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Manufacturing Soy-Protein Concentrates and Isolates by Membrane Technology

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Abstract: **Isolated soy-protein products are useful for food ingredients because they provide solubility, water binding, fat adsorption, emulsification, viscosity, gelation, foaming, adhesion and cohesion, texturization, and flavor formation. Soy-protein concentrates (SPCs) and soy-protein isolates (SPIs) are the representative soy-protein products. Conventionally, SPCs and SPIs have been produced by removing non-protein portions such as oil, soluble sugars, and minerals using dissolving solvents or different pH conditions. However, these extraction methods induce protein denaturation that negatively affects the soybean protein. An alternative method of soy-protein production, using membrane technology, has been proposed to produce SPCs and SPIs. The ultrafiltration (UF) method has attracted considerable interest because the major soy protein is retained by the membrane, while the soluble carbohydrates permeate the membrane. Recently, electro-acidification has been combined with UF and diafiltration technology, and the nanofiltration (NF) and reverse osmosis (RO) systems can be applied to increase protein yield by recovery of significant amounts of small molecular protein, which is permeated with UF. This review paper summaries the types, properties, and preparation methods of soy protein products and comparison of their production with conventional methods and advanced membrane technology.**

Keywords: **Soy-Protein, SPCs, SPIs, Membrane, Ultrafiltration**

1. INTRODUCTION

Soybeans, which originated from Easter Asia, are one of the most important crops in the world because they are a major source of protein. Soy protein is an easily digestible, widely available vegetable source that provides all essential amino acids in the appropriate amounts [60]. Also, soybean protein has some functional properties for food applications such as emulsification, binding of water or fat molecules, gel formation, and flavor and texture enhancement [35]. Based on research results, many types of soy-protein products (milk products, infant formula, baby food, cereal, bakery ingredients, etc.) have been developed (Figure 1). Since the late 1950s, the soy-protein industry has grown significantly due to the increasing human population and consumption around the world [21], [33], [67]. Production in 2013 was more than 35 million metric tons of soybean-meal products per year in the U.S. and 181 million metric tons in the world [76].

Full-fat soy flour, grit, defatted soy flakes, soy protein concentration, soy protein isolate, and texturized soy protein have been commercially produced as intermediate products from the soybean [72]. Soy-protein concentrates (SPCs) and soy protein isolates (SPIs) are the typical concentrated forms of soy protein that have been commercially produced for the past couple of decades. SPCs are defatted soy flour from which soluble carbohydrates have been removed, leaving about 60~70% protein content (w/w). SPIs are defatted soy flour from which soluble and insoluble carbohydrates, leaving about > 90% protein content (w/w). Normally, they have been produced by removing non-protein parts of the soybean components such as oil and carbohydrates using dissolving solvents or different pH conditions. However, the inherent properties of soybean protein are negatively affected by protein denaturation caused by the chemical reactions [33]. The alternative method of soy-protein production—using membrane technology—was proposed to produce SPCs and SPIs, and it offers several attractive features, including mild processing that leads to less protein denaturation compared with the conventional acid-precipitation method [56]. By proper choice of membrane configuration and operating parameters, undesirable molecules such as carbohydrates and oils can be selectively separated from the protein in soybeans, which leads to an increase in the protein concentration. The UF membrane system (~0.01-μm pore size) has been mostly applied to produce SPCs and SPIs either by itself or in combination with electro-acidification [1], [51]. The NF and RO systems also have great potential for recovery of soy-protein products due to the permeation of only soluble sugars and water, while small protein molecules (100–1,000 Da) are retained on the membrane surface.

This review paper comparing conventional soy-protein production with membrane technology, highlighted the advantages and disadvantages of this approach. More recently, advanced membrane technology has been applied to SPCs and SPIs productions have shown particular promise in soybean industry.

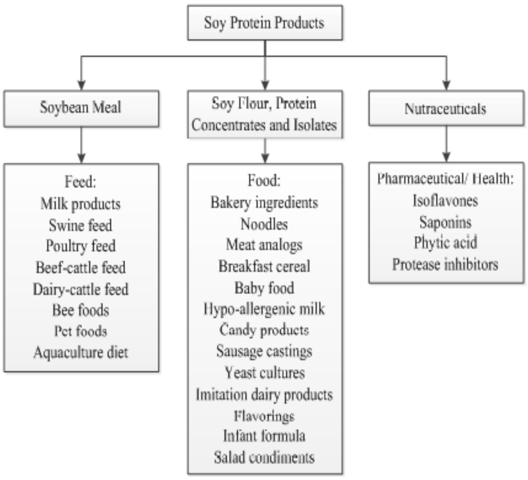

Fig.1. Soybean Protein Products Uses [21].

2. SOY PROTEIN FUNCTIONAL PROPERTIES

Soy protein are large and broad molecules (8–700 kDa) with minimum solubility around pH 4.3–4.5, and about 80% (w/w) of soy protein have a molecular weight greater than 100 kDa [79]. They are stored as dehydrated protein formations (>90%, w/w), mostly globulins, and are classified as 2S (S stand for Svedberg unit), 7S, 11S, and 15S based on ultra-centrifugal sedimentation properties. The 2S fraction is composed of 22% (w/w) of the water extractable from the soy protein, trypsin inhibitors, and cytochrome c [14], [25], [74], [81]. The 7S fraction (7S globulin or beta-conglycinin) accounts for 37 % (w/w) of the water extractable from soy protein, and the 11S fraction (11S globulin or glycine) makes up 31% of the protein (w/w). The 7S and 11S protein fractions are predominant, and they have quaternary structures composed of subunits, which lead to association and dissociation through changes in temperature and pH conditions [5], [54], [77], [81]. The remaining proteins, including 15S which is a likely a dimer of glycinin (11S), are composed of enzymes (lipoxygenase, urease, and amylase), hemagglutinin, protein inhibitors, and lipoproteins.[34]

Functional properties of soybean protein depend on the physical and chemical characteristics of the protein molecules. The functional properties of soybean protein products in food are summarized in Table 1 [21], [34]. Soybean protein has both lipophilic and hydrophilic groups in the same polymer chain, which can combine fat and water molecules. The polymer chain is composed of lipophilic, polar, and negatively and positively charged groups, which enable association with many different types of compounds. The protein may adhere to solid particles and act as a binder and as a dispersing and suspending agent in solution. These properties of isolated protein make them useful for food ingredients because they provide one or more of the following properties: solubility, water binding, fat adsorption, emulsification, viscosity, gelation, foaming, adhesion and cohesion, texturability, and flavor formation (Table 1) [21], [33].

Table 1.Functional Properties of Soy Protein Products in Food [21].

Functional Property	Protein Products	Food System Used
Solubility	F, C, I, H[a]	Beverages
Water absorption	F, C	Meats, sausages,
Viscosity	F, C, I	Soups, gravies
Gelation	C, I	Meats, curds, cheeses
Cohesion	F, C, I	Meats, baked goods,
Elasticity	I	Meats, bakery items
Emulsification	F, C, I	Sausage, bologna,
Fat absorption	F, C, I	Sausages, doughnuts
Flavor-binding	C, I, H	Simulated meats,
Foaming	I, W, H	Whipped toppings,
Color control	F	Breads

[a] Abbreviation: F: Soy Flour, C: Soy Protein Concentration, I: Soy Protein Isolates, H: Hydrolyzed, W: Soy Whey

A. Solubility

Solubility is considered to be an important, primary characteristic of soybean protein because it significantly affects the other functional properties [78]. Protein solubility is defined as a dissolved amount that is not precipitated by a moderate-speed centrifuge in solution or colloidal dispersion under specific conditions. Therefore, solubility provides important information for optimization of processing [33]. Several factors influence protein solubility, including the composition and ratio of amino acids, protein conformation, surface charge, pH, molecular size, ionic strength and type, and the temperature of the solvent [34]. The pH and ionic strength are considered the most significant effects on the solubility of soy protein. Alkali treatment (pH > 10.5) usually improves the solubility of proteins [60]. In addition, salts, especially sulfite salts, have negative effects on protein solubility. Protein solubility was increased by temperatures between 0 and 40–50 °C and that above 50 °C protein solubility is significantly decreased and the protein is denatured, which leads to conformational changes to noncovalent bonds involved in stabilization of secondary and tertiary structures of protein [78]. The protein dispersibility index (PDI) is widely used to measure the solubility of a protein in water using high-speed mixing. The PDI provides useful information to facilitate adjustments in food formulations when protein sources are interchanged. Some proteins with high water-binding capacities may absorb a disproportionate amount of water and relatively dehydrate other components, which can affect food quality [32].

B. Hydration Properties

The interactions of soy protein with water are important in relation to dispersibility or wettability, water absorption and binding, swelling, viscosity, gelation, and surfactant properties. These properties directly influence the important functions of soy protein in surface polarity, topography, and texture [30], [34].

C. Emulsifying Properties

An emulsion is defined as an immiscible liquid that is a dispersion of oil in water or water in oil. The amphiphilic character of proteins reduces the interfacial tension between two immiscible components and helps to stabilize emulsions. Hydrophobicity and solubility of protein are important characteristics for determining emulsifying properties [17]. Diffusion of the protein on the interface, where there is unfolding of the intermolecular association and spreading of absorbed molecules, causes protein adsorption, which leads to the reduction of interfacial tension [33]. The emulsifying properties of soy protein have been widely studied by several researchers [48], [75]. As the protein concentration increases, interfacial tension decreases, while emulsifying stability (ability of emulsion droplets to remain dispersed without flocculation) is increased and emulsifying capacity (ability of the protein solution or suspension to emulsify oil) is decreased. The emulsifying capacity is increased by increasing protein solubility, and the emulsifying ability of soy protein is significantly affected by the pH, temperature, and ionic strength conditions [15], [34].

D. Foaming Properties

Foaming properties are closely influenced by soy-protein solubility. Foam volume depends upon protein concentration. Therefore, SPIs have better foaming properties than soy flour and SPCs [36]. Protein foams are composed of gas droplets that are surrounded by a thin liquid layer containing surfactant protein [34]. Proteins for foaming should have flexible-enough formation strength to form a cohesive film at the air-liquid interface, and they are rapidly absorbed at the newly created air-liquid interface, where they undergo unfolding and molecular rearrangement. A proper balance between flexibility and intermolecular cohesiveness is essential for producing stable foams. Heat treatments at 75–80 °C enhance foaming properties [47].

E. Soy Protein and Flavors

Proteins affect the sensory properties of food, such as color, flavor, taste, and texture—attributes that determine consumers' acceptance. Despite the highly established health benefits and high nutritive value of soy-protein products, direct utilization of soy protein in foods is obstructed by its offensive, beany or grassy odor and its bitter, astringent, or chalky flavor [18], [34], [36], [37]. An understanding of protein functions in food flavors is essential, even though protein itself has no intrinsic flavor. For example, protein may modify flavor compounds by binding during cooking and hydrolysis. Table 2 shows major chemical compounds associated with beany odor and unusual flavoring in soy protein. At the same time soy protein easily and rapidly binds flavor compounds, which increases their concentration and the protein denaturation rate. Hydrophobic bonding is the major binding force of protein and flavor, but phenolic acids, such as syringic, vanillic, ferulic, gentisic, and chlorogenic acid, include flavors that are bitter and sour. While these combine with the aliphatic alcohols and carbonyls, astringent beany flavors may be significantly developed [34].

Many off-flavor compounds in soy-protein products originate by enzyme (lipoxygenase) or chemical oxidation of the lipid components.[19] Even though they are present in small amounts, these off-flavor compounds combine with protein to produce 2-pentyl furan, 3-*cis*-hexenal, and ethyl-vinyl-ketone, which are major beany-flavor compounds in soybean flour. Lipoxygenase generates lipohydroperoxides, which creates the beany flavor. The aldehydes, ketones, alcohols, and furans formed with soy protein show a high affinity for these lipid-derived flavors [4], [68], [73], and protein denaturation and acid-sensitive protein seem to enhance the beany off-flavor binding capacity [3], [4].

Several treatments have been studied and tested to remove off-flavors in soybean products, including (1) heat treatment to inactivate lipoxygenase and minimize lipid oxidation, (2) presoaking of soybean in a weak alkali solution followed by aqueous alcohol extraction, and (3) distillation/steaming to remove the off-flavors [19], [20], [71]. Heat rapidly inactivates lipoxygenase activity and eliminates volatilized off-flavors, but the functional properties are easily destroyed by heat treatment. Wet milling, or the soaking of soybeans in alkali solution, followed by aqueous ethanol extraction reduces lipoxygenase activity and improves the flavor, but protein solubility is also reduced [20]. Enzymatic treatment effectively removes the off-flavors, but it produces hydrophobic peptides, which possess a bitter taste, and leads to other problems. Adding desirable flavors to soybean protein products cover the impact of undesirable flavors. However, the addition of flavors may not have the desired positive effect because of interactions between the flavors and the soy protein. Alternative approaches have been suggested by Damodaran and Arora [18]. They removed protein-phospholipids complexes from soy protein isolates using a combination of ultrasound, enzyme, and molecular-inclusion technologies. In short, various efforts have been made to remove the off-flavoring from soybean, but more research is needed in the future.

Table 2. Major Chemical Compounds Associated with Beany-Flavor in Soy Proteins [18], [34].

Class	Compound
Alcohols	isopentanol, hexanol, octenol, pentanol
Aldehydes	heptenal, hexenal, decadienal, pentanal, 3-methyl butanal, nonenal, hexanal,
Ketones	hexanone, ethyl vinyl ketone, heptanone, nonanone, decanone
Phenols	4-vinylguaiacol, 4-vinylphenol
Furans	2-phentyl furan, 3-ethyl furan

3. TYPES OF SOY PROTEIN PRODUCTS

Soy-protein products can be divided into three major groups based on their protein content (which ranges from 40% to over 90%). There are soy flours and grits, soy-protein concentrates (SPCs), and soy-protein isolates (SPIs). Table 3 shows an approximate composition of soybean products, and Table 4 shows the amino-acid compositions of protein in soybean products. Conceptually, full-fat soy flours are soybeans from which the hull portion has been removed, followed by grinding. Partially defatted soy flours are soybeans from which hulls and oils have been removed, followed by grinding. SPCs are defatted flour from which soluble carbohydrates have been removed (70% protein minimum-dry-weight basis). SPIs are defatted soy flour from which soluble and insoluble carbohydrates, including cotyledon fibers, have been removed (90% protein minimum-dry-weight basis) [21]. SPCs and SPIs are increasingly used as food ingredients in meat analogues, and in dairy and bakery products. Their high nutritional value, along with their essential amino-acid content and functional properties, makes them a very useful ingredient in the food industry. In addition, the FDA indicated in 1999 that soy protein (>6.25 g/serving) may reduce the risk of coronary diseases [82]. A disadvantage of the SPCs and SPIs that are produced using conventional methods is that sometimes they have poor protein solubility and quality due to being exposed to extreme treatment conditions such as alcohol, acid, alkali, heat, or centrifugation. In addition, a significant amount of phytic acid in SPCs and SPIs can play an important role in decreasing the mineral bioactivity by forming phytate-mineral or protein-mineral-phytate complexes [59].Phytic acid also decreases protein solubility [2].

Table 3.Proximate Composition of Soybean Products (%, as is basis) [21], [33].

Components	Dehulled soybean	Defatted soy flour	SPC	SPI
Moisture	6.8	7.0	5.0	5.0
Crude protein	39.0	53.0	65.6	86.5
Crude fat	22.6	0.8	0.8	0.8
Ash	5.2	5.5	5.0	4.3
Carbohydrate	26.2	33.8	23.8	3.5

A. Soybean Meals, Flours and Grits

Soybean meal is the principal protein product originated from defatted soybean flakes for animal feed [72]. Figure 2 shows generic soybean protein processing, in which soybean meal is prepared by grinding, if necessary, and desolventized flakes, which contain 44 % to 50 % protein (w/w). Soy flours and grits are made by grinding and sieving soybean flakes either before or after removing the oil portion. The protein content of flour and grits is typically between 40 % and 54 % (w/w), which can apply to a variety of food products. Grits are made by rough grinding of the fatted/defatted flakes followed by sieving with coarse mesh (10–20), medium mesh (20–40), or fine mesh (40–80) [38], [63]. Soy flours are obtained by grinding the soy flakes to very-fine particles (100- or 200-mesh screens) [60]. Soy flours and grits are commonly divided based on the type and level of oil content: full-fat flours, high-enzyme flours, defatted flours, defatted grits, and lecithinated/refatted flours [63].

Table 4. Amino Acid Composition of Protein in Soybean Products (%, as is basis) [57].

Amino acid	Soy meal	Dehulled soy meal	SPC	SPI
Arginine	14.74	14.65	16.41	15.84
Histidine	5.74	5.44	5.10	5.19
Isoleucine	8.93	9.09	9.35	9.80
Leucine	15.63	15.37	15.02	15.31
Lysine	12.57	12.57	11.90	12.13
Methionine	2.73	2.80	2.55	2.33
Cystine	3.10	2.97	2.83	2.74
Phenylalanine	10.03	10.19	9.63	10.00
Tyrosine	7.06	6.75	7.08	7.15
Threonine	8.02	7.90	7.93	7.31
Tryptophan	2.69	2.80	2.55	2.49
Valine	8.79	9.47	9.63	9.71

B. Partially Defatted Extruded-Expelled Soy Flours

Extruding-expelling using a screw extruder is a relatively new mechanical technology to remove the oil from soybeans [55], [70]. This process enhances oil extraction with simple screw pressing and eliminates the solvent-extraction process, which meets consumer demand for attractive, natural foods. Extruded-expelled soybean meal has been reported to have higher digestible energy and amino-acid availability than solvent-extracted soybean meal [21], [22], [85]. Textured soy flour is produced by either a single- or double-screw extruder to compact the structure into fibers or chunks for use as a food ingredient. Textured soy flours are generally used to resemble beef, pork, seafood, or poultry in structure and appearance when hydrated for vegetarians [21].

C. Soy Protein Concentrates (SPCs)

The SPCs are prepared by removing water-soluble carbohydrates and non-protein constituents, including flavor compounds, from defatted soybean flakes (Figure 2). The remaining components are mainly protein, insoluble carbohydrates (fiber), and ash, and they contain at least 65~70% protein (dry basis). Three typical processes have been applied to produce SPCs: (1) acid leaching at pH 4.0-4.8, (2) aqueous alcohol (60~90%), and (3) moist heat-water leaching [63]. The globulins are the major soy protein, which are insoluble in water and precipitate in the region of their isoelectric points (pH 4.0–4.8). By the acid washing of defatted soy flakes, soluble carbohydrates are removed from the matrix of protein and polysaccharides. The remaining components are adjusted to neutral pH and dried, generally using spray-drying. Some soy proteins that are soluble at pH 4.0–4.8 may also be removed by acid washing and lead to a reduction in the protein recovery yield. The aqueous alcohol process is typically used to produce commercial SPCs, with the soluble carbohydrates being extracted by 60–90% aqueous alcohol. Due to the protein denaturation by aqueous alcohol, most of the protein becomes insoluble and remains with the insoluble fibers. The aqueous alcohol can then be recovered by a desolventizing process. The moist-heat-water process is gaining increased interest because it avoids solvent utilization and increases safety. Soy protein is easily denatured by moist heat and remains in the insoluble polysaccharide matrix [21], [24].

D. Soy Protein Isolates (SPIs)

SPIs are considered the most highly refined soy protein products that are currently available. They are prepared by separating most of the non-protein components, and they contain >90% protein (dry basis). SPIs may also be lecithinated to reduce dusting and to improve dispersibility. They are commercially produced using a mild alkali treatment, at pH 8–10, from defatted soybean flakes, followed by centrifugation to remove insoluble carbohydrates. Soluble proteins are precipitated by being acidified at pH 4.5, where most of the soy protein precipitates as a curd, and then by separating protein curd by centrifugation from the soluble carbohydrates (Figure 2). SPIs yield are in the range 30–40% of starting soybean flake weight, or 60% of the protein in the flakes [21], [63], [80].

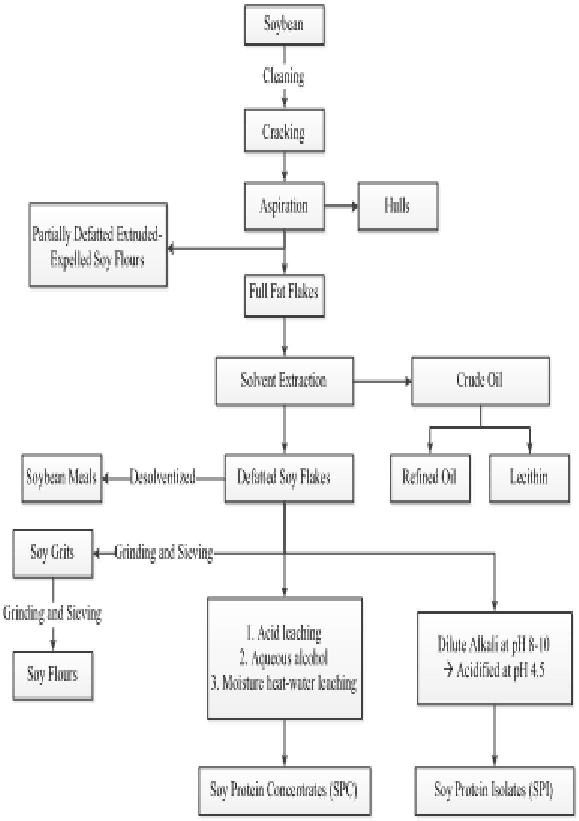

Fig.2. Soybean Protein Processing [21], [33].

4. MEMBRANE APPLICATION IN SOY PROTEIN PROCESSING

Membrane technology has been used to concentrate or fractionate from a two-liquid portion in which the two liquids differ in their composition. This method has become attractive because of its low energy consumption, the reduction in the number of processes, the high efficiency of separation, and the improved final product quality [16], [41], [62]. The separation performance of a membrane is affected by its chemical composition, temperature, pressure, flow rate, and interactions between components and the membrane surfaces. As mentioned above, pressure-driven membranes have normally been classified as (1) microfiltration (MF), (2) ultrafiltration (UF), (3) nanofiltration (NF), and (4) reverse osmosis (RO) [64]. Due to the relatively large pore size, MF has been used for pre-treatment of soybean product to separate particles from bacteria. Recently, the Separation Science Program of the Food Protein R&D Center has tried to develop special MF units to retain the oil portion in the membrane surface. UF has gained considerable interest over the past couple of decades because it concentrates soy protein, which is retained by the membrane, while the soluble carbohydrates and minerals permeate through the membrane. Porter and Michaels [61] were the first to suggest UF technology for fractionating soy protein extracts, and Okubo et al.[58]later studied soy protein isolate production using a combination of UF and continuous diafiltration. The biggest advantage of UF is that there is no excessive use of chemicals to produce SPCs and SPIs compared with the conventional method. However, membrane fouling and maintenance are unattractive for producing protein isolation using UF, and so combining UF with electro-acidification has been broadly studied for the production of SPIs [2]. The NF and RO can be applied to the separation of effluents of soybean processing, which are soluble peptides, glucose, fructose, and trace amounts of oligosaccharides such as raffinose [28], [29]. Large volumes of effluents, which are whey-like, liquid by-products, are produced during soy-protein production. A few studies about NF and RO to produce SPCs and SPIs have been conducted because their pore size is almost out of the range of major soy-protein molecular sizes. However, small soy protein fractions which are permeated with UF can be retained by NF and RO. The NF and RO can contribute to increasing soy protein recovery as well as to improving the overall economics of the process by reducing wastewater treatment costs through covering the extraction water and its by-products.

A. Microfiltration (MF)

Microfiltration rejects relatively large molecules with a pore size of 0.2–2 μm, and it can selectively separate protein particles with >200 kDa molecular weight. More than 80% of soy protein molecular weight is between 100 and 700 kDa, and thus some macro-molecular soy protein can be retained, but it is not significant. MF uses pressure from 3 to 50 psi for operation, which is primarily employed to remove particles, starch, emulsified oil, and micro-organisms such as bacteria, molds, and yeast from other, smaller solutes [6], [31], [38], [49], [50]. Recently, the Separation Science Program at the Food Protein R&D Center has tried to develop special MF units to retain the oil portion in the membrane surface to effectively reduce the oil content and increase the protein content.

B. Ultrafiltration (UF)

Ultrafiltration involves the general use of a pore size about 0.01 μm and a 1–300 kDa molecular weight cutoff (MWCO). It also uses pressures of 0.1–1 MPa to separate colloids like proteins from small molecules such as sugars and salts.[6] High-quality soy protein is readily obtained by isoelectric precipitation of the protein with acidic pH treatments followed by extraction, heat treatment, and centrifugation to separate the protein from the other components. However, this conventional separation method is expensive and time-consuming. In addition, this method is not suitable for other oil-seed protein-extraction methods because their protein solubility is higher than that of soybeans in the acidic pH range [11], [12]. UF represents a great opportunity to partially overcome these problems (nonthermal and nonchemical) in the conventional SPC and SPI preparation methods by carefully selecting the pore size of the UF, thus reducing protein loss during processing. Also, by using UF, the undesirable by-products such as soluble oligosaccharides, phytic acid, and some of the trypsin inhibitors can be permeated out and removed through the use of UF. UF has also been investigated as an alternative to the conventional

SPCs and SPIs methods due to its capability for application on a large scale, which seems to be commercially more feasible and acceptable [13], [43], [45], [46], [48]. Spray-dried products that are produced from UF have shown better functional properties and nitrogen solubility, and have less undesirable color and flavor, than those by produced by typical commercial alkali-solubilization or acidic precipitation procedures[42].

The production of SPCs and SPIs by UF technology involves complex interactions between UF membrane characteristics and operating parameters as well as feeding components. The combination of UF and diafiltration steps has been considered an efficient approach for the removal of soluble oligosaccharides [39], [40], [44], [56], [58]. The ideal pore size of UF for food applications, especially for soybean extraction, could be 100 kDa MWCO by the permeate method of using the small oil-body molecules associated with small proteins (17–34 kDa), which produce soy protein products with better off-flavor and organoleptic properties, even though 50 kDa MWCO UF could retain almost as many soluble proteins [42], [66]. The pH conditions have also been observed to have a significant effect on the flux efficiency of UF. The pH 8–9 of soy-protein extraction has been lower oligosaccharide removal efficiency with UF because phytic acid combined with protein and calcium to form a ternary complex, which makes it hard to permeate the UF [2], [27], [56]. More recently, the electro-acidification technology has been studied in association with UF. Electro-acidification generates protons from the dissociation of water (H_2O) molecules at the interface of a bipolar membrane (BP) exposed to an electric field. These protons migrate toward the cathode and acidify the protein solution (Figure 3). By the acidification process, proteins are able to precipitate at around pH 4.5 and can be recovered by centrifugation [7]-[9], [52]. Electro-acidification has several advantages compared with the traditional acidification process that uses chemicals. First, the acidification rate can be controlled by acid and base input rates into the system. Lower ash and salt contents of SPIs have been produced by the electro-acidification process compared with the conventional process [7]-[10]. However, the commercial application of electro-acidification is limited due to the gradual protein precipitation in the electro-dialysis cell as the solution pH moves below 6 (significant at the isoelectric point; pH 4.5), which decreases the system's efficiency by increasing the cell resistance. The result is a decrease in yield because of the loss of protein [2]. Figure 4 shows the typical process of combining electro-acidification and UF. The first step consists of the alkaline extraction of defatted soy flakes for 30 min at 50 °C adjusted to pH 9.0, followed by electro-acidification of soy protein extract to a final pH of 6.0. The SPIs (>90% protein) can be obtained by UF (100 kDa MWCO) and diafiltration. Removal of minerals (potassium, phosphorus, phytic acid, and calcium) during UF has been observed to increase for the pH 6.0 electro-acidified extract compared with the extract at pH 9.0 [52], [53].

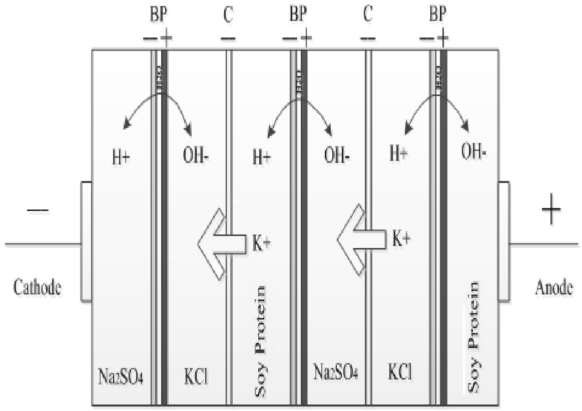

Fig.3. Electro-Acidification of the Soy Protein Extracts: BP, bipolar membrane; C, cationic membrane [8], [9], [52], [53].

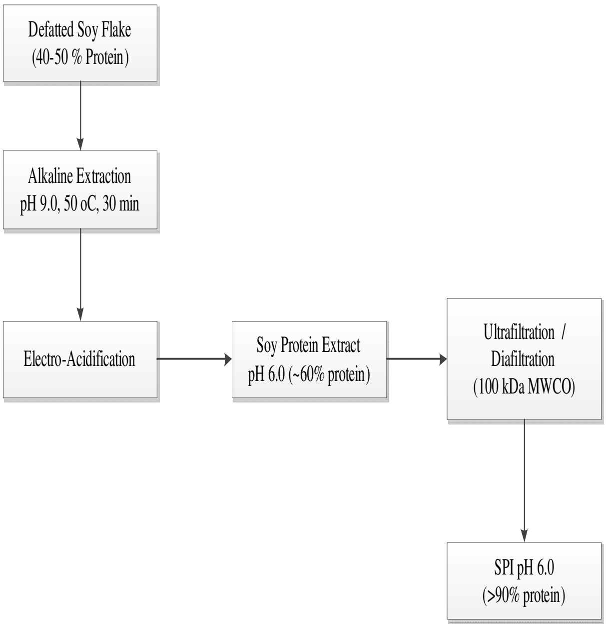

Fig.4. Production of SPI by Electro-Acidification and Ultrafiltration/Diafiltration [52], [53], [69].

C. Nanofiltration (NF)

Nanofiltration lies between the separation characteristics of the UF and RO processes and is widely used for several applications, including water softening, wastewater treatment, vegetable oil processing, and in the beverage, dairy, and sugar industries. NF has a pore size in the range 0.5–1 nm, and it concentrates and fractionates with a molecular weight of 100–1,000 Da with a pressure of 1–4 MPa. Currently, it is rare to use NF for soybean protein production processes such as SPCs and SPIs because the soluble small carbohydrates, phytic acid, and some of the trypsin inhibitors are retained in the membrane. However, small molecules (<100 kDa) of soybean protein can be also retained in NF, which potentially increases soy-protein recovery by UF permeation by careful selection of membrane size [6], [64], [65].

D. Reverse Osmosis (RO)

Reverse osmosis concentrates and fractionates with a molecular weight of ~100 Da, and it involves pressure of

4–10 MPa. The RO can reject nearly all solutes and can desalinate water [6]. Figure 5 shows a generic process flow for protein-isolate preparation from defatted soy flakes using UF and RO. Almost no soy protein permeates the RO membrane, including even small oligosaccharide molecules such as glucose, fructose, and salts. The RO usually has been applied to increase recovery of the soy-protein products and other compounds such as isoflavones by retentate. Soybeans typically contain 2–3% phytates which accounts for about 80% of the total phosphorus, and the chelated metal ions (>1,000 molecular weight). Therefore, an RO step can be introduced to remove these impurities with respect to isoflavones. The combination of UF and RO systems for the recovery of isoflavones from the waste stream of soy-protein processing showed a yield of 10.0 mg/g of dried extract [83], [84].

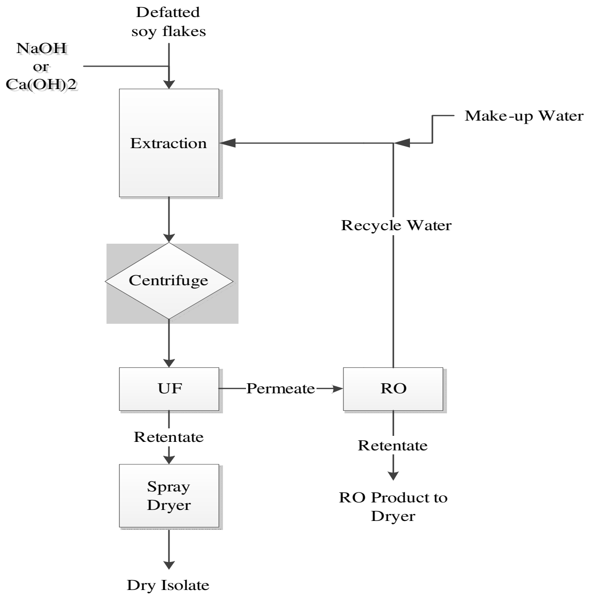

Fig.5. Generic Process Flow for Soy Protein Isolate Preparation from Defatted Soy Flakes using UF and RO [42].

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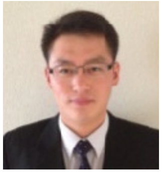

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