirements of the rat (Table 12). Since the amino acid requirements of man and the rat differ, use of the PER to evaluate protein quality for humans has beeu criticized and alternate methods are being sought.[80]

Recent tests have confirmed that soy proteins are of higher nutritional quality for humans than is indicated by rat PER assays.[88-92] Table 13 summarizes these studies that lead to the tentative conslusion that methionine supplementation of soy protein is unnecessary except perhaps for infants when soy is the sole source of protein.

Mineral availability has become of concern with increasing use of soy proteins as an important source of dietary protein. Bioavailability of zinc and iron has received major attention. Studies have been reported primarily for experimental animals, and only limited studies have been made with humans.[93]

In infants, absorption of iron from corn was 4.3% and from baked soybeans 9.4%, as compared to 28.5% from ferrous ascorbate. In a separate experiment, iron absorption from boiled soybeans was only 2.8%, while absorption from ferrous ascorbate was 16.7%.[94]

Human adults are able to absorb relatively high amounts of iron from soybeans as compared to other common plant foodstuffs:[95]

Food	% Iron absorbed
Black beans	3.2
Corn	5.9
Wheat	7.9
Hemoglobin	15.6
Soybeans (as cooked flour)	17.9
Fish	18.3
Veal	20.3

Metabolism of zinc in adolescent girls was not significantly affected by substitution of 30% of the meat in luncheon menus with textured soy flour. Soy protein in the diet had no effect on excretion of zinc in the urine or feces or retention of nitrogen by the subjects.[96]

Phytate, which constitutes about 70% of the total phosphorus in soybeans, has been found to decrease availability of zinc and may influence bioavailability of iron.[93] However, despite high concentrations of phytate in soy protein isolates, iron from these sources was 82 to 100% as available as ferrous sulfate when tested in rats. Naturally occurring phytate may behave differently than purified sodium phytate, which has been shown to inhibit absorption of iron.[97]

Four-week consumption of normal diets in which about 25% of the protein was replaced with soy protein concentrate showed no abnormalities in mineral metabolism in 92 human adult volunteer subjects. Blood serum levels of iron and zinc were the same for the soy diets as for the control diets containing conventional protein sources.[98]

FOOD USES OF SOYBEAN PROTEINS

Organoleptic Properties

Flavors associated with soybean protein products are regarded as one of the most important factors limiting their use in foods.[99] The level at which soy flavors are detectable depends on the type of soy protein and the kind of food. Bland foods, such as dairy products and white bread, are quite sensitive to flavor changes resulting from addition of soy proteins. In bread, soy flour levels of 2% cause detectable changes in flavor[100], whereas up to 20% of hydrated textured soy flour (10% on dry basis) is acceptable in beef patties.[101]

Descriptions of flavors are given in Table 14, which summarizes results of an organoleptic evaluation of an experimental raw, defatted soy flour and 18 samples of commercial samples of flours, concentrates, and isolates conducted in 1971. A 17-member taste panel evaluated 2% dispersions in charcoal-filtered tap water and scored them on a 10-point scale where 10 is bland and 1 is very strong. Only samples having the lowest and the highest scores for each protein type are given in Table 14. Raw flours typically have strong flavors of beany, green beany, and bitter. Moist heat treatment (toasting) decreases the intensities of these flavors and develops new ones such as "toasted" with the result that the flavor scores increase. Processing of flours and flakes into concentrates and isolates removes nonprotein constituents, yet scores for these products are about the same as for flours receiving the highest scores. Removal of beany and bitter flavors is obviously incomplete. Moreover, these flavors are detectable at low levels; beany flavor in a toasted soy flour was detected at a flour concentration of only 0.03%.[102]

Flavor compounds of various types have been isolated in the search for the constituents responsible for the objectionable flavors of soybean products. These include carbonyl compounds,[103] phenolic acids,[104] volatile fatty acids and amines,[105] volatile neutral compounds,[106] alcohols,[107] and phosphatidylcholine.[108] Among the many compounds isolated and identified, several have flavors similar to those attributed to soybean proteins (Table 15). Hexanal, for example, has a grassy flavor, a low threshold, and is often found to be the major volatile constituent obtained from soy protein products. It comprised 25% of the volatile fraction isolated from soy milk.[109] Oxidation of phosphatidylcholine results in bitterness, apparently as the result of conversion of linoleic acid to 9,12,13-trihydroxyoctadeca-10-enoic acid and 9,10,13-trihydroxyoctadeca-11-enoic acid. The level of these trihydroxy acids in ground soybeans and defatted meals increases on storage.[108,115] Phenolic acids have an astringent taste,[114] and at least nine of these compounds occur in soybeans. Among these are syringic, vanillic, ferulic, and *p*-coumaric acids.[104] The latter two are of additional interest because their thermal decarboxylation during cooking is believed to cause a cooked soybean odor.[116]

Origin of flavor compounds in soybean proteins is attributed largely to linoleic and linolenic acids. Their oxidation and degradation give rise to many of the compounds that contribute to the flavor. Such oxidation can occur by autoxidation and by lipoxygenase (lineolate/oxygen oxidoreductase, E.C. 1.13:11.12) catalysis. Soybeans are rich in lipoxygenase activity, and three isoenzymes have been isolated and characterized.[117,118] Evidence for a fourth isoenzyme also exists.[119] The isoenzymes have molecular weights of 100,000 but differ in a number of other physical properties, including pH optima and substrate preferences (Table 16).

In the intact seed, the oil is stored in the spherosomes or lipid bodies[121] and presumably is inaccessible to lipoxygenase catalysis, although the cellular location of the enzymes is still unknown. However, when the seed is crushed, enzyme and substrate can interact, especially if water is present. It has commonly been assumed that no reaction occurs when the seed is ground at ambient moistures, but recent studies make this assumption doubtful. In model systems of soybean lipoxygenase mixed with sunflower oil, oxidation occurred at relative humidities as low as 5%. Oxidation accelerated as the relative humidity was increased to 55 to 65%.[122] At a relative humidity of 5% at 25°C, defatted meal has an equilibrium moisture content below 5%;[123] hence, reaction may occur at very low moisture contents.

Commercial processing of soybeans into defatted flakes and oil is essentially a dry process, with the important exception of the conditioning step before flaking. At this point, the dehulled meats are tempered with steam to 11 to 12% moisture to make the meats plastic during flaking. The steaming step is, therefore, likely to cause additional lipid oxidation because of: (1) the large surface area; (2) the presence of oxygen; (3) the high surface moisture levels as the steam condenses; and (4) the warm temperature.

Early inactivation of lipoxygenase to prevent lipid oxidation is a key step in minimizing development of flavors during processing of soybeans into foods. Methods available for this purpose include: (1) grinding soybeans with water at 80°C or higher;[124] (2) dry heating of cracked beans followed by extrusion cooking;[125] (3) blanching of intact beans;[126] and (4) soaking of beans in aqueous alcohol.[127,128]

Functional Properties

Soybean proteins are often added to foods at low levels (>2%) to utilize their functional properties, i.e., physical attributes such as emulsification, water absorption, and adhesion that impart desirable characteristics to foods. At these levels, the contribution to nutrition is minor. At higher levels the proteins may be significant sources of protein, as well as contributing functional effects. Table 17 summarizes functional properties that have been ascribed to soybean proteins. For comprehensive coverage of functional properties, see recent reviews.[143,158-160]

Food Applications

Table 18 summarizes uses of the various soybean proteins in foods. For a detailed discussion of this topic, see the monograph by Smith and Circle.[1] A major outlet for soy flours is in baked goods — breads, sweet goods, and doughnuts. In many baked items, blends of soy flour and cheese whey have displaced the more expensive nonfat dry milk solids that were used formerly. Textured soy flours are used extensively as ground beef extenders both in the retail and institutional trade (restaurants, school cafeterias, and nursing homes). Textured flours are also used as meat analogs, where they replace the traditional products such as pizza toppings and bacon bits. A major use of concentrates is in processed meats for functional effects, including fat and water binding. Textured concentrates are added to ground beef and processed meats and are employed to extend sea foods such as shrimp.

Isolates, likewise, are widely used in meat products and are blended with other ingredients to formulate replacements for whole and nonfat dry milk. When textured, isolates can be given the fibrous structure of muscle fibrils. These products lend themselves to extension of ground beef, luncheon meats, and formed fish pieces, and to the complete replacement of meat when formulated into analogs.

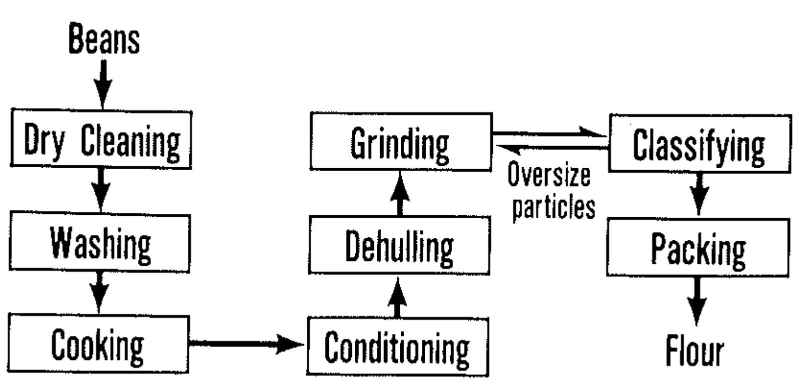

FIGURE 1. Flow diagram for production of full-fat soy flour.

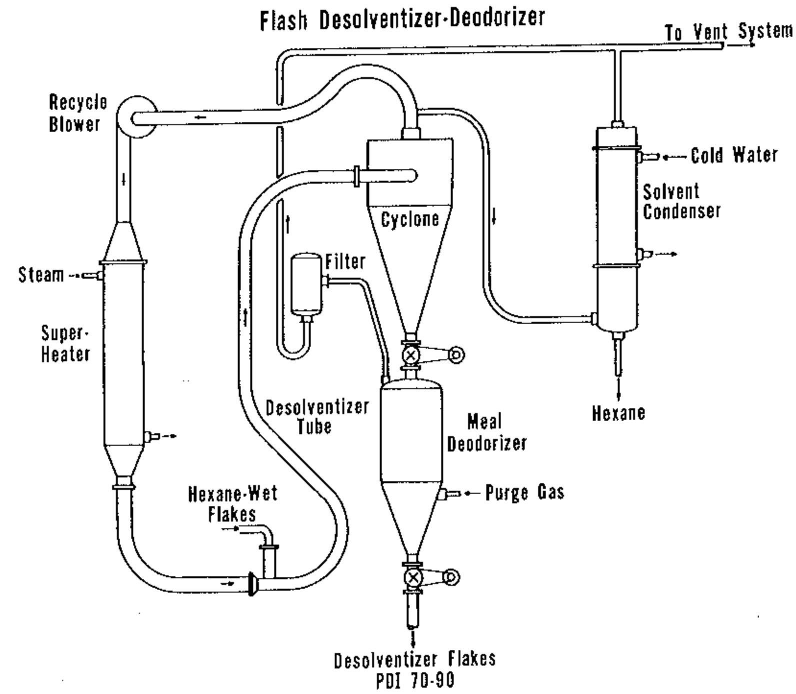

FIGURE 2. Flow diagram of flash desolventizer-deodorizer system for removing hexane from soybean flakes. (Courtesy of Blaw-Knox Chemical Plants, Inc.)

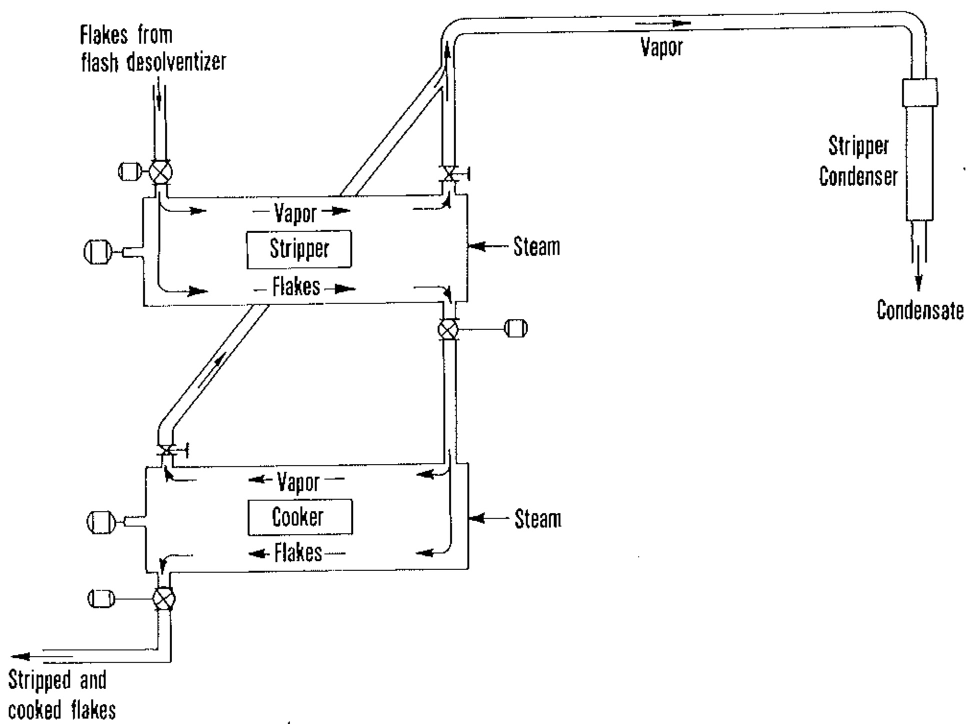

FIGURE 3. Flow diagram of flake stripper and cooker. (Modified from Milligan and Suriano, *J. Am. Oil Chem. Soc.*, 51, 158, 1974. With permission.)

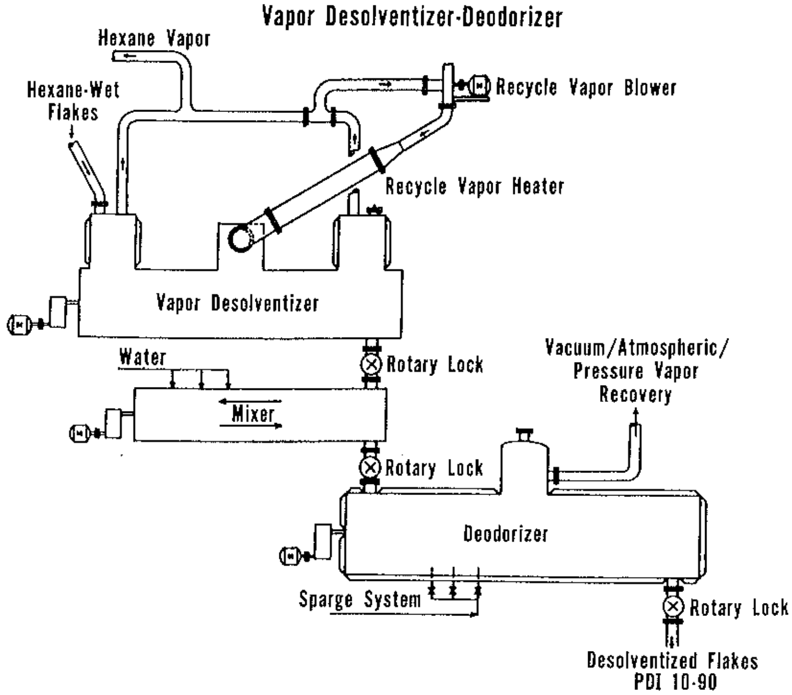

FIGURE 4. Flow diagram of vapor desolventizer-deodorizer system for removing hexane from soybean flakes. (Courtesy of Blaw-Knox Chemical Plants, Inc.)

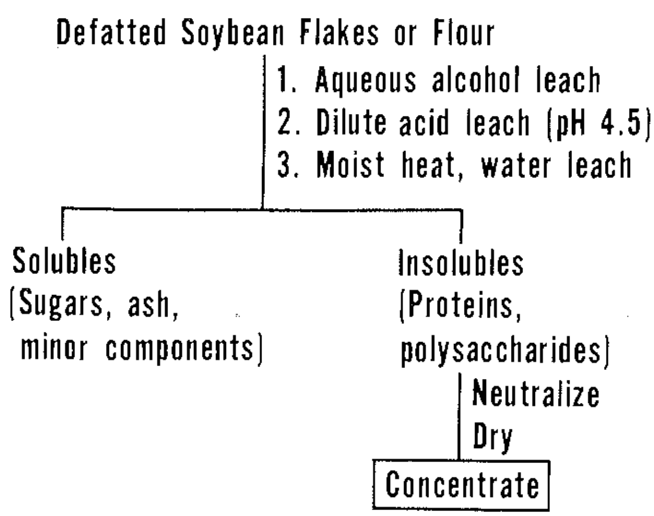

FIGURE 5. Outline of processes for preparing soy protein concentrates.

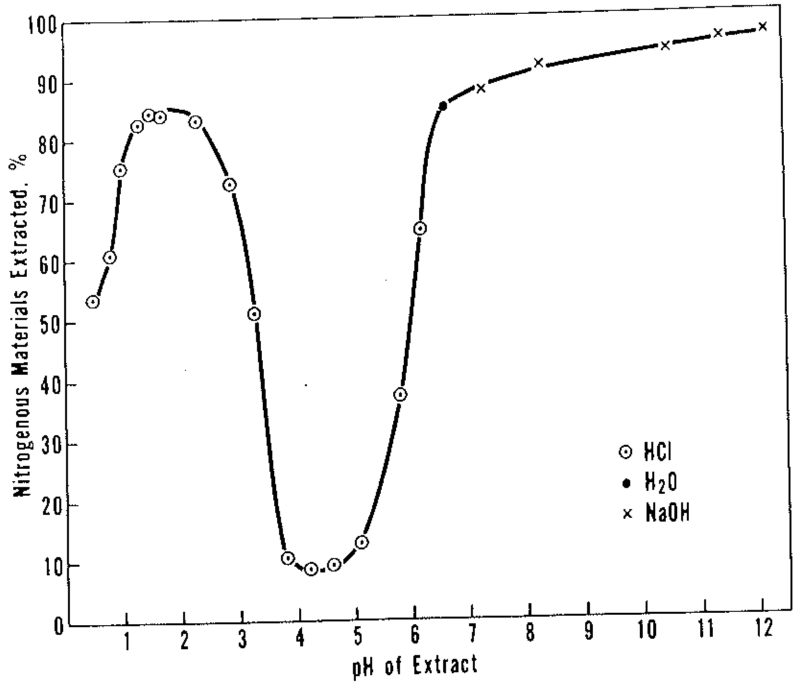

FIGURE 6. Extractability of proteins in defatted soybean meal as a function of pH. (From Smith and Circle, *Soybeans: Chemistry and Technology*, AVI Publishing, Westport, Conn., 1972. With permission.)

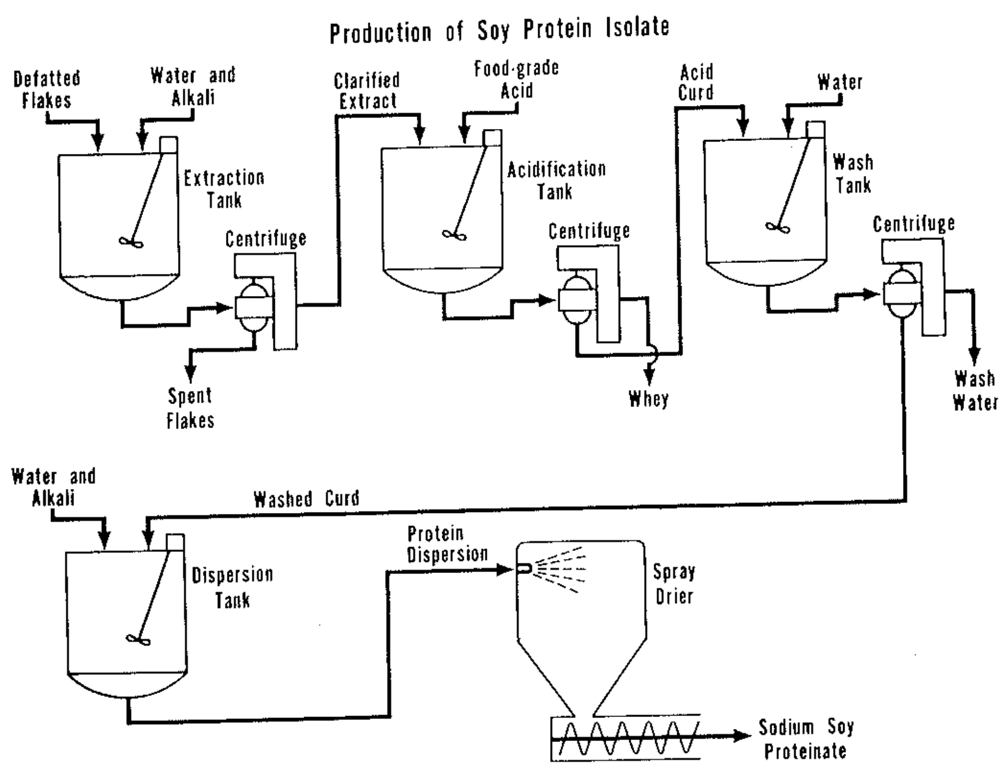

FIGURE 7. Flow diagram for commercial preparation of soybean protein isolates.

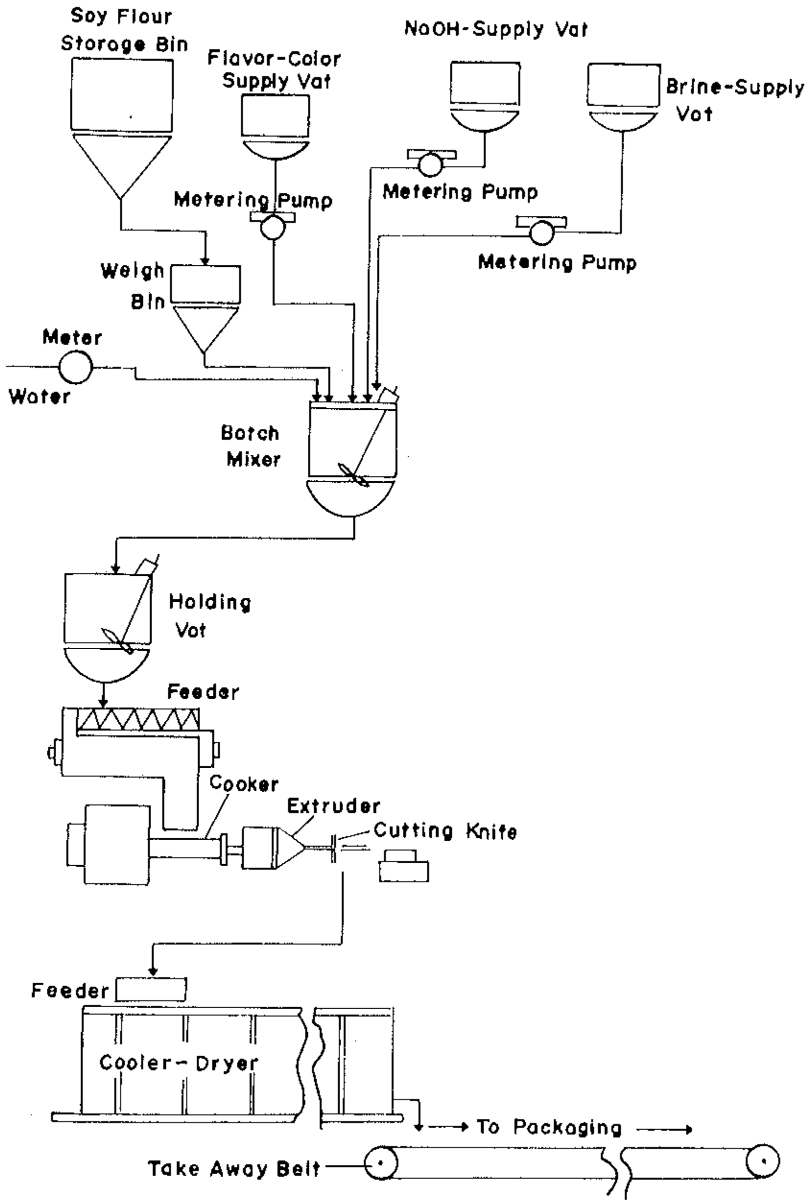

FIGURE 8. Flow diagram for texturizing soy flours by extrusion cooking. (From Ziemba, J., *Food Eng.*, Nov. 1969. With permission)

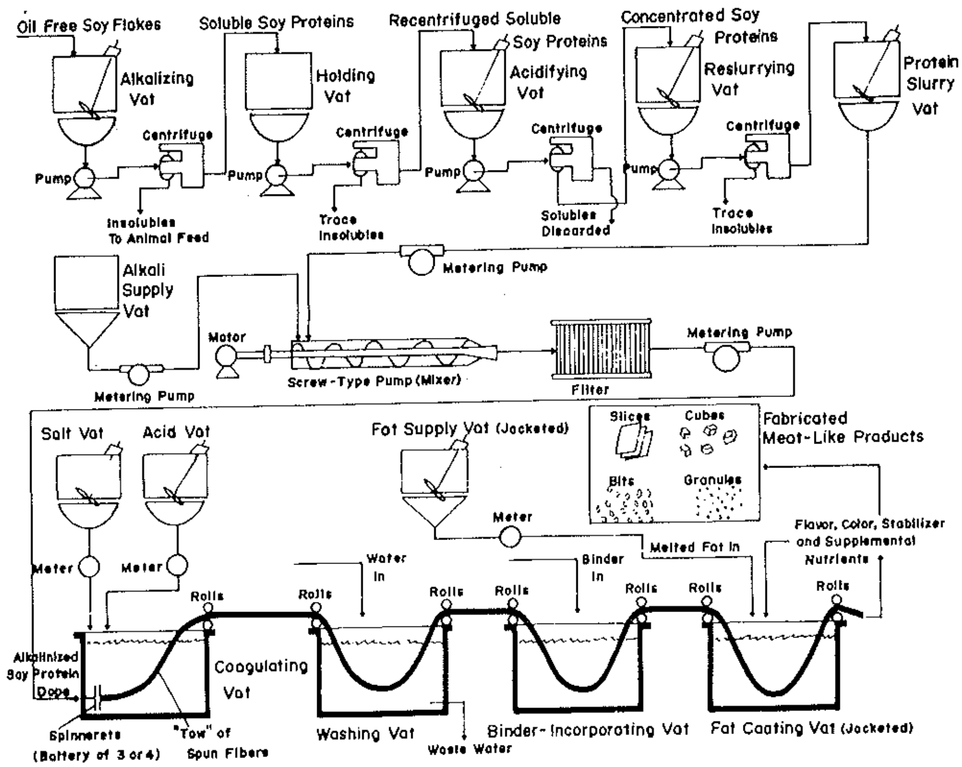

FIGURE 9. Flow diagram for manufacture of meat analogs by fiber spinning of protein isolates. (From Ziemba, J., *Food Eng.*, Nov. 1969. With permission.)

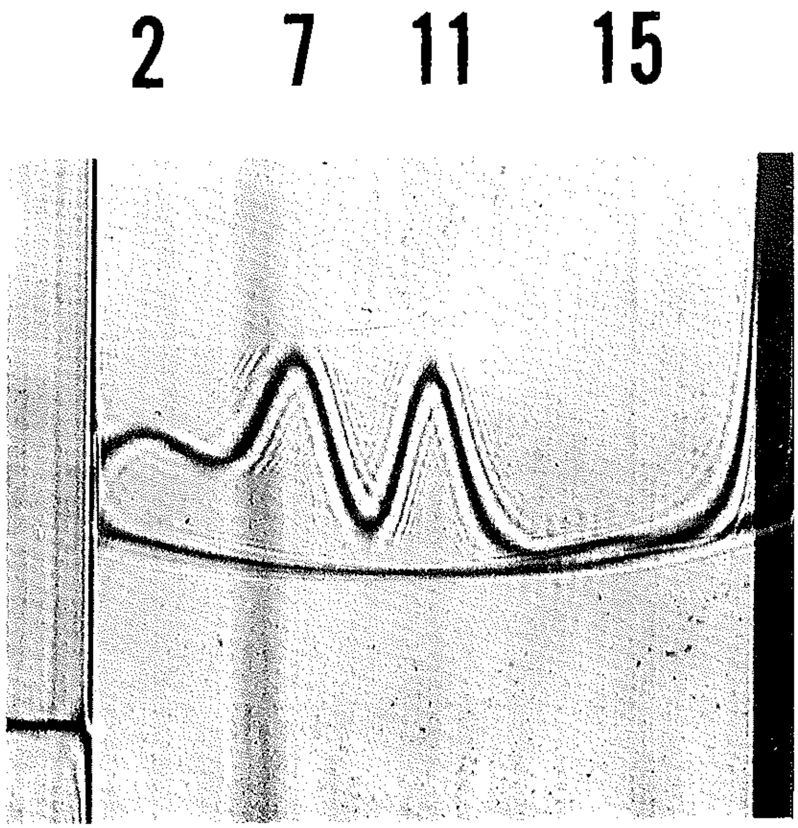

FIGURE 10. Utltracentrifuge pattern for water-extractable proteins in pH 7.6, 0.5 ionic strength buffer containing 0.01 *M* 2-mercaptoethanol. Numbers across top of pattern are sedimentation coefficients in Svedberg units.

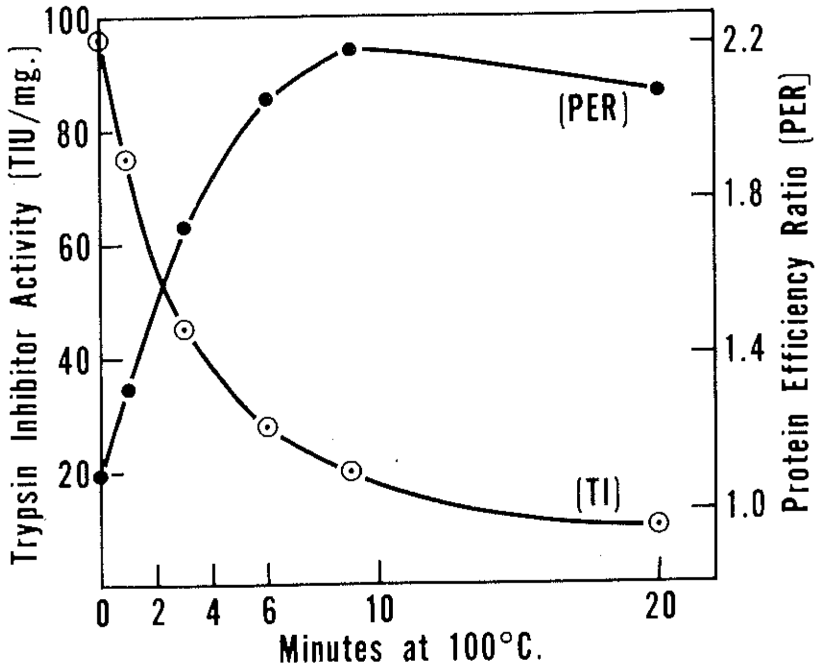

FIGURE 11. Effect of time of steaming at atmospheric pressure on trypsin inhibitor activity and protein efficiency ratio of soybean meal when fed to rats. (From Rackis, J. J., *J. Am. Oil Chem. Soc.*, 51, 161A, 1974. With permission.)

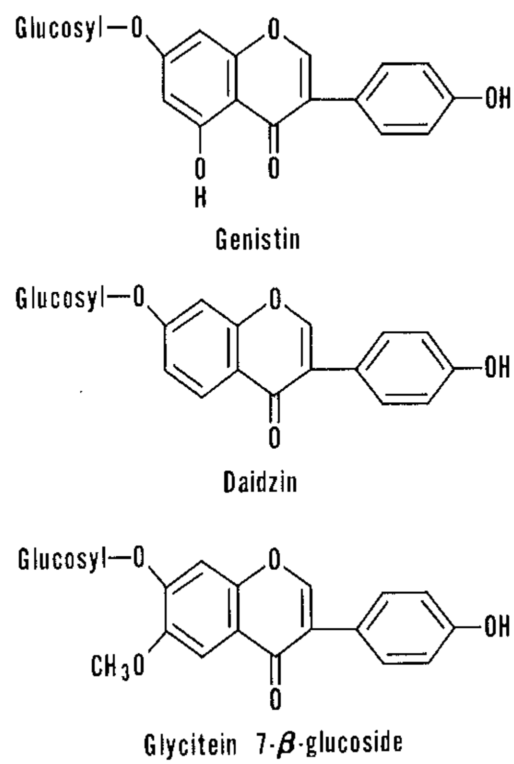

FIGURE 12. Structure of soybean isoflavone glucosides.

Table 1
U.S. PRODUCERS OF EDIBLE SOYBEAN PROTEIN PRODUCTS

	Product					
				Textured		
Company	Flours and grits	Concentrates	Isolates	Flours	Concentrates	Isolates
Archer Daniels Midland	+	+	+	+	+	
Cargill, Inc.	+			+		
Central Soya	+	+		+	+	
Dawson Mills	+			+		+
Far-Mar-Co., Inc.	+			+		
General Foods Corp.						+[a]
Grain Processing Corp.			+			
Griffith Laboratories		+		+		
Honeymead Products	+					
Kraft, Inc.			+			
Lauhoff Grain	+			+		
Miles Laboratories						+[a]
Ralston Purina			+	+		+
A. E. Staley Manufacturing	+	+	+[b]	+	+	

[a] Meat analog containing soy protein concentrate and isolate.
[b] Enzyme-modified isolates used as whipping agents.

Table 2
PRODUCTION ESTIMATES FOR EDIBLE SOYBEAN PROTEIN PRODUCTS (1979)[18]

Product	Minimum protein content (%)	Annual production (million lb)
Defatted flours and grits	50	625—650
Concentrates	70	60
Isolates	90	85—90
Textured flours	50	90—100
Textured concentrates	70	5
Textured isolates	90[a]	<0.5

[a] Dry basis.

Table 3
TYPICAL PROXIMATE ANALYSES OF COMMERCIAL EDIBLE SOYBEAN PROTEIN PRODUCTS[19]

Product	Moisture (%)	Protein[a] (%)	Fat (%)	Crude fiber (%)	Ash (%)	Carbohydrates[b] (%)
Full-fat flour	5.3	43.3	22.0	2.5	5.0	21.9
Defatted flour[c]	6.5	51.6	0.9	2.9	6.1	32.0
Low-fat flour[d]	5.9	48.8	7.0	2.6	5.6	30.1
Lecithinated flour	6.0	43.0	14.9	3.5	5.6	27.0
Concentrate	5.8	67.8	0.9	3.7	4.7	17.1
Isoelectric isolate	5.4	88.8	2.5	0.4	2.3	0.6
Sodium proteinate	5.2	87.8	3.0	0.2	3.6	0.2

[a] Kjeldahl N × 6.25.
[b] By difference.
[c] High nitrogen solubility index (>60).
[d] High nitrogen solubility index (>55).

Table 4
MINERAL AND TRACE ELEMENT CONTENT OF SOYBEANS AND COMMERCIAL EDIBLE PRODUCTS[a]

Element	Experimental soybean meal[b]	Commercial products[c] Defatted soy flour	Concentrate	Isoelectric isolate	Sodium proteinate isolate
Aluminum	4	9	9	14	27
Arsenic	<0.04	<0.05	0.14	<0.05	<0.05
Calcium	2220	2260	3015	1835	2500
Chlorine	105	1600	—	160	460
Cobalt	0.24	—	—	—	—
Copper	20	15	15	11	17
Fluorine	1.9	—	—	—	—
Iodine	0.84	<0.05	0.18	—	<30
Iron	137	82	10	140	124
Lead	1	<0.05	<0.12	<0.2	<0.20
Magnesium	3100	2818	2167	385	695
Manganese	38	32	41	15	27
Phosphorus	7100	7146	6200	7180	8293
Potassium (%)	2.52	2.35	1.29	0.11	0.21
Selenium	<0.5	—	—	—	—
Sodium	4	152	190-2250[d]	285	11,275
Sulfur	5000	4000	440	6520	5900
Zinc	52	53	36	55	70

[a] Expressed in ppm except for potassium, which is in percent.
[b] Defatted but not dehulled.[20]
[c] Reference 19.
[d] Varies with process used for preparation.

Table 5
VITAMIN CONTENTS OF SOYBEANS AND COMMERCIAL EDIBLE SOYBEAN PROTEIN PRODUCTS[a]

Vitamin	Mature soybeans	Defatted soy flour	Protein concentrate	Protein isolate
β-Carotene	0.2—2.4	<0.01	<0.01	<0.01
Thiamine	11.0—17.5	9.0[b]	3.1[b]	1.5[b]
Riboflavin	2.3	2.7	1.8	1.5
Niacin	20.0—25.9	21.1	11.6	6
Pantothenic acid	12	2.3	2.1	5.7
Pyridoxine	6.4	6.2	2.6	1.6
Biotin	0.6	0.5	0.5	0.1
Folic acid	2.3	2.6	3.6	0.9
Inositol	2.5—3.9	1.8	1.2	1.5
Choline	3.4	4.3	0.7	1.2
Ascorbic acid	0	0.1	0.06	0.1
Cyanocobalamin	—	0.11[b]	0.05[b]	<2[b]

[a] Reference 21 except as noted otherwise. Expressed as mg/g except for cyanocobalamin, which is mg/100 g.
[b] Reference 19.

Table 6
AMINO ACID CONTENT OF EDIBLE SOYBEAN PROTEIN PRODUCTS

	Content (g/16 g N)		
Amino acid	Flour[22]	Concentrate[23]	Isolate[24]
Essential			
Lysine	6.4	6.3	6.4
Methionine	1.1	1.4	1.3
Cystine	1.4	1.6	1.3
Tryptophan	1.4	1.5	1.4
Threonine	3.9	4.2	3.7
Isoleucine	4.6	4.8	4.9
Leucine	7.8	7.8	8.0
Phenylalanine	5.0	5.2	5.4
Valine	4.6	4.9	4.7
Nonessential			
Arginine	7.3	7.5	7.8
Histidine	2.6	2.7	2.7
Tyrosine	3.8	3.9	3.9
Serine	5.5	5.7	5.0
Glutamic acid	18.6	19.8	21.0
Aspartic acid	11.8	12.0	11.9
Glycine	4.3	4.4	4.1
Alanine	4.3	4.4	4.1
Proline	5.5	5.2	5.5
Ammonia	1.9	1.9	—

Table 7
CONSTITUENT SUGARS OF TOTAL CARBOHYDRATES AND SOLUBLE SUGAR CONTENT OF EDIBLE SOYBEAN PROTEIN PRODUCTS

Sugars	Flour (%)	Product concentrate (%)	Isolate (%)
Constituent sugars[a]			
Rhamnose	0.56	0.40	0.04
Fucose	0.09	0.09	0.03
Ribose	0.13	0.05	0.19
Arabinose	2.37	2.18	0.13
Xylose	0.97	0.92	0.07
Mannose	0.94	0.74	0.75
Galactose	7.60	5.69	0.51
Glucose	8.14	5.06	0.50
Fructose[b]	5.1	0.7	—
Pinitol	0.87	0.08	0.01
Soluble sugars[c]			
Monosaccharides	0.47	0.10	—
Sucrose	7.32	0.92	—
Raffinose	0.88	0.05	—
Stachyose	4.57	0.71	—

[a] Determined by acid hydrolysis and gas-liquid chromatography of alditol acetate derivatives except for fructose, which was estimated from the oligosaccharide content.

[b] Estimated from oligosaccharide content.

[c] Determined by liquid chromatography

From Eldridge, A. C., Black, L. T., and Wolf, W. J., *J. Agric. Food Chem.*, 27, 799, 1979. With permission.

Table 8
APPROXIMATE AMOUNTS AND COMPONENTS OF ULTRACENTRIFUGE FRACTIONS OF WATER-EXTRACTABLE SOYBEAN PROTEINS

Fraction	% of total[26]	Components	Mol wt	Ref.
2S	22	Trypsin inhibitors	8,000, 21,500	27
		Cytochrome *c*	12,500	28
		Chalcone-flavone isomerase	15,600	29
		Alcohol dehydrogenase	53,000	30
		β-Amylase	57,000	31
7S	37	Malate dehydrogenase	67,000—70,000	32
		Lipoxygenases	100,000	33
		7S Globulin (γ-conglycinin)	104,000	34
		Agglutinins	110,000	35
		Lactate dehydrogenase	140,000	36
		Malate dehydrogenase	140,000—145,000	32
		α-D-galactosidase	150,000	37
		α-D-mannosidase	170,000—180,000	38
		7S Globulin (β-conglycinin)	180,000	39
		Acid phosphatase	240,000	40
11S	31	11S Globulin (glycinin)	307,000—317,000	41
15S + >15S	11	Urease	480,000	42

Table 9
BIOLOGICALLY ACTIVE SUBSTANCES IN RAW SOYBEANS, THEIR BIOLOGICAL RESPONSES, AND MEANS FOR ELIMINATION

Substance	Biological response	Method of elimination	Ref.
Trypsin inhibitors	Increased synthesis and secretion of pancreatic enzymes, pancreatic hypertrophy, and inhibition of growth	Moist heat treatment	48
Agglutinins	Agglutination of red blood cells	Moist heat treatment; pepsin digestion	49—51
Goitrogen	Enlargement of thyroid gland	Addition of iodide to diet; autoclaving	52—53
Estrogens	Inhibition of growth; increased uterine weight	Extraction with aqueous ethanol; preparation of isolates	54—58
Allergen	Allergy and asthma	Autoclaving	59—61
Raffinose and stachyose	Flatulence	Aqueous extractions as used in preparation of concentrates and isolates, soaking, germination, or fermentation	62—69

Table 10
ISOFLAVONE AND COUMESTROL CONTENT OF SOYBEANS

Compound	Concentration in soybeans[a] (ppm)	Relative estrogenicity[b]
Genistein	14	1
Genistin	1644	
Daidzein	6	0.75
Daidzin	581	
Glycitein	1	
Glycitein 7-β- glucoside	338	
Coumestrol	0.05[c]	35
Diethylstilbestrol	—	10^5

[a] Reference 54 except as noted otherwise.
[b] Reference 72.
[c] Reference 73.

Table 11
FLATUS PRODUCTION BY EDIBLE SOY PRODUCTS IN HUMANS

Product	Daily intake (g)	Flatus vol (cm^3/hr)
Full-fat flour	146	30
Defatted flour	146	71
Protein concentrate	146	36
Soy proteinate (isolate)	146	2
Water-insoluble residue[a]	146	13
Whey solids[b]	48	300
80% ethanol extractives[b]	27	240
Basal diet	146	13

[a] Fed at a level three times that present in defatted flour diet.
[b] Amount equal to that present in 146 g of defatted flour.

Table 12
COMPARISON OF ESSENTIAL AMINO ACID REQUIREMENTS FOR MAN AND THE RAT WITH COMPOSITION OF SOYBEAN PROTEINS[a]

	Requirement			Content in soy products[e]		
	Man					
Amino acid	FAO/WHO[b] (%)	FNB[c] (%)	Rat NRC/NAS[d] (%)	Flour (%)	Concentrate (%)	Isolate (%)
Lysine	5.5	5.1	5.8	6.4	6.3	6.4
Threonine	4.0	3.5	4.2	3.9	4.2	3.7
Methionine + cystine	3.5	2.6	5.0	2.5	3.0	2.6
Tryptophan	1.0	1.1	1.3	1.4	1.5	1.4
Valine	5.0	4.8	5.0	4.6	4.9	4.7
Leucine	7.0	7.0	6.3	7.8	7.8	8.0
Isoleucine	4.0	4.2	4.2	4.6	4.8	4.9
Phenylalanine + tyrosine	6.0	7.3	6.7	8.8	9.1	9.3
Histidine	—	1.7	2.5	2.6	2.7	2.7
Arginine	—	—	5.0	7.3	7.5	7.8

[a] Expressed as percent of protein.
[b] Food and Agriculture Organization/World Health Organization.[81]
[c] Reference 82.
[d] National Research Council, National Academy of Sciences.[83]
[e] From Table 6.

Table 13
SUMMARY OF RESULTS OF FEEDING SOY PROTEINS TO HUMANS

Subjects	Test materials	Results	Ref.
Infants	Isolate plus methionine, cow's milk, human milk	No significant differences in growth between three protein sources	88
Young children	Isolates, cow's milk	Nitrogen retention of isolates equal to that of milk	89
Adults	Textured soy flour, beef	50 g soy protein/day gave positive nitrogen balance and equal to that of beef	90
Adults	Isolate with and without added methionine	Methionine is limiting at low intake but requirement is met at higher intakes	91
Adults	Isolate with and without added methionine	Dietary allowance for protein meets methionine requirement; methionine supplementation unnecessary and probably undesirable	92

Table 14
FLAVOR SCORES AND DESCRIPTIONS OF EDIBLE SOYBEAN PROTEIN PRODUCTS

Product	NSI[a]	Score[b]	Description
Raw flour	92	4.1	Raw beany, beany, bitter, green beany
Flour A	80	4.2	Bitter, beany, green beany
Flour G	48	5.7	Beany, bitter
Concentrate A	—	5.6	Bitter, beany
Concentrate E	—	7.0	Beany
Isolate A	—	5.9	Beany, cardboard
Isolate F	—	6.4	Beany, flour, nutty, chalky, bitter

[a] Nitrogen Solubility Index.
[b] 1 = strong; 10 = bland.

N AND

.ucts[e]

Isolate (%)
6.4
3.7
2.6
1.4
4.7
8.0
4.9
9.3
2.7
7.8

Table 15
COMPOUNDS WITH FLAVORS ATTRIBUTED TO SOYBEAN PROTEIN PRODUCTS

			Flavor threshold		
Compound	Source	Flavor description	Conc. ppm	Dispersion medium	Ref.
n-Hexanal	Soybean milk	Green, grassy	0.15	Paraffin oil	109, 110
Ethyl vinyl ketone	Soybean milk	Green bean	<5	Soybean milk	111
2-Pentyl furan	Soybean milk	Beany	1	Soybean oil	109, 112
Oxidized phosphatidylcholine fractions	Soybean flakes	Bitter	500	Water	108
Mixture of 9,12,13-trihydroxy-octadec-trans-10-enoic and 9,10,13-trihydroxy-octadec-trans-11-enoic acids	Oxidized linoleic acid	Bitter	200—300	Water	113
Vanillic, ferulic, and syringic acids	Soybean flour	Astringent	30—240	Water	104, 114

Table 16
PROPERTIES OF SOYBEAN LIPOXYGENASE ISOENZYMES[117-119]

Property	Isoenzyme L-1	Isoenzyme L-2	Isoenzyme L-3
Isoelectric point	5.68	6.25	6.15
pH optimum	9.5	6.5	5.5—8.0
Effect of Ca^{++}	None[120]	Stimulatory	Inhibitory
Heat stability	Stable	Unstable	—
Substrate preference[a]	Free acid	Ester	Ester

[a] Comparison of activity with linoleic acid and methyl linoleate.

Table 17
FUNCTIONAL PROPERTIES OF SOYBEAN PROTEINS IN FOOD SYSTEMS

Functional property	Protein form used[a]	Food system	Ref.
Adhesion	C, I	Sausages, luncheon meats, meat patties, meat loaves, and rolls	129
	I	Dehydrated meats	130
Aeration	I	Whipped toppings, chiffon mixes, confections	131—134
Color control			
Bleaching	F	Breads	135
Browning	F	Breads	136
	F	Snack crackers	137
Dough formation	F, C, I	Baked goods	131, 138
Emulsification			
Emulsifying capacity	F, C, I	Frankfurters, bologna, sausages	129, 139
		Breads, cakes, soups	135
Emulsion stability	F, C, I	Frankfurters, bologna, sausages	129, 139—140
	F	Soups	135
Fat absorption			
Promotion	F, C, I	Frankfurters, bologna, sausages, meat patties	129, 135
Prevention	F	Doughnuts	141
		Pie crusts	142
Solubility-Dispersibility	Soybeans, I	Beverages	126, 143, 144
Texture			
Viscosity	F	Soups	135
Film formation	I	Frankfurters, bologna	131
	I, soy milk	Yuba	145, 146
Gelation	F, C, I	Fish paste	147
	Soy milk	Tofu	148, 149
	I	Cured meats	150
Chip and chunk formation	F, C	Extruded meat extenders and analogs	151—153
Fiber formation	I	Meat extenders and analogs	151—154
Water binding	I	Minced fish	155
	I	Turkey rolls	156
	I	Minced meat	157
	I	Cured meats	150

[a] F, C, and I represent flours, concentrates, and isolates, respectively.

Table 18
FOOD USES OF SOYBEAN PROTEIN FORMS

Protein form	Minimum protein content (%)	Food product use
Flours	50	Baked goods
		Nonfat dry milk replacers
		Breakfast cerals
		Diet foods
		Infant foods
		Soup mixes
		Confections
Textured flours	50	Ground beef — soy blends
		Processed meats
		Meat analogs
		Baked snacks
		Ground beef extenders
Concentrates	70	Processed meats
		Frozen meat dinners
		Breakfast cereals
		Infant foods
Textured concentrates	70	Ground beef — soy blends
		Processed meats
		Seafood extenders
		Meat analogs
Isolates	90	Processed meats
		Whole and nonfat dry milk replacers
		Coffee whiteners
		Infant foods
		Casserole mixes
		Cake mixes
		Beverage products
		Confections
Textured isolates	90	Meat extenders
		Meat analogs

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