Soy Protein Products: Processing and Use[1]

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ABSTRACT Soy protein products are mainly used as ingredients in formulated foods and seldom are seen by the public. They consist of four broad categories. (1) Most soy proteins are derived from "white flakes," made by dehulling, flaking and defatting soybeans by hexane extraction. These may then be milled into defatted flours or grits containing ~50–54% protein; extracted with ethanol or acidic waters to remove flavor compounds and flatulence sugars, producing soy protein concentrates containing 65–70% protein; or processed into soy protein isolates containing 90+% protein by alkali extraction of the protein, removal of fiber by centrifugation and reprecipitation and drying of the protein. (2) Full-fat products are made in enzyme-active and in toasted forms. (3) Various dried soyfoods, including soy milk and tofu, are produced. (4) Mixtures of soy proteins with cereals, dried milk or egg fractions, gelatin, stabilizers and emulsifiers are offered for specific baking, whipping, breading and batter applications. Texturized products, resembling meat chunks or bacon chips, are made by extrusion of flours and concentrates or spinning of isolates. Soy protein ingredients are used in compounded foods for their functional properties, including water and fat absorption, emulsification, aeration (whipping) and heat setting and for increasing total protein content and improving the essential amino acids profile. J. Nutr. 125: 573S–580S, 1995.

INDEXING KEY WORDS:

- *soy protein ingredients* • *flours*
- *concentrates* • *isolates*

Soy food protein products are sold primarily in bulk as ingredients for remanufacture into formulated foods. The public can directly purchase only a few products, such as imitation bacon bits and "all-vegetable meats." Extrusion-texturized pieces, resembling ground or chunk meats, may be noticed in commercially made hamburgers, pizza toppings and canned stews. Most soy ingredients are dry powders used for functional purposes and assume the appearance of the manufactured food.

The major tonnage of soy protein products is derived from dehulled, solvent-extracted intermediates known as defatted or "white" flakes. Domestic production figures are not made public because of the limited number of manufacturers. Lusas (1993) estimated world production of soy flours at 2,300,000 metric tons, soy protein concentrates (SPCs)[3] at 150,000 metric tons and soy protein isolates (SPIs) at 200,000 metric tons, with most produced in the United States for food, pet foods and feed uses. Exports and installations of overseas manufacturing facilities have increased in recent years.

Other soy proteins include enzyme-active and deactivated full-fat flours, dried soymilks and tofus and mixtures of soy proteins, dairy and egg fractions, gelatin and stabilizers for special uses. Kosher and pareve ingredients, which carry O.U. symbols of identification, are offered domestically. Organically grown and nonchemically processed soy protein ingredients also are available in health food stores.

A general processing flow sheet is shown in **Figure 1**. Manufacturers typically are secretive about the details of their processes, and essentially similar products are produced by different techniques. Compositions of selected commercially produced products are shown in **Table 1**; protein is expressed as N × 6.25.

Two major analytical methods are used to assess effects of heat received during manufacturing and subsequent storage on loss of protein solubility. The protein dispersibility index (PDI; AOCS Official Method Ba-10-65, 1993) rapid-stir method uses a blender, whereas the nitrogen solubility index (NSI; AOCS Official Method Ba-11-65 1993) slow-stir

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[3] Abbreviations used: NSI, nitrogen solubility index; PDI, protein dispersibility index; RPE, relative protein efficiency; SPC, soy protein concentrate; SPI, soy protein isolate.

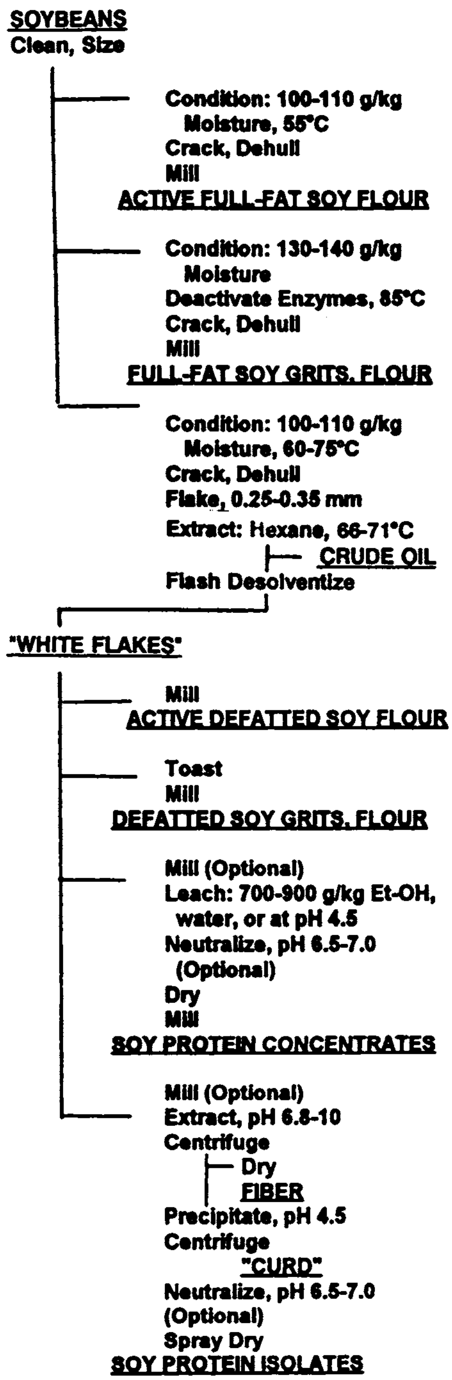

FIGURE 1 Flow sheet for production of soy protein food ingredients.

method uses a laboratory stirrer (AOCS Official Methods, 1993). In both methods the protein or nitrogen that is leached into the liquid phase is compared with total protein or nitrogen in the sample by Kjeldahl analysis. The NSI method gives lower values (Central Soya Company 1988) and has been related to PDI by the formula: PDI = 1.07 (NSI) + 1.

Full-fat flours and grits

Enzyme-active flours. Limited quantities of enzyme-active soy flour have been produced since the mid-1930s for use as dough conditioners in the baking industry (Heiser and Trentleman 1989). Mature, whole, yellow soybeans are used for human food production (Figure 1). They are cleaned, preferably sorted into uniform size to minimize variations in processing, equilibrated to 10–12% moisture and cracked into six to eight pieces by using corrugated rolls. Preheating enhances loosening of hulls from the cotyledons during cracking and aids their removal by aspiration. The raw cotyledons are then milled into full-fat enzyme-active flours. It should be noted that high-PDI, hexane-defatted flours also are enzyme-active, but the nonextracted full-fat versions also continue to be used in the baking industry.

Full-fat flours and grits. Most domestic fat-containing flours are prepared by "refatting" solvent-extracted flours as described later. Direct manufacture of full-fat soy flour was suspended in the United States because of objections to strong "beany" flavors developed by lipoxygenase under the favorable moisture, heat and time conditions of processing. The development of strong off-flavors has been greatly reduced in recent years by enzyme-deactivating techniques including (1) conditioning soybeans at 13–14% moisture in hot air before dehulling and milling (Figure 1), (2) microwave heating before cracking and dehulling and (3) rapid processing of dehulled cotyledons by extruders (Kanzamar et al. 1993). The flavor of full-fat soybean flour can be made more nutty by toasting at higher temperatures or for prolonged periods, which also reduces the PDI. The term "toasting" refers to moist cooking with steam under atmospheric or pressurized conditions and may be misleading to people from outside the industry (Soya Bluebook 1993).

White flake products

White flakes. Defatted soy flours and grits and SPCs and SPIs typically are made from white flakes. Their many uses have also led to storage and sales of white flakes as an intermediate form in its own right. White flakes are produced (Figure 1) by cleaning, heating and cracking soybeans; removing the hulls by aspiration; flaking the chips to ~0.25–0.30 mm thickness and extracting the oil by hexane to 0.5–1.0% (Fulmer 1989, Kanzamar et al. 1993, Milligan 1981). Oil in soybeans occurs in spheresomes in cotyledon cells and is normally walled off from enzymes. Flaking ruptures the spheresomes and allows the oil to flow together, where it becomes accessible to lipases, and especially to lipoxygenase, in the presence of heat and moisture. Significant advances have been made in reducing beany flavor in defatted-soy flours by rushing the flakes into the extractor and by preheating the soybeans before dehulling or flaking where appropriate for the PDI objective of the specific product.

Extracted soybean meals intended for animal feeds typically are steamed in toasters to distill the residual

TABLE 1

Claimed approximate compositions of commercial soy food ingredients

Material	Moisture	Protein (N × 6.25)	Fat (pet. ether)	Crude fiber	Ash	Carbohydrates (by difference)
Full-fat soy flours						
Enzyme-active, as is, g/kg	<100	420 mfb	210	—	47	—
White flake products						
High PDI white flakes						
as is, g/kg	70	550 mfb	7	31	61	—
Defatted flours & grits[1]						
as is, g/kg	60–80	520–420	5–10	25–35	50–60	30–32
mfb, g/kg	0	560–590	5–11	27–38	54–65	32–34
Concentrates[1]						
as is, g/kg	40–60	620–690	5–10	34–48	38–62	19–21
mfb, g/kg	0	650–720	5–10	35–50	40–65	20–22
Isolates[1]						
as is, g/kg	40–60	860–870	5–10	1–2	38–48	30–40
mfb, g/kg	0	900–920	5–10	1–2	40–50	30–40
Specialty products						
Whipping protein						
(with salt), as is, g/kg	<70	>630	—	—	<180	—
Whipping protein B						
(salt, sucrose) as is, g/kg	<70	>630	<4	—	<160	—
Fiber (from isolate processing)				Dietary		
as is, g/kg	60	120	2	750	45	—
Fiber (from soy hulls)				Dietary		
as is, g/kg	35	15	5	920	25	—
Spray-dried soy foods						
Soymilk						
Full-fat, as is, g/kg	<100	380	180	—	<70	—
Low-fat, as is, g/kg	<50	480	90	—	<50	
Tofu						
Full-fat, as is, g/kg	<100	380	180	—	<70	
Low-fat, as is, g/kg	<50	480	90	—	<50	

mfb, moisture-free basis.

[1] Soy Protein Council (1987).

solvent and produce products with PDIs of 10–50. White flakes intended for food use are processed by flash solvent-removing systems and have PDIs as high as 95; rapidly moving super-heated hexane vapors and then vacuum are used to vaporize the solvent and prevent condensation of water on the surface of flakes (Vavlitis and Milligan 1993). The older Schnecken systems are able to achieve PDIs of up to 70 (Johnson and Kikuchi 1989). Soybean processors often produce white flakes with PDIs of 20, 70 and 90. Although high-PDI soy ingredients are more soluble, they also have highly active enzymes and antinutritional factors, which should be deactivated by heat before the final product is consumed. Horan (1974) reported the following relationships between heat treatment, PDI and relative protein efficiency (RPE, casein = 100): negligible heat treatment: PDI 90–95, RPE 40–50; light heat treatment: PDI 70–80, RPI 50–60; moderate heat treatment: PDI 35–45, RPE 75–80; and toasted: PDI 8–20, RPI 85–90.

Traditionally, soy flour has been defined as containing a minimum of 50% protein expressed on an as-is basis, and SPCs and SPIs have been defined as containing 70% and 90% protein minimums on a moisture-free basis, respectively. SPCs and SPIs containing <70% and 90% moisture-free protein are marketed. Further, protein in flours may be expressed on a moisture-free basis, protein in concentrates and isolates may be expressed on an as-is basis, and protein in some products may be expressed on a moisture-free basis with the other components expressed on an as-is basis. The user needs to be alert to these details when estimating compositions of formulas.

Flours, grits, refatted and lecithinated products. Defatted soy flour consists of white flakes milled to achieve over 97% passage through a U.S. 100-mesh sieve; finer grades (through 150, 200 and 325 mesh screens) also are available. Defatted soy grits are made by coarse milling white flakes, followed by sieving and recycling. Granulations of grits vary with manufacturers, e.g., coarse, through 10 mesh on 20 mesh; medium, through 20 mesh on 40 mesh; and fine, through 40 mesh on 80 mesh (Kanzamar et al. 1993). Most domestic fat-containing flours are refatted by the addition of refined soy oil or lecithin, often at 6% or 15%.

Soy protein concentrates. SPCs and SPIs may be made by extraction of white flakes or milled flours, depending on the extractor and drying system used. The main objective in producing SPCs is to remove strong-flavor components and the flatulence sugars (stachyose and raffinose), but other soluble compounds and some minerals also are extracted. In turn, both the protein and dietary fiber contents are increased. Three processes are used: extraction with aqueous (70–90%) ethyl alcohol, extraction with water at isoelectric pH (4.5) and denaturing the protein with moist heat before extraction with water (Ohren 1981, Soy Protein Council 1987). Alcohol extraction is considered to produce the blandest products. Mild-heat drying conditions are used in acidic water extraction processes to retain high PDIs and NSIs. Leaching with aqueous alcohol may reduce protein SFI to as low as 30, but this property can be restored to 70, equivalent to isoelectric-leached SPC in functionality, by a patented treatment using controlled heat, pH and shear. If an aqueous isoelectric extraction is used, the SPC may be neutralized to pH 6.5–7.0 before drying to increase its solubility in neutral pH food systems. A variety of granulations (from grits to ultrafine flours) may be produced if the SPC was made from white flakes, extracted and dried with minimum breakage (Beery 1989).

Soy protein isolates. Historically, SPIs were developed for making spun fibers by extruding alkaline soy protein solutions through rayon-making spinnerettes into acid-precipitation baths. SPCs were developed later as lower-cost, intermediate-flavor compromises between flours and SPIs for use in extrusion, meat processing, baking and baby food applications.

High-PDI (70–90) white flakes and flour milled to U.S. 200 mesh are used in making protein isolates. The protein is solubilized at pH 6.8–10 at 27–66°C by using sodium hydroxide and other alkaline agents approved for food use. The protein solution is then separated from the flakes or flour by centrifugation. The solids are recovered as a by-product, containing 16–36% protein, 9–13% crude fiber and 45–75% total dietary fiber when dried to 6–7% moisture content and have been marketed for food use. The solution is then acidified to pH 4.5, by using hydrochloric or phosphoric acid, and the protein is precipitated as a curd. The flow sheet shown in Figure 1 is greatly simplified, and a typical process includes several extractions of white flakes or flour and washings of the curd. The curd is then concentrated by centrifugation and can be neutralized to pH 6.5–7.0 or spray dried in its acidic form (Johnson and Kikuchi 1989).

Enzyme-modified isolated proteins. The precipitated SPI curd may be chemically or enzymatically modified, with adjustment to the optimum pH for the reaction, before drying. Current commercial product examples include whipping proteins used in aerated foods. In their production, acid-precipitated curd is adjusted to a pH range of 2.0–3.5; hydrolyzed with proteolytic enzymes such as pepsin, papain, ficin and trypsin or bacterial proteases to albumins with molecular weights of less than 14,000 and concentrated by evaporation. The pH is raised to 4.8–6.6 before spray drying. The resulting proteins can whip faster and to greater volumes than egg albumin, even in fat-inhibited systems, but do not have the heat-setting characteristics (Gunther 1978). These products may contain salts, resulting from neutralizing hydrochloric or other acids with sodium hydroxide or other bases and have high apparent ash contents. Sodium hexametaphosphate may be added as a whipping enhancer, and sucrose may be used to standardize performance.

Dried soyfoods

Dried soyfoods typically are first prepared by traditional processes—e.g., manufacturing of soy milk or tofus set by calcium or magnesium salts—and are then dried.

Mixtures of soy and other proteins

Various dry or coprocessed mixtures of soy and other proteins have been offered in the marketplace, usually to extend the functional properties of more expensive animal-source ingredients. Examples include mixtures of hydrolyzed proteins with egg albumin, gelatin and sodium hexametaphosphate for whipping applications; lecithinated soy flours and SPCs and egg yolks for emulsification applications in bakery applications; and soy flours and SPCs with dried nonfat milk or lactose-reduced whey for processed-meat applications.

Compositions of soy food proteins

Approximate compositions of selected soy food protein ingredients, as claimed by manufacturers, are shown in Table 1. Enzyme-active and toasted, nonextracted full-fat soy flours have the same compositions. Extrusion-texturized defatted flours and SPCs have essentially the same composition as the starting ingredient. The components of refatted products are diluted in proportion to the oil or lecithin added to the original flour or SPC. The compositions of flours, SPCs and SPIs are remarkably similar between competitors and seldom vary by >5% of the specific component.

Essential amino acid patterns for flours, SPCs and SPIs, claimed per unit weight of protein, are compared with U.S. National Research Council requirements (NRC 1989) in **Table 2**. The three types of products meet or exceed NRC requirements, with methionine plus cystine being the limiting amino acids.

SPCs and SPIs, alone, and texturized flours and SPCs must be fortified with prescribed vitamins and minerals when used as meat alternatives in school lunch and child nutrition programs. These requirements are shown in **Table 3**. Separate requirements exist for use in military ground beef applications.

Importance and alteration of functional properties

The establishment of today's soy food protein industry is well beyond the financial and technical limitations of developing countries. It has been driven primarily by the ability of soy products to meet functional needs in processed foods at lower cost than animal-origin ingredients.

The major functional properties sought include water and fat absorption, emulsification, aeration (foam volume and stability) and imparting of texture. The larger-molecular-weight soy proteins are thermosetting and result in firming of the final product on heating. Soy whipping proteins can be used to extend dried egg whites but do not heat set like egg albumen when used exclusively. However, they can be used in the manufacture of aerated confections, including marshmallows, which rely on drying of the foam rather than heat setting. Thermoplasticity—the ability to repeatedly melt and resolidify as imparted by casein to cheeses—is a much-desired functional property that has not been duplicated yet by soy proteins. However, SPIs can be used to extend sodium caseinate in imitation cheeses and other applications. It also is desired that functional food ingredients be light colored and bland and not detract from the appearance of the final product.

Functional properties of soy proteins can be altered in many ways, including heating, to reduce solubility; grinding, to increase particle surface area for adsorptive types of ingredients interactions; coating the particles with oil or lecithin or including surfactant compounds in product formulas; drying precipitated protein at the isoelectric point in contrast to neutralizing before drying; shearing ethanol-extracted SPCs to increase protein solubility; selecting pH and other conditions during extraction of SPIs; enzymatically hydrolyzing SPIs before drying and codrying proteins with food-grade dissociating agents and other additives for specific applications.

Fulmer (1989) recommended the following applications for defatted soy flour based on PDI: 90+—bleaching of white bread, fermentation and production of soy protein isolates and fibers; 60–75—doughnut and bakery mixes, pasta enrichment, baby foods, meat products, breakfast cereals and production of SPIs; 30–45—meat products and bakery mixes and 10–25—

TABLE 3

USDA-FNS soybean food protein fortification requirements for meeting a portion of the meat or meat alternative requirement of child nutrition programs

Component	Vitamins and minerals
	minimum per g protein
Vitamin A, *I.U.*	13
Thiamin, *mg*	0.02
Riboflavin, *mg*	0.01
Niacin, *mg*	0.30
Pantothenic acid, *mg*	0.04
Vitamin B6, *mg*	0.02
Vitamin B12, *μg*	0.10
Iron, *mg*	0.15
Magnesium, *mg*	1.15
Zinc, *mg*	0.50
Copper, *μg*	24
Potassium, *mg*	17

TABLE 2

Comparison of essential amino acid requirement patterns with soy food proteins

	NRC (1989) requirements by age			Soy protein ingredients[1]		
Amino acid	2–6	6–13	Adult	Defatted flours & grits	Protein concentrates	Protein isolates
	mg/g protein			*mg/g protein*		
Histidine	19	19	11	26	25	28
Isoleucine	28	28	13	46	48	49
Leucine	66	44	19	78	79	82
Lysine	58	44	16	64	64	64
Methionine + cystine	25	22	17	26	28	26
Phenylalanine + tyrosine	63	22	19	88	89	92
Threonine	34	28	9	39	45	38
Tryptophan	11	9	5	14	16	14
Valine	35	25	13	46	50	50

[1] Soy Protein Council (1987).

TABLE 4

***Functional properties of soy protein products in food*[1]**

Functional property	Mode of action	Food system	Product
Solubility	Protein solvation, pH dependent	Beverages	F, C, I, H
Water absorption and binding	Hydrogen-bonding entrapment of water, reduced product drip	Meats, sausages, breads, cakes	F, C
Viscosity	Thickening, water binding	Soups, gravies	F, C, I
Gelation	Protein matrix formation and setting	Meats, curds, cheeses	C, I
Cohesion-adhesion	Protein acts as an adhesive material	Meats, sausages, baked goods, pasta products	F, C, I
Elasticity	Disulfide links in deformable gels	Meats, bakery items	I
Emulsification	Formation and stabilization of fat emulsions	Sausages, bologna, soups, cakes	F, C, I
Fat absorption	Binding of free fat	Meats, sausages, doughnuts	F, C, I
Flavor binding	Adsorption, entrapment, release	Simulated meats, bakery items	C, I, H
Foaming	Forms film to entrap gas	Whipped toppings, chiffon desserts, angel cakes	I, W, H
Color control	Bleaching, (lipoxigenase)	Breads	F

[1] Kinsella (1979). F, flour; C, concentrate; I, isolate; H, hydrolysate.

baby foods, protein beverages, meat products and hydrolyzed vegetable proteins.

The classical Osborne classification of proteins as albumins (soluble in salt solutions), globulins (sparingly soluble in water but soluble in salt solutions), prolaminies (soluble in 70–80% ethanol but insoluble in water and absolute ethanol), glutelins (insoluble in all of the above solvents but soluble in acid or alkali) and scleroproteins (insoluble in aqueous solvents) provides some insight into mechanisms of separating oilseed proteins and their use. Approximately 20% of total nitrogen is lost as albumens when preparing isoelectric-leached SPCs or in production of SPIs. This includes the smaller (molecular weight < 20,000) proteins that are highly active as enzymes and antinutritional factors but also constitute the best amino acid-balanced protein fraction when heat deactivated. Although the Osborne classification is determined sequentially, the preparation of SPIs by alkali extraction essentially sweeps all soluble Osborne groups into one, except for the water-soluble fraction. Our pilot plant has been successful in capturing some of the albumins by ultrafiltration and reverse osmosis and demonstrating improved nutritional performance of the resulting SPCs and SPIs. However, membrane processes are not yet broadly used in the production of soy food proteins.

Most soy proteins are globulins, whose solubility and dissociation is greatly affected by pH and salt content of the solution. These can play a role in their extraction and performance in food systems where salts and acids are present. When preparing proteins for specific applications, e.g., the fortification of acidic juices or beverages, it may be advantageous to extract them under conditions that simulate their eventual use.

An often quoted, but still valid, guide to soy protein applications was developed by Kinsella (1979) and is shown in **Table 4**. A larger variety of modified proteins exists today, and many details should be considered with regard to the results sought in the product.

Food protein ingredients applications

Meats. Soy proteins are used as processing aids to bind and emulsify water and fat in making processed meats, as meat extenders or replacements in texturized forms, and in protein solutions pumped or absorbed into meat tissues. Essentially the same technology is applied to poultry and fish. Soy proteins will absorb three to four times their weight of water, compared with an equal weight of water for nonfat dry milk solids and are less costly to use in emulsified meat products. Current domestic laws permit the use of soy flour or SPCs at 3.5% or SPIs at 2% in cooked or fresh sausages without changing the category names of the products. Up to 8% soy flour, grits, SPCs or SPIs can be used individually or collectively in chili con carne. Up to 12% of these ingredients can be used in spaghetti with meat balls or Salisbury steak.

Two major advances in meat technology in recent years include restructuring of small pieces and trimmings into solid loaves and extending meats by pumping various solutions directly into the muscle. In restructuring meats, the small pieces are tumbled with dry SPCs or SPIs in the presence of salt and phosphates and then stuffed into casings or reusable holders and the texture is set by heat. Solutions of salt, phosphates and SPCs may be injected into muscle cuts, and the product can be tumbled to aid dispersion (Beery 1989, Bonkowski 1989, Hoogenkamp 1993, Rakes 1993.)

Typically, less pumping proteins are used than allowed by law to retain textures desired in the products.

Spun SPI fibers are sold for restructuring foods and also worked into tows and then colored, flavored and shaped to simulate fibrous meats. However, most texturized soy proteins are produced from soy flours or SPCs by extrusion. These products typically are texturized at the production site, dried and shipped in bags or bulk.

Extruders compress and work soy ingredients into a flowing, hot, plastic mass (Rokey et al. 1993). Before discharge, the mass is allowed to flow in a laminar fashion that enables the protein molecules to align under pressurized conditions. At the discharge die, long cells of superheated steam form and expand along the aligned molecules. They collapse with cooling and depressurization, leaving a palisade structure that resembles meat. In recent years, extruder manufacturers have learned how produce texturized products from flours and SPCs as low as 20–30 SFI. Red or brown colors may be added to the soy protein before texturization and flavors added before drying or packaging.

Up to 30% hydrated soy protein is permitted in commercially made hamburger patties provided the final product meets specified water-to-protein requirements. Except for low-cost applications, less than the maximum amount of permitted protein is usually used to achieve desirable product textures.

Bakery products. The use of enzyme-active soy flour at up to 0.5%, flour-weight basis, is permitted in standardized bakery foods. The active lipoxidase enzymes are credited for bleaching carotenoid pigments and producing peroxides that strengthen gluten proteins (Dubois and Hoover 1981).

Defatted flours are permitted in standardized bakery items at a maximum of 3%, flour-weight basis. The degree of toasting is especially important in bakery products, because soy flours will compete for water with other ingredients in the formula. Most flours for bread use have PDIs of 50–75, and 1 g of soy flour increases absorption of water by 1 g. By the use of soy flours, crumb body and resiliency, crust color (from reducing sugars) and toasting characteristics of breads and buns are improved. Usage of defatted soy flour in cakes at 3–6% produces smoother batters with more even distribution of air cells, a more uniform texture and softer and more tender crumbs. The inclusion of 2–4% defatted soy flour in sweet goods and yeast-raised doughnuts improves their water-holding capacity, sheeting characteristics and finished-product quality. The inclusion of 2–4% defatted soy flour improves structure, texture and eating qualities of cake doughnuts and reduces fat absorption during frying.

Lecithinated flours act as emulsifiers, blending aids, pan release agents and enhancers of vitamin stability because of the antioxidant effects of lecithin. They also are used to reduce amounts of egg yolks and shortening in formulas. Ingredients such as toasted soy grits and soy bran and fiber are used in multigrain breads (Dubois and Hoover 1981).

Other applications. SPIs have been used in making liquid coffee creamer and combined with fluid milk in making yogurts (Kolar et al. 1979). Tofus and plain and flavored soy milks are marketed in wet and dried forms. SPCs can be used for reconstituting soy beverages; production of yogurts, soy ice creams, sauces and low-fat spreads and replacement of dry skim milk in compound chocolate products used for coatings (Pedersen 1993).

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