1-1-2000

Extrusion texturization of extruded-expelled soybean flours

Troy Willis Crowe
Iowa State University

Recommended Citation

Crowe, Troy Willis, "Extrusion texturization of extruded-expelled soybean flours" (2000). *Retrospective Theses and Dissertations*. 21150.
https://lib.dr.iastate.edu/rtd/21150

Extrusion texturization of extruded-expelled soybean flours

by

Troy Willis Crowe

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Food Science and Technology
Major Professor: Lawrence A. Johnson

Iowa State University
Ames, Iowa
2000

Graduate College
Iowa State University

This is to certify that the Master's thesis of

Troy Willis Crowe

has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy

TABLE OF CONTENTS

ABSTRACT

There has been a nationwide growth in small-scale extrusion-expelling (E-E) facilities. In order to compete in a highly competitive market, these E-E operations must look for ways to add value to the resulting products (oil and meal (flour)). One potential use for E-E produced partially defatted soy flour (PDSF) is in the production of texturized soy proteins (TSP). The objectives of this study were to 1) produce and characterize PDSF with a wide range of residual oil (RO) contents and protein dispersability indexes (PDI) using both whole and dehulled soybeans, and 2) determine the influence of RO and PDI on the texturization of PDSF via twin-screw extrusion. RO and PDI ranges in PDSF were 4.73-12.65% and 12.45-69.10, respectively. E-E conditions significantly influenced enzyme (lipase, lipoxygenase (1-3), and trypsin inhibitor) activities, and protein solubility curves of PDSF. For objective 2, ten PDSF were texturized using a Leistritz-18 (Leistritz Corp., Allendale, NJ) twin-screw extruder. Extrusion parameters for texturization were optimized using the median (RO and PDI) PDSF. The influence of RO and PDI on texturization was analyzed using response surface methodology with texture profile analysis (TPA), water holding capacity (WHC) and bulk density (BD) as dependent variables and PDI and RO as independent variables. A TSP-extended ground beef system was evaluated by TPA and a trained sensory panel. In general, lower RO and higher PDI flours exhibited better texturization and extrudate qualities. However, textural, functional and sensory properties of all TSP from E-E produced PDSF were comparable to commercially produced TSP.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

The number of extrusion-expelling plants, otherwise known as "mini-milling" operations, has been increasing in number over the past several years. These mills utilize extrusion technology to increase the effectiveness of the screw press that expels the oil. In order to compete with larger operations, mini-mills must develop technologies to add value to the resulting products (oil and meal). Currently the partially defatted soybean flour produced from these operations is not used extensively in food applications due to its novel nature, lack of familiarity with its functional characteristics, and the lack of research capital in smaller extrusion-expeller operations. One potential use for partially defatted soybean flour is to produce texturized soy proteins. Parameters necessary for extrusion-texturization of partially defatted soy flours and the influence of the novel properties of these flours on texturization are currently unknown. Most believe that extruded-expelled soybean flour will perform differently, and probably more poorly, than will hexane-extracted flours when used in food systems due to changes in protein functionality caused by extrusion processing and the presence of additional fat.

Thesis Organization

This thesis includes a General Introduction, which consists of an introduction to the study and a thesis organization section. This chapter is followed by a Literature Review encompassing topics related to extrusion, background and methodology of the study. Two manuscripts (Chapters 3 and 4) to be submitted for publication in the *Journal of the American Oil Chemists' Society* are included in the thesis. These chapters include an introduction, followed by materials and methods, results and discussion, and figures and tables. The General Conclusions for the entire study are included in Chapter 5. References cited in thesis Chapters 1, 2 and 5 are included in the References section at the end of the thesis. References cited in the manuscript chapters (Chapters 3 and 4) are included at the ends of each of those sections.

CHAPTER 2. LITERATURE REVIEW

Extrusion

General Principles

Extruders are essentially pumps which use a rotating screw or screws to force material to flow through a die (Seib, 1976). Extruders can be classified as being of either single- or twin-screw design. The actions of both extruder types are affected by the configurations of the screws and their rotational speeds, the back-pressure requirements of the dies, and the characteristics of the material being extruded (Harper, 1986).

An extruder consists of a flighted Archimedean screw that rotates in a tightly fitting barrel. The screw serves three functions: (1) accepting and conveying the feed, (2) compressing and working the food material, and (3) uniformly working and mixing the extrudate (Harper, 1979).

The extruder screw (or screws) is basically a shaft, or root, around which a helical flight is wrapped. The flights may vary in height, width and orientation to the shaft. The channel is the open area between the flights and the barrel wall surrounding the screw. A typical section of an extruder screw is shown in Figure 2-1.

The diameter of the screw (D) is the inside diameter of the barrel, and the flight height (H) is the distance from the root of the screw to the barrel. The helix angle of the screw (θ) is the angle that the helical flight makes with the perpindicular to the shaft axis. The flight clearance is δ, the flight thickness in the axial direction is b, the flight thickness flight is e, the axial distance between flights is B, and the distance between flights perpendicular to the flights is W.

The feed material entering the screw is compacted, or in the case of a twin-screw system, kneaded and worked into a molten, plasticized, dough-like material. Screw filling is controlled by internal restrictions or compressions along the screw in a single-screw extruder, and is controlled primarily by feed rate, screw speed and reverse screw elements in a twin-screw system (Harper, 1992).

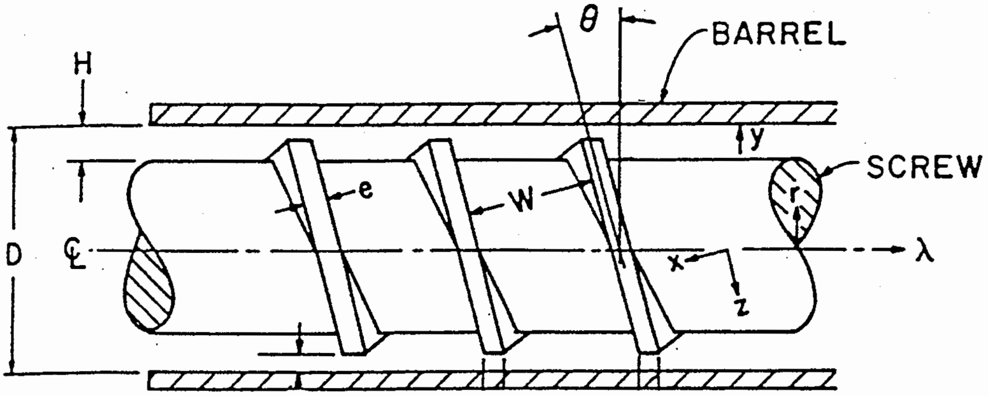


Figure 2-1. Geometry of an extrusion screw metering section (Harper, 1979)

As the material progresses toward the die, both temperature and pressure increase as a result of the relatively shallow screw flights, reduced θ, or increased restriction or interruption of the channel area. In a single-screw extruder, shallow flights increase shear in the screw, increase pressure capability, and improve mixing; but, reduce extruder output at a fixed screw speed. In addition, heat sensitive materials are often damaged in shallow-flighted screws. In a twin-screw extruder, kneading lobes, reverse screw elements and external heating sources (e.g., steam, electric, etc.) are mainly responsible for increased shear and energy input (Harper, 1992).

The barrel length (L) and diameter (D), and the L/D ratio are important extruder design specifications. These variables impact both surface area for heating or cooling, and residence time. Temperature control systems are often added to extruders to control the temperature of specific barrel sections.

The extruder die uses geometric openings or holes to mold and/or shape feed material as it emerges from the extruder. The sudden pressure drop as the product is forced through the die causes expansion of the extrudate. Entrapped water vaporizes or "flashes off" because the extrudate temperature is often higher than the normal boiling point of water (Kinsella, 1978). Assuming that the loss of moisture is small compared to the mass flow rate of the material, the quantity of moisture flashed can be estimated by a heat balance around the discharge of the extruder assuming an adiabatic process as:

$$M_2 = (M_1\lambda - C_p\,(T_1 - T_2))/\,\lambda$$

where C_p = heat capacity, M = moisture content (wet basis), and λ = latent heat of vaporization at ambient pressure. Subscripts 1 and 2 denote before the die and after the die, respectively (Harper, 1979).

Modeling the flow of extruded products is extremely important in determining extrusion parameters. However, the application of flow equations relies on the validity of the following assumptions (Harper, 1979):

1. Flow is laminar
2. Flow is steady

3. Flow is fully developed
4. Barrel is rotating and the screw is stationary
5. Channel is "peeled off" the screw and laid flat
6. Slip does not occur at the walls
7. Fluid is incompressible
8. Gravity forces are negligible
9. Inertial forces are negligible

For a Newtonian fluid, the Hagen-Poiseuille equation can be applied as:

$$Q = K\,(\Delta P/\mu_d)$$

Where K = geometric constant, depending on the type of die opening (e.g. circle, slit, annulus), ΔP = pressure drop across the die, and μ_d = viscosity of dough at the die.

The relationship between Q and ΔP is shown in Figure 2-2.

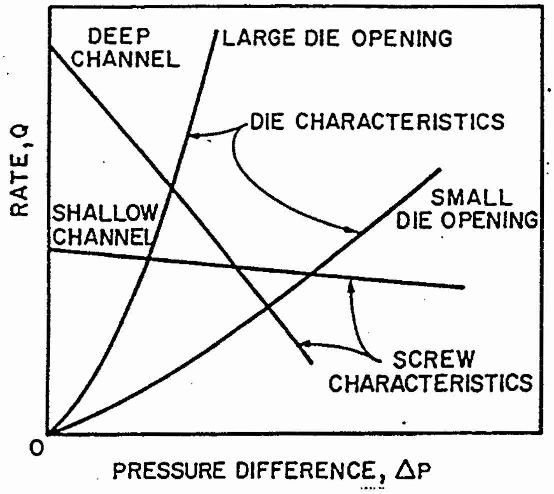


Figure 2-2. Flow vs. pressure drop for varying screw and die characteristics (Bernhardt, 1962).

Food Extrusion

Food extruders first emerged as pasta shapers during the mid-1930s (Rossen *et al.*, 1973). Soon after, ready-to-eat (RTE) breakfast cereal was produced using an extruder equipped with a die. Food extruders now perform one or more of the following functions (Seib, 1976; Frame, 1994):

1. Mixes, disperses and homogenizes ingredients
2. Cooks and melts
    a) denatures protein
    b) gelatinizes starch
    c) produces flavor and color
3. Creates texture through pressure and flow, with or without heat
4. Shapes and divides
5. Dries or puffs the product
6. Sterilizes the product
7. Encapsulates flavors

Different types of extruders may perform one, or in the case of a cooker-extruder producing instant breakfast cereal, the first six of these functions.

Most food extruders can be classified as being of either single- or twin-screw design. Screw configuration and speed, back-pressure requirements of the die, and ingredient characteristics are the primary variables affecting the extruded products produced by both of these machine types (Harper, 1986).

Single- versus twin-screw extrusion

There are numerous mechanical, functional, economic and capability differences between single- and twin-screw extrusion systems (Table 2-1). Although up to one-half of the mechanical energy necessary for single-screw extrusion comes from direct steam addition, single-screw extruders are generally associated with higher energy costs with high moisture extrusion due to limited mechanical energy dissipation, heat transfer and poor mixing capabilities (Harper, 1992). Single-screw extrusion of low moisture, high viscosity, feed materials results in high shear and disruption of the starch and protein molecules of the extrudate. Functionally, these molecular disruptions manifest as increased solubility and decreased water-holding capacity, paste viscosity, and hardness (Harper, 1992).

In contrast, twin-screw extrusion systems have increased mixing and heat exchange capabilities for viscous food materials. The increased ingredient conveying angle (Table 2-1) allows twin-screw extruders to handle a wide range of ingredients compared with single-screw systems. In addition, reproducibility of processing is generally increased due to uniformity of shear rate across the channel depth, narrower residence time distribution and greater mixing capabilities of twin-screw extruders.

From a purely economic standpoint, twin-screw extruders require significantly greater capital investment than do single-screw extruders. However, twin-screw extrusion systems are more versatile than single-screw systems, primarily due to their abilities to accommodate wider ranges of feed materials (e.g., high-fat or high-moisture).

Table 2-1. Relative comparison of single- and twin-screw extruders (Harper, 1992).

Item	Single-screw	Twin-screw
Relative cost/unit capacity		
• Capital		
- Extruder	1.0	1.5-2.5
- System	1.0	0.9-1.3
Relative maintenance	1.0	1.0-2.0
Energy		
• With preconditioner	Half from steam	Generally not used
• Without precondition	Mechanical energy	Mix of mechanical energy and heat exchange
Screw		
• Conveying angle	~ 10°	~ 30°
• Wear	Highest at discharge and transition section	Highest at restrictions and kneading disks
• Positive displacement	No	No
• Self-cleaning	No	Self-wiping
• Variable flight height	Yes	No
• L/D	4-25	10-25
• Mixing	Poor	Good
• Uniformity of shear rate	Poor	Good
• Relative residence time distribution	1.2	1.0
• Venting	Requires two extruders	Yes
Drive		
• Relative screw speed	1.0-3.0	1.0
• Relative thrust bearing capability	Up to 5.0	1.0
• Relative torque and pressure	Up to 5.0	1.0
• Gear reducer	Simple	Complex
Heat transfer	Poor- jackets control barrel wall temperature and slip at wall	Good in filled sections
Operations		
• Moisture	12-35%	6% to very high
• Ingredients	Flowing granular materials	Wide range
• Flexibility	Narrow operating	Greater operating

Systems analysis of extrusion

As evident from the previous section on general extrusion principles, extrusion processing may be modeled using mechanical and thermodynamic principles. Thus, it is theoretically possible to optimize products via changes in processing variables. However, as food ingredients may undergo complex, or unpredictable, reactions, and are often heterogeneous in nature, modeling of food extrusion is difficult. Further, most foods exhibit non-Newtonian flow, i.e. shear stress is not directly proportional to shear rate via viscosity.

Van Lengerich *et al.* (1989) developed a systems analysis model delineating process variables, system variables, and desired product parameters. An example of this model as it applies to starch-containing food materials is shown in Figure 2-3. Structural and molecular changes in a product are primarily dependent on the specific mechanical energy (SME) input (Meuser *et al.*, 1992). The relative amount of energy, both thermal and mechanical, added to a raw material moving through the screw barrel may be calculated using torque, angle velocity of the screws, and product mass flow (Meuser *et al.*, 1982).

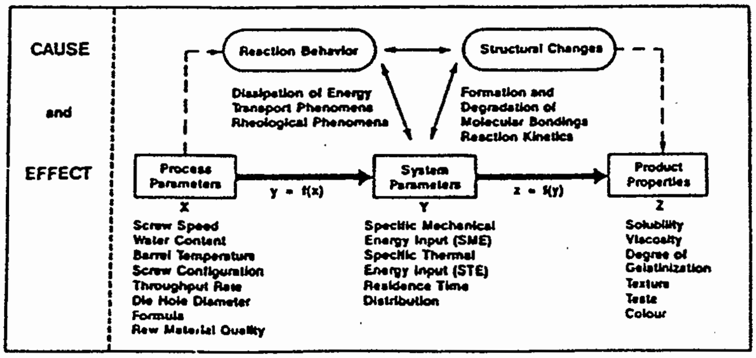


Figure 2-3. Systems analytical model (van Lengerich *et al.*, 1989).

Texturization of Proteins

Extrusion can be used to produce fabricated foods, such as meat analogs or extenders, from plant proteins. Texturized soybean protein (TSP) is produced primarily by extruding defatted soybean flour, soybean protein concentrate, and soybean protein isolate (Harper, 1981).

The exposure of proteins to high temperature, pressure and mechanical shear in the extruder causes the development of the continuous plastic "melt" (Harper, 1981). Linked protein molecules align themselves parallel to the screw, and expand when forced through the die. The sudden pressure drop when the extrudate leaves the die causes part of the water to flash off, resulting in an expanded, porous structure.

Figure 2-4 depicts the five stages of extrudate expansion: viscoelastic melt, nucleation, extrudate swell, bubble growth and bubble collapse. If it is assumed that a uniform viscoelastic melt is formed and nucleation is heterogeneous and instantaneous, extrudate expansion is controlled by bubble growth secondary to moisture flash-off (Kokini *et al.,* 1992).

Mercier and Feillet (1975) found moisture content of the feed and extrusion temperature to be the most important factors influencing extrudate expansion. In protein systems, expansion is also dependent on both protein type and concentration, with soy protein isolate causing increased expansion ratios (Faubion *et al.,* 1982). In addition, various other processing parameters, screw speed and configuration, heat input, etc., have been found to inconsistently influence expansion depending on feed type (Oliveira *et al.,* 1992).

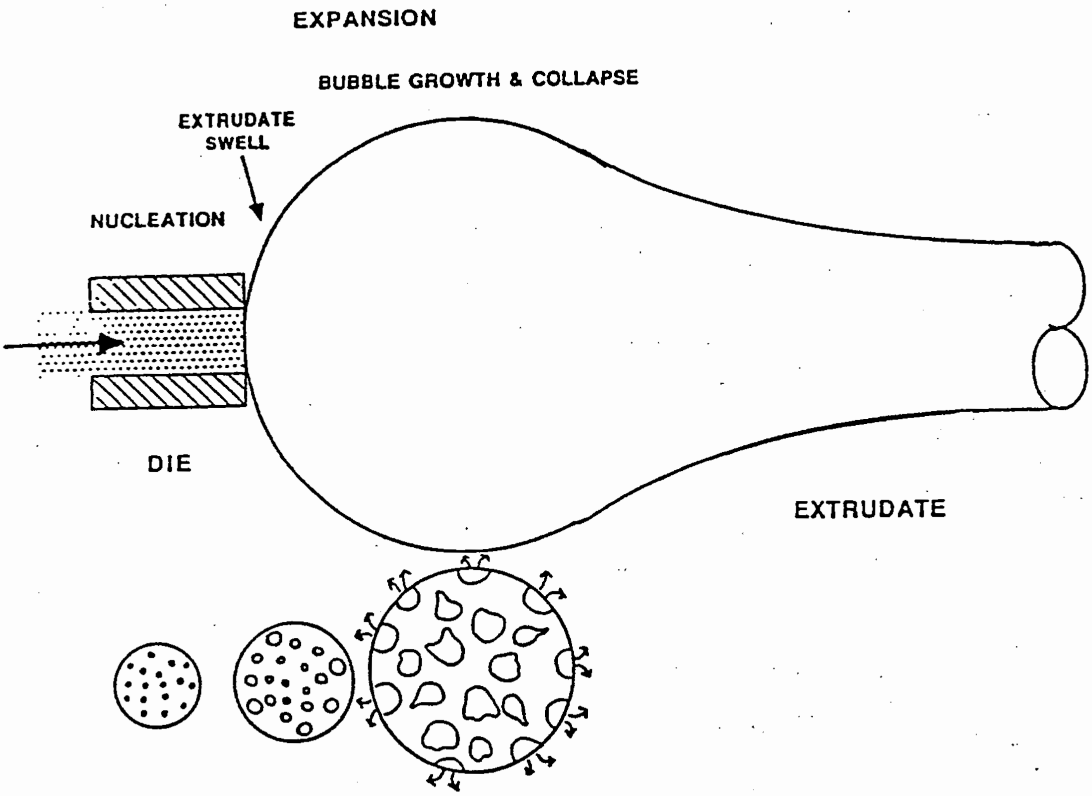


Figure 2-4. Schematic diagram of extrudate expansion (Kokini *et al.*, 1992)

As outlined in the systems analytical model (van Lengerich *et al.,* 1989), the specific mechanical energy input necessary to produce a viscoelastic melt will vary with the type and properties of feed used. Further, changes in processing parameters may have only limited potential to increase specific mechanical energy input depending on other processing and/or feed variables. For this reason, it is erroneous to generalize the influence of individual parameters (e.g., screw speed) on expansion characteristics without examining the entire extrusion process.

Effects of extrusion on protein microstructure

Although the precise mechanisms for protein texturization via extrusion are not well elucidated, both physical and chemical changes in protein micro- and macrostructure are clearly important.

The effects of protein heating during extrusion results in numerous structural changes, including hydrolysis of peptide bonds, amino acid side chain modification, and covalent cross-linking (Cheftel *et al.,* 1985). The influence of temperature on soy protein structure is outlined in Figure 2-5. Initial heating results in denaturation, followed by association of the protein subunits. Some or all of the associated subunits are disrupted with further heating and aggregate to form a concentrate solution or melt phase. At higher temperatures, covalent bonding may occur following protein unfolding. Finally, cooling leads to reformation of disulfide and noncovalent bonds.

Texture-structure relationships are dictated primarily by protein cross-linking, either with protein or other macromolecules (Areas, 1992). Stabilizing forces for cross-linking may include hydrophobic, hydrogen, cation-mediated electrostatic interactions, and nondisulfide covalent and disulfide bonds (Areas, 1992; Stanley, 1989). However, the high level of stability of soy extrudates has led investigators to consider stronger cross-linking interactions, such as peptide and isopeptide bond formation, and reactions with Maillard products (Stanley, 1989).

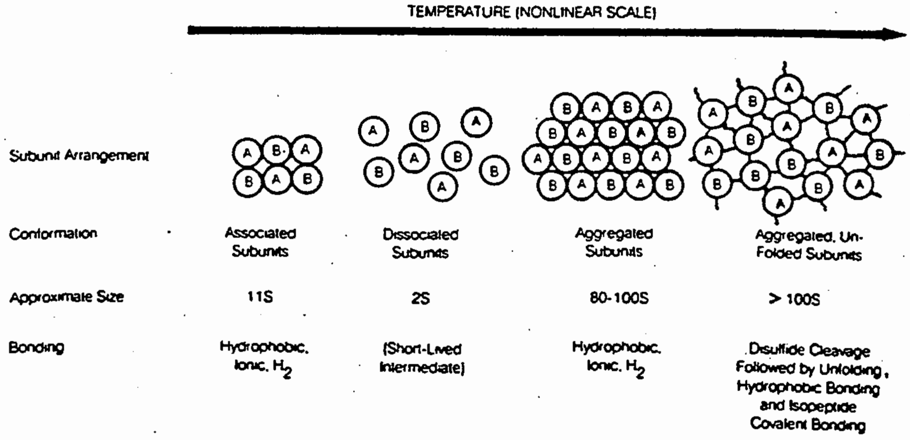


Figure 2-5. Molecular changes in soy proteins following heating (adapted from Stanley, 1989 and Armstrong *et al.*, 1979).

Proponents of the newly formed peptide bond mechanisms for texturization of proteins point to the decreased availability following extrusion of amino acids important in isopeptide cross-linking (asparagine, aspartic acid, cysteine, glutamine, glutamic acid, histide, lysine and methionine) as evidence for this theory (Jeunink *et al.*, 1979). However, Otterburn *et al.* (1977) found no correlation between isopeptide formation and the concentration of reactive amino acids.

Other investigators have pointed to disulfide-hydrophobic-electrostatic bonds as the primary interactions responsible for protein texturization (Shimada *et al.,* 1988; Utsumi *et al.,* 1985). Areas *et al.* (1992) found that the entire structure of soy extrudates collapsed following the addition of disulfide bond reducing agents. In addition, conditions necessary to produce the energy of activation for peptide bonds are not present at the end of the extruder barrel (Areas, 1992).

Effects of extrusion on protein macrostructure

The production of a well-aligned protein fiber matrix is integral to the texturization process. Specific mechanical energy input, processing variables and feed composition all play important roles in texturized protein structure, quality and functionality.

In soy proteins, heating during the extrusion process denatures 7S and 11S proteins, and mixing prevents structural realignment until the viscoelastic melt begins to flow through the die (Guy, 1994). Moisture release at the die causes air-space vacuole formation resulting in a spongy texture. Vaporization occurs during cooling causing plasticity loss and solidification of the extrudate, and the ultimate generation of a porous, structure with parallel alignment of the protein fiber matrix (Rhee *et al.,* 1981).

Smith (1975) outlined six major processing variables which influence the morphological properties of extrusion-texturized proteins:

1. Control of product moisture levels and selection of moisture application point during processing, and determination of moisture type (e.g., water, steam, syrup, etc.).

2. Control of product temperatures throughout each point in the extrusion process.
3. Selection of ingredients appropriate to achieve the desired functional characteristics.
4. Control of ingredient pH.
5. Selection of extruder configuration and components designed to achieve appropriate temperatures and residence times in each section.
6. Selection of dies to produce desired shape and expansion characteristics of the final product.

Clearly, extrusion cooking temperatures are a major factor in producing texturized protein extrudates. Plastification of soy proteins generally requires a minimum temperature of 150° C, with greater temperatures required for lower moisture contents (Cheftel *et al.,* 1992). Lower temperatures may result in an unstable product which disintegrates in boiling water (Kinsella, 1978). An appropriate time-temperature relationship is also necessary to achieve plastification. A minimum residence time of ~ 150 sec, obtained via barrel length, screw speed, feed rate or screw reversal segments, is generally recommended for soy proteins.

Die configuration and temperature also strongly influence protein texturization. Side-discharge dies can be used to produce a highly layered structure and meat-like texture (Harper, 1986). Excessive shear at the die generally results in extrudates of poor textural quality secondary to disruption of protein cross-linking (Holay *et al.,* 1982). Die cooling can be used to reduce expansion, resulting in a high-density extrudate (Crocco, 1976).

Present Study

Extruding-Expelling

Extruding-expelling (E-E) was first developed by Nelson *et al.* (1987) at the University of Illinois as a method of mechanically extracting oil from soybeans. This process is lucrative due to low capital investment costs, enhanced extraction capabilities, and ability to produce oxidatively stable oils and meals low in free fatty acids. Recently, there has been interest in utilizing E-E flour to produce texturized soy flour (Lusas *et al.*, 1996) as a means of adding value to E-E operations.

A simplified diagram of the E-E process of Nelson *et al.* (1987) is shown in Figure 2-6. The extrusion portion of the process is used as a pretreatment for tissue disruption and heating. The expeller (continuous screw press) causes further tissue disruption and forces oil from the meal via pressure.

Conventional screw-pressing operations often require holding cracked beans at high temperatures (116-132 °C) for a relatively long period of time to enhance oil extraction. Extrusion offers the advantage of being a high-temperature, short-time treatment (135° C, 30 sec). Compared with traditional preparation methods, extrusion conditioning of soybeans allows screw presses to handle up to the three times the capacity of normal soybeans due to moisture flash-off at the extruder (Williams, 1993). Higher moisture beans (> 10%) generally require the use of a steam dryer, however, high-moisture-extrusion-prepared beans are handled well by screw-presses provided there is adequate aeration of the extrudate prior to pressing (Williams, 1995).

E-E Mini-mills

E-E mini-milling operations have been increasing in number during the past several years. These mills utilize extrusion technology to expand the structure and increase the porosity of soybeans, thereby increasing the effectiveness of screw pressing to expel the oil.

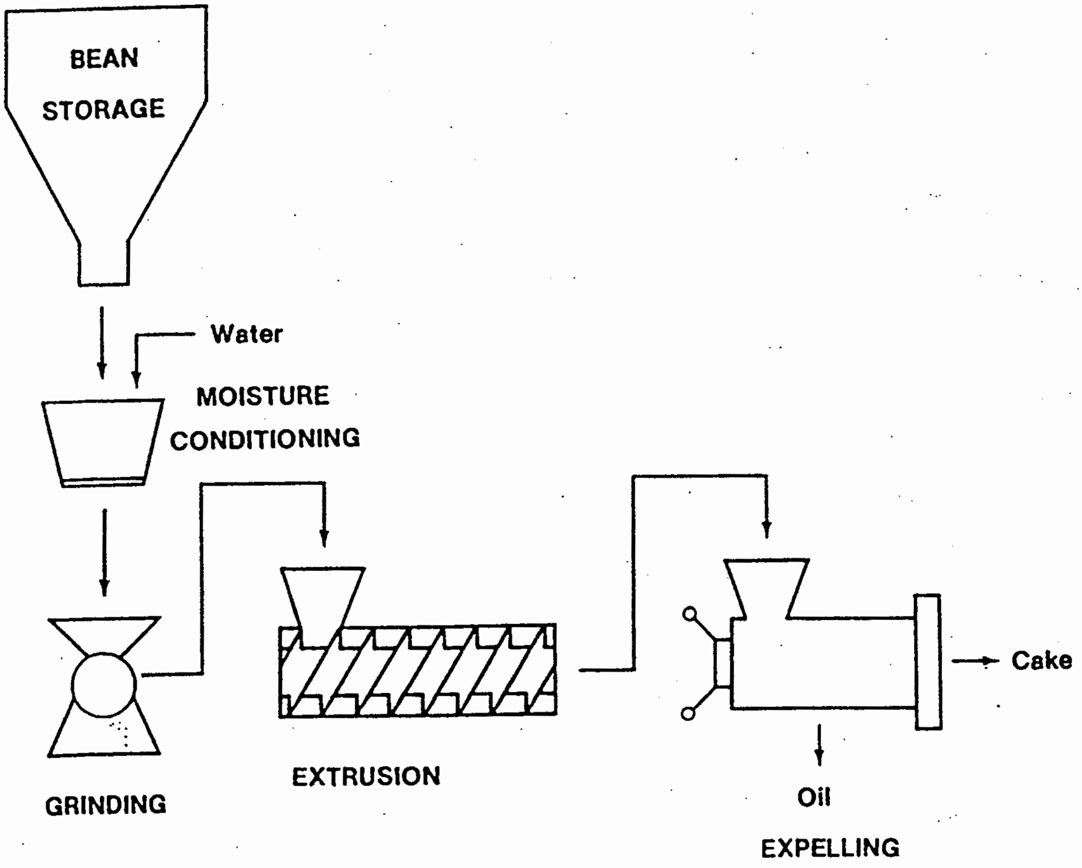


Figure 2-7. Flow diagram of E-E of soybeans (Nelson *et al.*, 1987).

E-E mills are small, with a capacity of only ~6-120 ton/day (200-4,000 bu), but are inexpensive to construct ($150,000-200,000 capital investment), and have relatively low operating costs ($25/ton for fixed and variable costs including electrical, labor, maintenance and depreciation) (Van Dyne, 1997; Said, 1999). These low investment costs offer opportunities to add value to soybeans in many rural communities, creating jobs and economic activity.

These E-E operations offer several unique advantages compared with traditional soybean extraction plants. First, large-scale extraction facilities are not designed to preserve identity of soybeans. Growing concern about genetically modified (GM) crops from both consumer acceptance and regulatory standpoints reinforces the need for operations with the capability to ensure GM-free products. In addition, value-added crops obtained via both traditional plant breeding and GM methods must also be identity preserved. Larger scale extraction facilities may not be economically feasible due to low production/yield during the early stages of development of these crops, and because of the large number of value-added traits currently being developed.

E-E mills are attractive in locations where the cost of large-scale solvent extraction facilities is not justified due to inadequate seed supply. Environmental laws in some areas, such as California, restrict the size and type of extraction facilities via stringent air-pollution standards. The use of hexane as an extraction solvent has also come under increased scrutiny by the Environmental Protection Agency as a result of the 1990 Clean Air Act. The elimination of this chemical in E-E oilseed processing allows mini-mills to meet growing consumer demands for hexane-free oils and products (Hauman, 1997). In addition, because E-E is solvent-free, crude oil and meal can be marketed as organic provided organic farming methods were used in soybean production. This is particularly important in light of the ever increasing organic and health food market. Finally, mini-milling operations are ideal for processing niche market products, including value-added food and industrial products such as gourmet food oils, lubricants, herbicide adjuvants, printing inks, and biodiesel.

Experimental Objectives

This study involved two broad objectives: 1) to optimize extrusion conditions and fully characterize partially defatted soybean meals (flours) produced by E-E, and 2) to re-extrude partially defatted E-E soybean flours to produce texturized vegetable proteins.

Partially defatted soybean flour optimization and characterization

In order to compete with larger-scale operations, mini-mills must investigate methods to add value to the resulting E-E products (oil and meal). Currently, the partially defatted soybean flour produced from these operations is being used primarily in the natural foods market in baked goods, ready-to-eat cereals, and high-energy beverages. Partially defatted soy flour is not used extensively in mainstream products because of its novel nature, the lack of familiarity with its functional characteristics, and the lack of research capital in smaller E-E operations.

One potential use for partially defatted soy flour is the production of texturized vegetable proteins. However, it is believed that partially defatted soy flour will perform much differently than full-fat soy flour or grits because of functionality changes brought about by extrusion and its reduced oil content. The exposure to heat and shear during the extrusion process causes denaturation of proteins and exposes functional groups of amino acids to reducing sugars resulting in the formation of Maillard reaction products (Harper, 1989).

Traditionally, defatted soy flakes or flours with the following characteristics have been used in the production of texturized vegetable proteins: 50% protein minimum, 3.5% fiber maximum, 1.5% fat maximum, and a protein dispersibility index (PDI) of 60-70 (Kearns, 1988). These properties are necessary to ensure flavor and functional characteristics of the final product. In general, the soy flours obtained via E-E have higher fat contents (5-9%) and lower PDI values.

The goal of the present study was to determine the range of PDI and residual oil contents possible when using E-E processing and to characterize these flours to determine their suitabilities for human food or animal feed applications. The partially defatted soy flour was produced at a commercial mini-mill (Iowa Soy Specialties, Vinton, IA) using configurations and settings selected based on operator experience at that facility. Most points are commonly or could be easily produced at similar mini-mills with no change in infrastructure.

Many commercial E-E operations used a dry extrusion system, where oil is used as a plasticizer. In contrast, most expansion systems utilize moisture, in the form of steam, as both energy input and to increase moisture to ~12%. Following moisture flash-off, dry extrusion results in a product with ~5-7% moisture. Production of partially defatted soy flour with a range of PDI values and residual oil contents was achieved by changing extruder and expeller operating conditions. Extruder screw configuration was manipulated by altering shear locks and using single or double flighted screws. Expeller conditions were modified by changing choke settings and by passing twice through the expeller in some instances.

Extrusion-texturization of partially defatted soy flour

Texturized vegetable proteins are normally produced by introducing raw material, generally soy flour previously moistened to 10-40%, into an extruder where it is conveyed by an Archimedes screw or screws through a grooved barrel under high shear and pressures at temperatures of 140-180 °C (Areas, 1992). The physical characteristics (texture, density, chewiness, rehydratability and color) of extruded products can be altered by manipulating several processing parameters, including moisture content, pH, temperature gradients, pressure, shear rates (screw speed), residence time, extruder type and configuration, die shape, size, temperature and geometry, and post-extrusion treatments (Kinsella, 1978).

The goal of this portion of the study was to select a range of partially defatted soy flour from the first portion of the study based on characterization tests, to reextrude these flours to produce texturized vegetable proteins, and to determine the effects of PDI and residual oil content on texturized soy protein. Process conditions were optimized using the center point of PDI versus oil content for the selected flours.

Partially defatted soy flour with different residual oil contents and PDI values were reextruded under the same conditions (moisture content, temperature, screw speed and configuration, residence time, etc.) using a lab-scale Leistritz Micro-18 twin-screw extruder (Leistritz Extruder Corp., Somerville, NJ) (Figure 2-7).

Hypothesis

It is the central hypothesis of this study that E-E processing parameters can be manipulated to produce soybean meal with a wide range of properties. Additionally, it is hypothesized that texturized soy protein produced by reextruding the soybean meals with the highest PDI and lowest residual oil content will exhibit the most desirable textural and sensory characteristics.

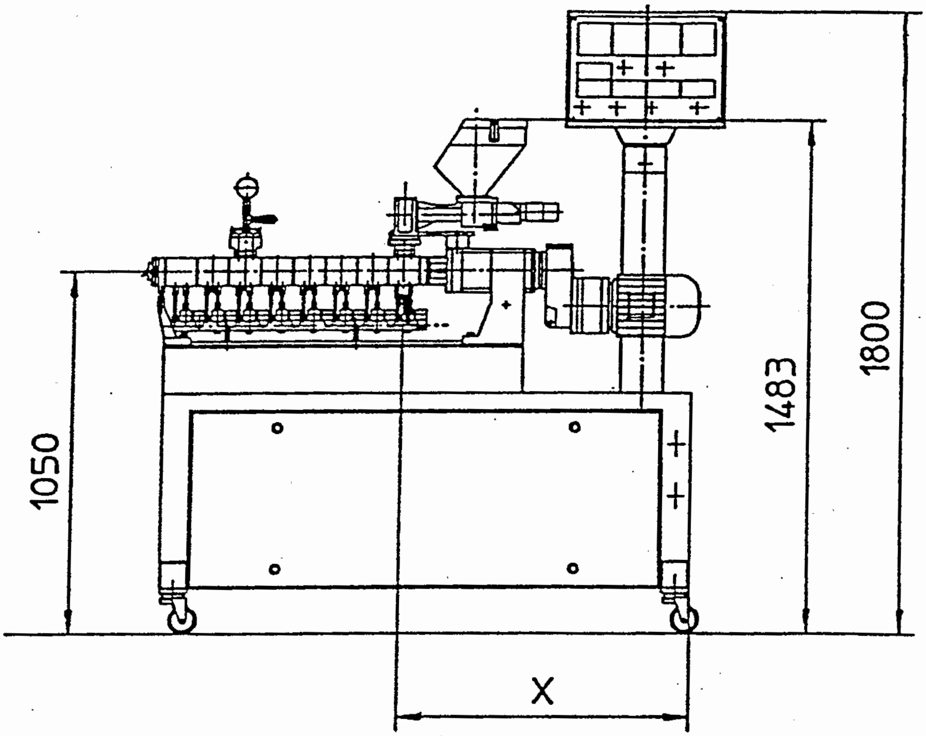


Figure 2-7. Leistritz extruder.

CHAPTER 3. CHARACTERIZATION OF EXTRUDED-EXPELLED SOYBEAN MEALS AND EDIBLE FLOURS

A manuscript to be submitted to the *Journal of the American Oil Chemists' Society*

T.W. Crowe and L.A. Johnson

Keywords: Extrusion, expelling, partially defatted soy flour, PDI, soybean meal, soybean processing, oil extraction, screw pressing

Abstract

There has been nationwide growth in small-scale extruding-expelling (E-E) facilities. In order to compete in a highly competitive market, these E-E operations must look for ways to optimize production of their products (oil and meal). The objective of this study was to determine the range of residual oil contents and protein dispersibility indices (PDI) possible with E-E processing of soybeans. We also characterized the partially-defatted meal for other factors important in food and feed applications. Residual oil and PDI values ranged from 4.7-12.7% and 12.5-69.1, respectively. E-E conditions significantly influenced residual lipase, lipoxygenase (L1-L3), and trypsin inhibitor activities. Chemical analyses were different for whole, dehulled and reduced-moisture soybeans, with dehulled soybeans tending to have higher residual oil contents at higher PDI values. It was possible to process soybeans with different characteristics (e.g. moisture content, whole, dehulled) to produce meals and flours with wide ranges of properties, providing mini-mills with an excellent opportunity for marketing value-added products.

Introduction

Extruding-expelling (E-E) is a relatively new process developed by Nelson *et al.* (1) to mechanically recover oil. This process eliminates the need for costly steam dryers and conditioners and associated steam generation, enhances oil extraction, and eliminates the use of organic solvents. Small-scale E-E facilities, or mini-mills, are increasing in popularity because of the low capital investment required, and the ability to process identity-preserved and organic products. These low-fat, high-protein, high-energy meals are desirable products for use as animal feeds, especially dairy cattle. E-E soybean meal reportedly has increased digestible energy and amino acid availability compared with solvent extracted meal (2). In addition, the lack of residual organic solvents in E-E meals make them acceptable for human consumption.

To develop value-added products from E-E soybean meal, it is important to understand the range of protein solubility, oil content, and enzyme and protease inhibitor activities that are possible with this new processing technology. Soy flours with higher protein dispersibility indices (PDI) and lower oil contents are generally considered to produce higher quality texturized proteins with fewer processing difficulties. The activities of certain enzymes are often associated with off-flavor development or anti-nutritional effects (3). Increasing the range of potential PDIs for E-E soybean mills will facilitate the use of these products in a wider variety of food applications.

The objective of this study was to determine the range of residual oil contents and PDIs of partially defatted soy flours that are possible by changing extruder and expeller conditions within the confines of a commercial E-E mini-mill operation. These partially defatted soy flours were characterized to determine their suitabilities for human food and animal feed applications.

Experimental Procedures

Experimental design. This experiment was designed to use E-E to produce partially defatted soy flours with the widest possible range of residual oil and PDI. The targeted PDI and residual oil values were selected to represent the widest range believed to be possible and useful using different processing conditions that are easily attainable or commonly used at E-E mini-mills (Fig 1). Both whole and dehulled soybeans were used.

Raw materials. Whole soybeans (L610) were obtained from Iowa Soy Specialties (Vinton, IA) and stored at 9.5% moisture content in the plant until processed. Some soybeans were dried to 6.7% moisture using ambient temperature (22 °C) air. The beans were dehulled using traditional methods of cracking the soybeans into 6-8 pieces with a corrugated roller mill (Ferrell-Ross, Oklahoma City, OK), and then aspirating the hulls with a Multi-Aspirator (Kice, Wichita, KS).

Extrusion and expelling. An Insta-Pro 2500 dry extruder (Triple "F"/Insta-Pro, Des Moines, IA) was used to extrude whole and dehulled soybeans. Oil expression was carried out with an Insta-Pro 1500 screw press. The extruder is capable of varying barrel temperature and mechanical input by manipulating the screw design and shear lock configuration, as well as via die (nose cone) restriction and design. Additionally, feed rate to the extruder could be changed. Residence time within the extruder was approximately 20-25 sec. Processing parameters used to obtain the selected residual oil contents and PDI are shown in Table 1. Three samples were expelled twice to produce very low residual oil contents. After the initial expelling, samples were collected into large tubs and held until sufficient sample was produced to be refed into the expeller. E-E processing was carried out in duplicate. Following E-E, the press cake (both single- and twice-expelled) was placed into plastic-lined paper bags and allowed to cool to ambient temperature in the open bag until sealing for transport. Samples were stored at –20 °C until milled.

Flour milling. The soymeal press cake was milled to (94.7% < 100 mesh) by first passing it through a set of cracking rolls and then through a Fitzmill (The Fitzpatrick Company, Elmhurst, IL). The Fitzmill was operated at 7000 rpm using the blades in a blunt hammermill configuration, at 30 rpm feed rate, and fitted with a 1536-0060 screen. Milled samples were stored at –20 °C until analyzed.

Meal characterization. Moisture contents of soy flours were determined according to the 2-hr oven drying method (AOCS official method Ba-38). Crude fat content was determined by Goldfisch extraction (AACC method 30-25). Crude protein was measured by using a Perkin Elmer Series II Nitrogen Analyzer 2410 (Perkin Elmer Corp., Norwalk, CT). Nitrogen was multiplied by a factor of 6.25 for estimating crude protein content. Lipase activity was measured in duplicate as outlined by Moscowitz *et al.* (4) with the modifications of Guzman *et al.* (5). Lipoxygenase activity was measured in duplicate as outlined by Zhu *et al.* (6). Trypsin inhibitor (TI) activity and PDI values were analyzed according to AOCS official methods at Woodson-Tenent Laboratories (Des Moines, IA). Moisture content, crude protein and crude fat were analyzed in triplicate.

Statistical analysis. Statistical analyses were performed using the General Linear Model procedures of SAS 6.06 (SAS, 1991). Significance was established at $P < 0.05$.

Results and Discussion

Proximate analyses. Results from the compositional analysis of the E-E soymeal samples are presented in Table 2. Partially defatted soy flours with a wide range of PDIs (12.45-69.10) and residual oil contents (4.73-12.65%) were produced by E-E. Highest and lowest oil extraction recoveries were 76.0% (13/5/1) and 35.8% (63/13/1), respectively. Dehulled soybeans tended (not significant at $P < 0.05$) to have increased PDI values and higher residual oil contents compared with whole soybeans under identical E-E conditions, as in the case for sample 14/7/1 (dehulled) versus 20/5/1 (whole). These results are contrary to those of Nelson *et al.* (1) who reported significantly higher oil yield when using dehulled soybeans, although that difference diminished following removal of oil fines or foots. We also observed higher foots contents during oil collection when dehulled soybeans were processed. This is an important consideration for processors. More oil settling capacity will be required when dehulling soybeans prior to E-E processing.

Whole soybeans produced significantly higher extrusion barrel temperatures compared with dehulled soybeans (Table 3). Jin *et al.* (7) reported that fiber addition caused extruder torque, die pressure, and specific energy to increase which they attributed to increased dough mass viscosity. Additionally, total dietary fiber content (not measured) is expected to be significantly higher for E-E meal from whole soybeans than that of dehulled soybeans. Given the reported health benefits associated with dietary fiber (8) the use of whole soybeans might be attractive in human food applications, if fiber was not detrimental to performance, taste and texture of foods in which the flour is incorporated.

As expected, twice-expelled samples had significantly lower residual oil contents compared with single-expelled flours processed under identical conditions (Table 2). Single-expelled meal had approximately 2 percentage points higher residual oil content than the twice-expelled meal. Nelson *et al.* (1), using a different type of expeller, found PDI was ~ 2 percentage points lower in single-expelled flours. In the present study, no significant changes in PDI were observed in twice-expelled flours. Thus, expelling in series may be an effective in decreasing the residual oil content while maintaining protein functionality. This may be significant for use in lower fat flours for human food applications.

The E-E meals produced from reduced-moisture (6.7%) soybeans did not differ significantly from higher moisture (9.5%) soybeans in compositional analyses (Table 2). Drying did not improve oil recovery. The relationship between drying and PDI is unclear. There was a 5 percentage point decrease in PDI associated with dried samples 58/8/1 vs 54/8/1. In addition, increased barrel temperatures were observed during extrusion of the dried soybeans (Table 4). Zhu *et al.* (6) found that PDI significantly decreased during dry extrusion with increasing extrusion temperature and moisture content.

PDI was strongly correlated with residual oil content ($R = 0.824$, $P < 0.0001$). Comparison of low (10-40), medium (40-60) and high (> 60) PDI samples revealed significantly higher mean residual oil content for high- compared to low-PDI flours (high PDI = 10.9%, low PDI = 5.9%, $P < 0.05$; Fig 2). Temperatures in the three extruder zones were the most important factors affecting PDI and residual oil of E-E partially defatted soy flour. As the temperature of extruder zone 1 increased, both PDI and residual oil content decreased ($R = -0.861$ (PDI), $R = -0.946$ (residual oil), $P < 0.05$; Fig 3). Similar correlations were found with respect to the temperatures of extruder zones 2 and 3. These data indicate that altering the final PDI and residual oil content of E-E partially defatted soy flour is possible by adjusting the feed rate, screw and shear lock configurations, thereby changing the extrusion zone temperatures.

The low extrusion temperatures necessary to produce high PDI generally is less efficient in rupturing soybean spherosomes, and therefore does not facilitate oil extraction as evidenced by high residual oil content. Because this study was designed to produce wide ranges of PDI and residual oil values (e.g., high PDI, low residual oil), the correlation between PDI and residual oil was not linear. This may indicate that producing partially defatted soy flour with high PDI may require further alterations in feed materials and processing conditions to concurrently obtain low residual oil content.

Enzyme activities of E-E soy flour. TI activities (Table 4) ranged from 4.5 to 97.5% of the activity of raw soybeans and decreased with increasing extruder barrel temperature (R = -0.816, $P < 0.05$; Fig 4). Guzman *et al.* (5) varied extrusion temperatures from 127 to 160 °C and reported residual TI activities in non-expelled samples between 31 and 2% of the original activity. Eweedah *et al.* (2) and Nelson *et al.* (1) used similar extrusion systems at temperatures of 150 °C and 135-141 °C, respectively. In both studies, TI was reduced to ~6% of its original activity.

Lipase activities were not significantly different between samples and were not significantly correlated with extruder barrel temperature. These data are in agreement with those previously reported by Guzman *et al.* (5) who found no trend for lipase activity in extrusion processed soybean-corn mixtures.

The activities all three lipoxygenase isozymes (L1, L2 and L3) decreased with increasing temperature ($P < 0.05$) and were not detectable in most of the partially defatted soy flour samples (Table 5). Enzyme activities were expected to be relatively low following E-E processing because of the high temperature and long hot hold times in both the extruder and expeller. Activity levels of L-3, the most heat labile isozyme, were much lower than those observed for the L-1 and L-2 isozymes (Table 5). No lipoxygenase activity was detected in partially defatted soy flours extruded at temperatures greater than 89 °C. These results are consistent with those reported by Zhu *et al.* (6) and Guzman *et al.* (5) who detected no lipoxygenase activity at temperatures greater than 107 and 127 °C, respectively. These data suggest that only those partially defatted soy flours produced using low temperatures to achieve a high PDI may contain appreciable lipoxygenase activity. This may be important in human food applications of E-E partially defatted soy flour because these enzymes may significantly affect the color and flavor of foods in which the flours are incorporated.

References

1. Nelson, A.I., W.B. Wijeratne, S.W. Yeh, T.M. Wei, and L.S. Wei, Dry Extrusion as an Aid to Mechanical Expelling of Oil from Soybeans, *J. Am. Oil Chem. Soc. 64*:1341-1347 (1987).
2. Eweedah, N, J. Gundel, and T. Matrai, Protein Degradability, Amino Acid Composition, Trypsin Inhibitor and Urease Activity of Raw and Heat-treated Fullfat Soybean, *Arch. Anim. Nutr. 50*:361-367 (1997).
3. Schwimmer, S., *Source Book of Food Enzymology*, Avi Publishing, Westport, CT, 1981.pp. 196-200.
4. Moscowitz, G.J., R. Cassaigne, I .R. West, T. Shen, and L.I. Feldman, Hydrolysis of Animal Fat and Vegetable Oil with Mucor Mihei Esterase: Properties of the Enzyme, *J. Agric. Food Chem. 25*:1146-1150 (1977).
5. Guzman, G.J., P.A. Murphy, and L.A. Johnson, Properties of Soybean-Corn Mixtures Processed by Low-Cost Extrusion, *J. Food Sci. 54*:1590-1593 (1989).
6. Zhu, S., M.N. Riaz, and E.W. Lusas, Effect of Different Extrusion Temperatures and Moisture Content on Lipoxygenase Inactivation and Protein Solubility in Soybeans, *J. Agric. Food Chem. 44*:3315-3318 (1996).
7. Jin, Z., F. Hsieh, and H.E. Huff, Extrusion Cooking of Corn Meal with Soy Fiber, Salt, and Sugar, *Cereal Chem. 71*:227-234 (1994).
8. Gordon, D.T., Functional Properties vs. Physiological Action of Total Dietary Fiber, *Cereal Foods World 34*:517-525 (1989).

Table 1. Extruder and Expeller Operating Conditions for Production of Extruded-Expelled Soybean Flour

Sample Code[a]	Extruder Configuration[b]	Nose Cone, cm	Choke Setting, cm	Current, Amps	
				Extruder	Expeller
13/5/1-W	11-6-6-6, DF	0.8	1.0	128	28
26/5/1-W	11-11-6-6, SF	0.8	1.0	119	28
20/5/1-W	11-6-6-6, DF	1.0	1.1	112	25
14/7/1	11-6-6-6, DF	1.0	1.1	105	22
43/6/1	11-11-6-6, SF	1.0	1.9	107	21
38/8/1	11R-11R-11R-11, SF	Tight	0.9	94	21
45/7/1	11R-11R-11R-11, SF	0.8	1.1	95	22
61/10/1	11R-11R-11R-11R, SF	1.0	0.9	81	21
63/13/1	11R-11R-11R-11R, SF	1.6	Tight	72	25
54/12/1	11R-11R-11R-11R, SF	1.6	0.9	81	21
69/12/1	11R-11R-11R-11R, SF	1.6	1.1	74	20
35/5/2	11R-11R-11R-11, SF	0.8	1.0	109	24
43/7/1-L	11R-11R-11R-11, SF	0.8	1.0	119	34
67/10/2	11R-11R-11R-11R, SF	1.6	1.1	72	22
58/8/1	11R-11R-11R-11R, SF	1.6	1.0	107	28
55/6/2	11R-11R-11R-11R, SF	1.6	1.0	107	28
54/8/1-L	11R-11R-11R-11R, SF	1.6	1.0	98	28

[a] Denotes PDI/residual oil content/times expelled; W indicates whole beans; L indicates low moisture.

[b] Numbers and R denote shear lock type used from feed end to die end of the extruder; DF denotes double flighting of the screw; SF denotes single flighting of the screw.

Table 2. Chemical Analyses of Extruded-Expelled Soybean Flour[a]

Sample Code[b]	Dry Matter, %	Crude Protein, % mfb	PDI	Residual Oil, % mfb
13/5/1-W	96.1^{gh}	50.4^{cd}	12.5^{a}	4.7^{a}
26/5/1-W	94.5^{e}	48.1^{b}	25.6^{b}	5.3^{ab}
20/5/1-W	95.6^{fg}	49.4^{bc}	20.0^{ab}	5.2^{ab}
14/7/1	95.9^{g}	50.2^{cd}	14.3^{a}	6.8^{bc}
43/6/1	94.1^{de}	51.1^{d}	42.9^{cd}	6.3^{b}
38/8/1	95.2^{f}	51.4^{d}	37.8^{c}	7.8^{c}
45/7/1	94.8^{ef}	51.2^{d}	45.2^{cd}	7.6^{c}
61/10/1	94.2^{de}	50.6^{cd}	61.4^{efg}	9.6^{d}
63/13/1	93.8^{d}	49.6^{c}	63.0^{efg}	12.7^{e}
54/12/1	92.8^{c}	48.6^{bc}	54.0^{def}	11.6^{e}
69/12/1	91.8^{b}	49.6^{c}	69.1^{gh}	11.7^{e}
35/5/2	94.3^{de}	51.6^{d}	35.4^{bc}	5.4^{ab}
43/7/1-L	96.5^{h}	50.9^{d}	43.0^{cd}	6.6^{bc}
67/10/2	94.2^{de}	50.6^{cd}	66.7^{fg}	9.9^{d}
58/8/1	93.7^{d}	50.9^{cd}	58.1^{efg}	7.8^{c}
55/6/2	94.0^{de}	52.4^{d}	55.4^{def}	5.7^{ab}
54/8/1-L	96.0^{gh}	50.4^{cd}	53.8^{def}	8.1^{c}
Control	91.3^{a}	39.7^{a}	98.7^{i}	19.7^{f}

[a] Means within each column with different superscripts are significantly different at $P<0.05$.

[b] Denotes PDI/residual oil content/times expelled; W indicates whole beans; L indicates low moisture.

Table 3. Feed Rates and Extruder Barrel Temperatures[a]

Sample Code[b]	Feed Rate, kg/hr	Barrel Temp., °C		
		Zone 1	Zone 2	Zone 3
13/5/1-W	590	162	147	107
26/5/1-W	615	138	88	56
20/5/1-W	590	144	107	89
14/7/1	590	144	102	76
43/6/1	730	129	80	48
38/8/1	590	132	72	28
45/7/1	590	126	57	31
61/10/1	590	117	42	27
63/13/1	950	86	55	27
54/12/1	590	89	34	24
69/12/1	590	88	27	23
35/5/2	730	129	99	41
43/7/1-L	730	137	76	46
67/10/2	590	85	54	27
58/8/1	730	119	64	29
55/6/2	730	119	64	29
54/8/1-L	730	129	56	37
Control	N/A	N/A	N/A	N/A

[a] Mean values of two replications.

[b] Denotes PDI/residual oil content/times expelled; W indicates whole beans; L indicates low moisture.

Table 4. Lipase and Trypsin Inhibitor Activities of Extruded-Expelled Soybean Flours

Sample Code[a]	Lipase, mM H^+/min/g	Trypsin Inhibitor, trypsin inhibitor units
13/5/1-W	18.6	≤ 2,000
26/5/1-W	21.0	5,200
20/5/1-W	16.2	N/A[b]
14/7/1	15.8	5,000
43/6/1	11.8	N/A
38/8/1	28.0	N/A
45/7/1	15.4	13,950
61/10/1	18.8	N/A
63/13/1	15.1	N/A
54/12/1	17.9	26,900
69/12/1	10.7	36,500
35/5/2	20.9	10,200
43/7/1-L	13.8	N/A
67/10/2	10.1	43,500
58/8/1	19.2	N/A
55/6/2	17.5	27,275
54/8/1-L	13.2	N/A
Control	19.4	44,600

[a] Denotes PDI/residual oil content/times expelled; W indicates whole beans; L indicates low moisture.

[b] N/A denotes not applicable.

Table 5. Lipoxygenase Isozyme (L-1, L-2, L-3) Activities of Extruded-Expelled Soybean Flours[a]

Sample Code[b]	Lipoxygenase, % of original		
	L-1	L-2	L-3
13/5/1-W	ND[c]	ND	ND
26/5/1-W	ND	ND	ND
20/5/1-W	ND	ND	ND
14/7/1	ND	ND	ND
43/6/1	ND	ND	ND
38/8/1	ND	ND	ND
45/7/1	ND	ND	ND
61/10/1	ND	ND	ND
63/13/1	16.4^{b}	12.9^{b}	4.4^{a}
54/12/1	9.3^{ab}	8.1^{a}	3.9^{a}
69/12/1	10.7^{ab}	14.1^{b}	5.1^{a}
35/5/2	ND	ND	ND
43/7/1-L	ND	ND	ND
67/10/2	7.8^{a}	12.1^{ab}	2.1^{b}
58/8/1	ND	ND	ND
55/6/2	ND	ND	ND
54/8/1-L	ND	ND	ND
Control	100.0^{c}	100.0^{c}	100.0^{c}

[a] Means within each column with the different superscripts are significantly different $P<0.05$.

[b] Denotes PDI/residual oil content/times expelled; W indicates whole beans; L indicates low moisture.

[c] ND denotes not detectable.

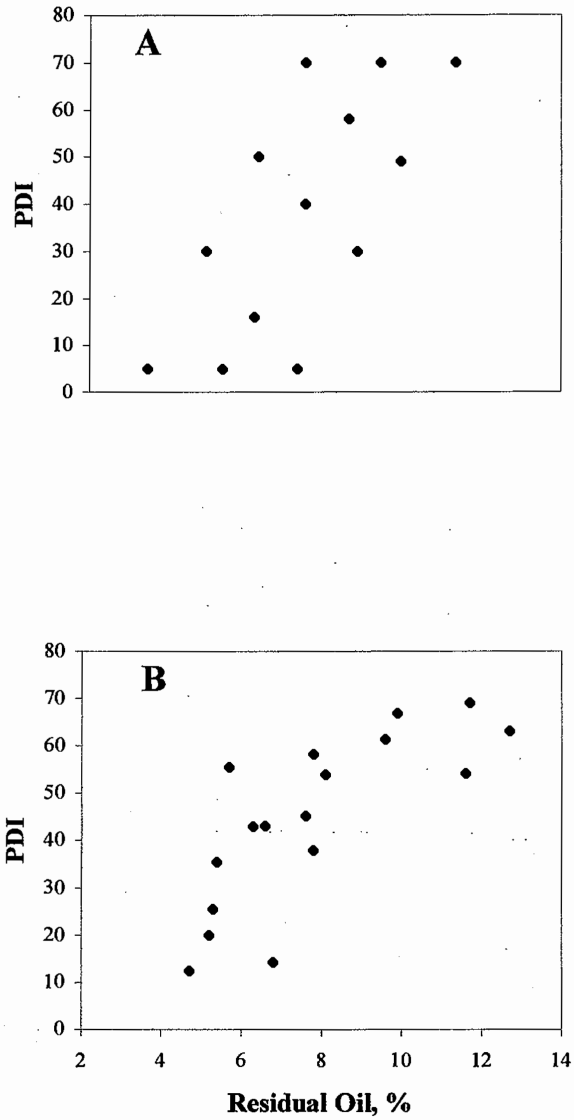


Fig. 1. Projected (A) and actual (B) distributions of residual oil content vs PDI of extruded-expelled soy flours.

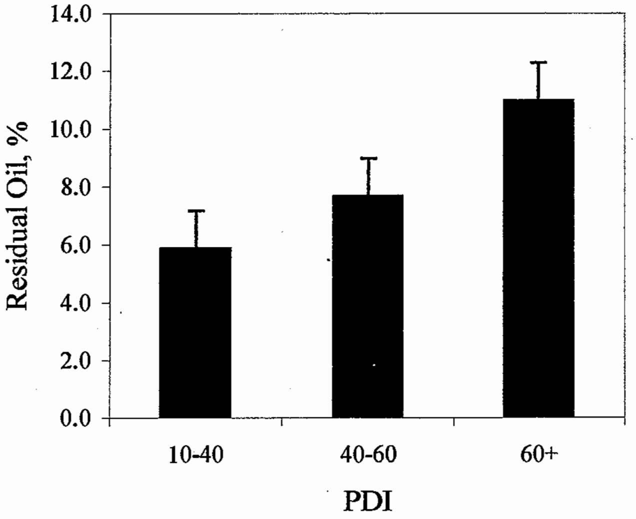


Fig. 2. Residual oil contents of extruded-expelled soy flours for low, medium, and high PDI ranges.

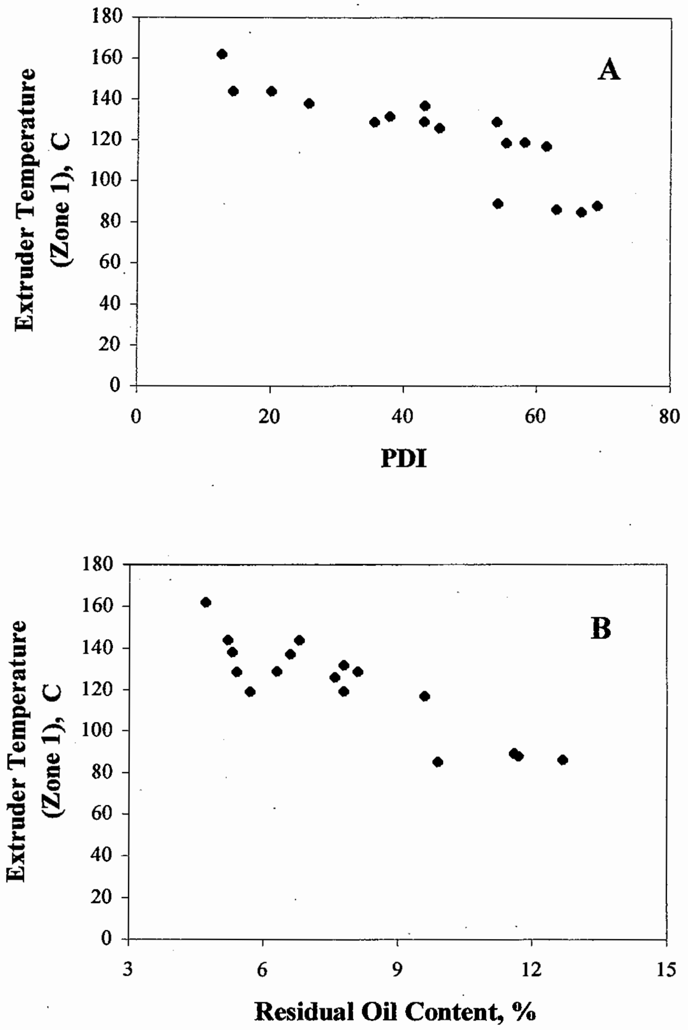


Fig. 3. Relationship between PDI (A) and residual oil content (B) of extruded-expelled soy flour, and extruder temperature (zone 1, °C).

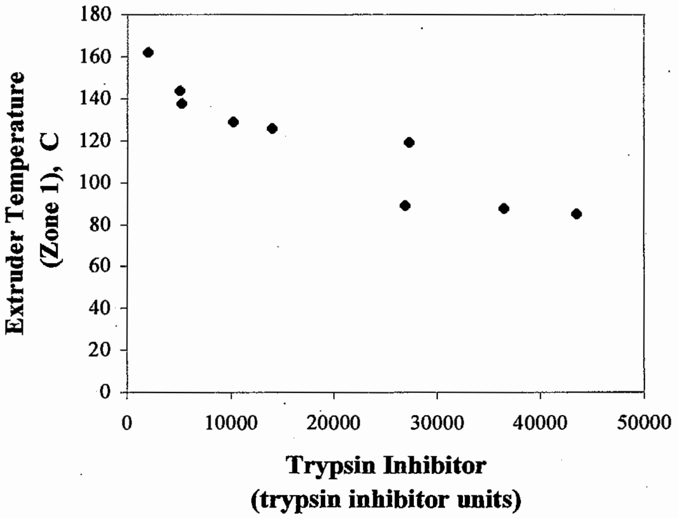


Fig. 4. Relationship between extruder temperature (zone 1, °C) and trypsin inhibitor activity of extruded-expelled soy flour.

CHAPTER 4. TWIN-SCREW EXTRUSION TEXTURIZATION OF EXTRUDED-EXPELLED SOYBEAN FLOURS

A paper to be submitted to the *Journal of the American Oil Chemists' Society.*

T.W. Crowe and L.A. Johnson

Keywords: Extrusion, texturized protein, soy protein, soy flour, PDI, fat.

Abstract

Texturized soy proteins (TSP) have been produced from hexane-extracted soy flours having a narrow range of characteristics. The objective of this study was to determine the influence of protein dispersibility (PDI) and residual oil content on the extrusion texturization of partially defatted soy flours produced by extrusion-expelling (E-E). Ten partially defatted soy flours with residual oil contents and PDI values ranging from 5.5-12.7% and 35.3-69.1, respectively, were successfully texturized using a twin-screw extruder. Water-holding capacity was greater in TSP prepared from flours with lower residual oil contents. Bulk density was significantly lower in TSP prepared from E-E soy flours compared to a commercial product made from hexane-extracted soy flour. The texture of extended ground beef patties prepared from texturized E-E soy flours was similar to that of 19% fat ground beef. Overall flavor acceptability was strongly correlated (R = 0.761) with residual oil content of the E-E flours. In general, lower residual oil and higher PDI flours exhibited better texturization and extrudate qualities.

Introduction

Defatted soybean flours and flakes are valuable material sources for extrusion-texturized vegetable proteins (1), a product used in ground meat products and meat analogs (2). Small-scale extruder-expeller (E-E) operations, or mini-mills, have been increasing in popularity because of their low capital investment, local feed demand for high-energy protein supplements, and abilities to process identity-preserved and organic products (3). Partially defatted soybean flours are important co-products of this process, particularly as these flours can be used for human as well as animal consumption. In order to compete in highly competitive oil and meal markets, E-E operations must explore potential markets for these partially defatted soy flours, such as the production of texturized soy protein (TSP).

Hexane extracted and flash desolventized soybean flours and flakes are widely used to produce TSP. These flours typically contain less than 1% fat and have PDI values > 80. It is uncertain whether E-E meal can be texturized and the conditions necessary for extrusion-texturization of E-E partially defatted soy flour are unknown. The objective of this study was to extrusion-texturize E-E produced partially defatted soy flours having wide ranges of protein dispersability indices (PDI) and residual oil contents. The hypothesis of this study was that partially defatted soy flours with higher PDIs and lower residual oil contents can be extruded to produce a better quality TSP compared with partially defatted soy flours having lower PDIs and higher residual oil contents.

Experimental Procedures

Materials. Whole soybeans (Latham 610) were obtained from Iowa Soy Specialities (Vinton, IA) and stored at 9.5% moisture content on their premises until processed. The soybeans used to study the effect of low moisture content on oilseed processing were dried to 6.7% moisture content using ambient air grain driers in the Center for Crops Utilization Pilot Plant at Iowa State University (Ames, IA). Dehulled samples were processed using traditional methods of first cracking the soybean into 6-8 pieces with a roller mill (Ferrell-Ross, Oklahoma City, OK) and then aspirating the hulls with a Multi-Aspirator (Kice, Wichita, KS). A commercial TSP, ADM 165-118, was provided by Archer Daniels Midland Co. (Decatur, IL).

Extruding and expelling. Extruding-expelling whole and dehulled soybeans was performed at Iowa Soy Specialties (Vinton, IA) using an Instra-Pro 2500 dry extruder and an Insta-Pro 1500 screw press (Triple "F"/Insta-Pro, Des Moines, IA). Following E-E processing, the presscake was placed into plastic-lined paper bags and allowed to cool at ambient temperature and then sealed for transport. The soymeal cake was milled to <100-mesh (94.7%) by using Fitzmill (The Fitzpatrick Company, Elmhurst, IL). The Fitzmill was operated at 7000 rpm using the blades in a blunt hammermill configuration, at 30 rpm feed rate, and fitted with a 1536-0060 screen. Milled samples were stored at –20 °C prior to texturization.

Texturization. A co-rotating lab-scale Leistritz Micro-18 (American Leistritz Corp., Somerville, NJ) twin-screw extruder with a screw diameter of 18 mm and an L/D ratio of 25 was used. The barrel was divided into six electrically heated sections including the die. The twin screws had segmental screw elements so that the amount of shear input could be varied. A high-shear screw design with six temperature zones (Fig 1) operating at a screw speed of 300 rpm was used for all treatments. Feed rate, screw speed, die, screw design, temperature and flour moisture content were constant for each treatment. All partially defatted soy flours were hydrated to 27% moisture, mixed and allowed to stand overnight at 4 °C for tempering. The flours were supplied to the extruder at a uniform feed rate of 150 g/min using a metering feeder (Accurate Inc., Whitewater, WI). The extruder was brought to steady state for each treatment for a minimum of 5 min prior to sample collection. The extrudate was collected and dried at 50 °C for 24 hr.

Extruder torque and pressure. Measurements for screw torque and die pressure during extrusion were monitored by a digital control panel readout, and were recorded after steady state had been reached and held for approximately 2 min.

Extrudate milling and sizing. The dried extrudates (TSP), including a commercial sample (ADM 165-118, Archer Daniels Midland Co., Decatur, IL), were milled and sized using a set of corrugated cracking rolls (Witt Corrugating Inc., Wichita, KS) to pass through a 6-mesh screen and be contained on a 12-mesh screen. Milled TSP was stored in sealed polyethylene bags at 25 °C until analyzed.

Soy flour composition. Moisture contents of soy flours were determined according to the 2-hr oven drying method (AOCS official method Ba-38). Crude fat contents were determined by Goldfisch extraction (AACC method 30-25). Crude protein was measured using a Perkin Elmer Series II Nitrogen Analyzer 2410 (Perkin Elmer Corp., Norwalk, CT). Nitrogen contents were multiplied by a factor of 6.25 to estimate crude protein content.

Water-holding capacity. Water-holding capacity was determined by weighing 30 g TSP into a 400-ml beaker and adding 150 ml of 4 °C water. The sample was held in a refrigerator for 1 hr. The beaker was emptied onto a pre-weighed 20-mesh screen tilted at a 25° angle and allowed to drain for 3 min. The screen was blotted with a paper towel to remove excess water and weighed. Water-holding capacity was calculated as (hydrated weight-dry weight)/dry weight.

Bulk density. TSP was added to a 100-ml graduated cylinder in 20-ml intervals. At each interval the cylinder was lightly tapped against a bench surface 20 times. The filled cylinder was emptied into a tared beaker to determine the weight of texturized soy protein. Bulk density was calculated as weight of texturized soy protein per 100 cc volume.

Texture analysis of TSP. Texture analysis was performed using a TA-XT2 Texture Analyzer (Texture Technologies Corp., Scarsdale, NY) using the texture profile analysis measurement. About 10.0 g of hydrated TSP (2.6 parts H_2O:1 part TSP) were placed in an aluminum cylinder (internal diameter = 27 mm, depth = 27 mm) and pressed to make a smooth surface. A smooth 13-mm plastic probe was used to determine 70% compression at a rate of 5 mm/sec. Samples were evaluated for hardness, springiness, cohesiveness and chewiness as described by Breene and Barker (4). Six texture analyses were performed for each sample.

Preparation of TSP-extended ground beef. Based on the residual oil content of TSP, coarse ground beef with different fat levels (~7% and ~19%) was blended with hydrated TSP to give a final product with 7% fat content. The mixture of ground beef and TSP was then ground through a 0.32 cm plate and held at 4 °C until used to make patties. TSP-extended ground beef patties were prepared by placing 48 g of 25% TSP ground beef into a cylindrical mold and hand patting to a uniform thickness of 1.3 cm. The patties were held at -20° C until used for texture analysis.

Texture analysis of TSP-extended ground beef. Frozen patties were thawed at 4 °C for 24 hr and then cooked at 185 °C for 3.5 min, flipped, and allowed to cook for an additional 2.5 min to an internal temperature of 70 °C. The patties were allowed to cool to room temperature and a 25-mm core sample was taken from the center of each patty. Texture profile analysis was performed using a TA-XT2 Texture Analyzer (Texture Technologies Corp., Scarsdale, NY). A 38-mm anvil was used to determine 70% compression at a rate of 5 mm/sec. Samples were evaluated for hardness, springiness, cohesiveness and chewiness. Six texture analyses were performed for each sample.

Cooking loss. Cooking loss was the gravimetric difference in weight between uncooked and cooked patties. Cooked patties were cooled to room temperature and blotted with a paper towel to remove excess surface fat and water. Weight differences were based on the sum of four patties and calculated as (uncooked weight – cooked weight)/uncooked weight.

Sensory evaluation. Five partially defatted soy flour TSP-extended ground beef samples representing a wide range of PDI and residual oil contents were selected for human sensory analyses. Frozen patties were thawed at 4 °C for 24 hr and then cooked at 185 °C for 3.5 min, flipped, and allowed to cook for an additional 2.5 min to an internal temperature of 70 °C. Patties were held at 60 °C and served within 15 min following cooking. Ten students of the Department of Food Science and Human Nutrition were trained to evaluate hardness, cohesiveness, chewiness, soy flavor and overall flavor during two 1-hr training sessions with samples similar to those they were to evaluate. In addition, texture and flavor references were provided. Panelists were asked to evaluate 7 different samples (5 partially defatted soy flour TSP-extended ground beef samples, commercial TSP control, 19% fat ground beef control) presented in duplicate. Samples were evaluated under red light on two separate sittings.

Experimental design. Sample 45/8/1 (PDI/residual oil/times expelled) represents the midpoint of samples with regard to PDI value and residual oil content. The extrusion process conditions for texturization were optimized at this point based on instrumental textural comparison to the commercial TSP. All other samples were texturized under identical conditions with respect to moisture, temperature, screw speed, etc..

Statistical analysis. A randomized complete block design was used with each block replicated three times. In the third block, however, only eight of the ten treatments were measured because of insufficient sample. Statistical analyses were performed using the General Linear Model procedures of SAS 6.06 (SAS, 1991). Significance was established at $P < 0.05$.

Results and Discussion

Partially defatted soy flour characteristics. The properties of the partially defatted soy flours are summarized in Table 1. By design, the partially defatted soy flours chosen represented a wide range of PDI value (35.4-69.1) and residual oil content (5.4-12.7%) with little variability in crude protein contents (49.3-52.4%). The pH of the partially defatted soy flours used in this study ranged from 6.5 to 6.7. The pH of the feed material affects the fluidity of the dough in the extruder, and thus influences the shaping, density, chewiness and rehydration properties of the product (5,6). Characteristics of raw materials, including source, previous handling or milling history, extraction conditions, and extrusion parameters may influence the functional properties of extrudates. These partially defatted soy flours were produced at maximum temperatures ranging from 86 to 162 °C. Three samples (35/6/2, 67/10/2, and 58/6/2) were twice-expelled and therefore were subjected to longer periods of thermal processing. Dahl and Villota (7) suggested that physico-chemical properties may be modified by excessively heated flour because of non-uniform melting of carbohydrate fractions and intermolecular peptide cross-linking.

Water-holding capacity and bulk density. Water-holding capacities and bulk densities of TSP produced from partially defatted soy flour are reported in Table 2. Residual oil was negatively correlated with water-holding capacity ($R = -0.473$, $P < 0.05$; Fig 2). There were no significant differences in water-holding capacity for extrudates produced from low PDI (< 55) versus high PDI (> 55) partially defatted soy flour. These results are similar to those reported by Bhattacharya *et al.* (8) who observed water-holding capacity to decrease as lipid content increased, and Kearns *et al.* (9) who found no significant difference in the water-holding capacity of extrudates produced from flours with PDI levels ranging from 20-70. Heating disrupts the quaternary structure of the 11S soy protein and subsequently dissociates the subunits (10). These fractions initially form soluble aggregates that are converted to insoluble aggregates with continued heat treatment as evidenced by increased water-holding capacity with increasing PDI. This may be indicative of protein unfolding, which allows active amino acid R-groups to become exposed for binding water. With extended thermal processing (lower PDI), the production of insoluble aggregates is favored as noted by decreased water-holding capacity.

Water-holding capacity was negatively correlated with bulk density ($R = -0.474$, $P < 0.05$; Fig 3). Similarly, Rhee *et al.* (11) reported an inverse relationship between water-holding capacity and bulk density in extrudates produced from flours with a wide range of nitrogen solubilities. The lack of available water-binding sites makes these low-solubility or insoluble protein aggregates unable to incorporate sufficient water to develop proper dough consistency within the extruder barrel. Upon release from the die the extrudate does not properly expand due to insufficient entrapped moisture as evidenced by decreased bulk density. The bulk density range of partially defatted soy flour extrudates was narrow 0.22 – 0.26 g/cm^3, despite the relatively wide ranges of PDI values and residual oil contents.

Extruder conditions. The extrusion of proteins is associated with dissipation of mechanical energy caused by increased dough viscosity and frictional effects. Extruder torque and pressure are indirect measurements of these effects (Table 3). The relatively high residual oil content of the partially defatted soy flour may have had protein plasticizing and lubricating effects, reducing protein interactions and attenuating extruder torque and pressure. Texturization of sample 35/6/2 resulted in the highest extruder torque and pressure levels. This sample, which was twice-expelled, was exposed to excessive thermal processing, as evidenced by a low PDI value (35.4). However, sample 57/8/1 showed no significant change in torque or pressure with single versus twice expelling. These samples (57/8/1 and 58/6/2) had higher PDI values (55.3 and 58.0, respectively) indicating less thermal treatment. In general, lower PDI samples (38/8/1, 35/6/2, 45/8/1) were associated with increased torque (Table 3). Kearns *et al.* (9) also reported increased energy requirements for PDI values < 50. Mitchell and Areas (12) suggested that the presence of insoluble protein aggregates negatively affects flow behavior. However, Alcocer *et al.* (13) found that increasing flour lipid content resulted in decreased protein aggregation, resulting in less energy input in comparison to low lipid containing flours. Indeed, higher residual oil samples (71/13/1, 55/13/1, 40/12/1 and 70/11/1) had significantly lower torque and pressure compared with other partially defatted soy flours (Table 3).

Textural and sensory characteristics. TSP hardness was significantly reduced in high residual oil samples (71/13/1, 55/13/1, 40/12/1, 70/11/1) and in the twice-expelled sample 67/10/2 (Table 4). The negative correlation between residual oil and all instrumental texture measurements indicates that the higher lipid contents of these samples may have inhibited protein interactions responsible for desirable extrudate textural attributes. Both Faubion *et al.* (14) and Bhattacharya *et al.* (8) found that removing lipids from flours favorably influenced TSP textural qualities, and Kearns *et al.* (9) reported a maximum recommended fat level of 6.5% in raw materials.

Neither PDI value nor residual oil content affected textural attributes measured in the TSP-extended ground beef system. In addition, no relationship was noted between texture measurements in the TSP-extended ground beef system versus the TSP alone. All hydrated TSP samples had decreased hardness compared with the commercial sample, however, this decrease was not significant in samples 38/8/1 (PDI 37.7) and 58/6/21 (twice-expelled) (Table 4). Texture attributes in nearly all samples in the TSP-extended ground beef system were comparable to the commercial sample (Table 5). In addition, despite the lower fat content (7%), texture measurements of samples in the TSP-extended ground beef system were similar to those measured in the 19% fat ground beef control (Table 5).

Results from human sensory evaluation of TSP-extended ground beef patties are presented in Table 7. No significant differences in hardness or chewiness were observed in the TSP-extended ground beef compared with the 19% fat control. As expected, soy flavor was significantly higher ($P < 0.05$) in the TSP-extended ground beef versus the 19% fat control. However, panelists judged overall flavor (like versus dislike) in most of the TSP-extended ground beef samples to be similar to the 19% fat control and the commercial sample. Sample 71/13/1, produced from high-lipoxygenase, partially defatted soy flour (data not shown) was judged to have the least desirable overall flavor. Residual oil content of partially defatted soy flour was strongly correlated with overall flavor (R = 0.761, $P < 0.05$; Fig 4). In general, TSP from low-fat, partially defatted soy flour had less soy flavor and better overall flavor compared to TSP from high-fat partially defatted soy flour.

Cooking loss. Eight of the ten samples produced from the partially defatted soy flours had cooking losses that were between the values for the 7% fat control and the 19% fat control (Table 6). The remaining two samples, 45/8/1 and 57/8/1, did not have cooking losses significantly different from the 19% fat control. The cooking losses of most of the

TSP-extended patties were less than reported by others for low-fat hamburger patties (15). Cooking losses for all samples were similar to those of the commercial TSP.

Characteristics of TSP from partially defatted soy flours produced by E-E were significantly influenced by PDI value and residual oil contents. Residual oil content was negatively correlated with instrumental texture analysis results and water-holding capacity. High PDI and low residual oil flours positively affected extruder performance as evidenced by significantly decreased torque and pressure values. Hydrated TSP and TSP-extended ground beef texture characteristics were comparable to a commercial product. When incorporated into a low-fat (7%) TSP-extended ground beef system, most of the extrudates exhibited textural attributes similar to the high fat (19%) ground beef control, with reduced cooking loss. These results are surprising as all E-E partially defatted soy flours produced acceptable TSP, despite the relatively wide range of PDIs and residual oil contents. It is clear from these results that partially defatted soy flours produced by E-E have the functional characteristics necessary for extrusion-texturization of value-added products suitable for human food applications.

References

1. Lusas, E., and M. Riaz, Texturised Food Proteins from Fullfat Soybeans at Low Cost, *Extrusion Comm. 9*:15-18 (1996).

2. Lusas, E.W., and M.N. Riaz, Soy Protein Products: Processing and Use, *Am. Inst. Nutr.* 573S-580S (1995).

3. Breene, W.M., and T.G. Barker, Development and Application of a Texture Measurement Procedure for Textured Vegetable Proteins, *J. Texture Studies* 459-472 (1975).

4. Harper, J.M, Food Extrusion, *Crit. Rev. Food Sci. Nutr.* 155-215 (1979).

5. Smith, O.B., Textures by Extrusion Processing, in *Fabricated Foods*, edited by G.E. Inglett, The AVI Publishing Company, Inc., Westport, CN, 1975, pp. 89-108.

6. Dahl, S.R., and R. Villota, Effect of Thermal Denaturation of the Texturization of Soybean Protein Via Twin-Screw Extrusion, *Can. Inst. Sci. Technol. J. 24*:143-150 (1991).

7. Bhattacharya, M., and M.A. Hanna, Effect of Lipids on the Properties of Extruded Products, *J. Food Sci. 53*:1230-1231 (1988).

8. Kearns, J.P., G.J. Rokey, and G.R. Huber, Extrusion of Texturized Proteins, in *Proceedings of the World Congress on Vegetable Protein Utilization in Human Foods and Animal Feedstuffs* edited by T. H. Applewhite, American Oil Chemists' Society, 1988, pp. 353-362.

9. Wolf, W.J., and T. Tamura, Heat Denaturation of Soybean 11S Protein, *Cereal Chem. 46*:331-339 (1969).

10. Rhee, K.C., C.K. Kuo, and E.W. Lusas, Texturization. in *Protein Functionality in Foods*, edited by J.P. Cherry, ACS Symposium Series, 1981, pp. 51-87.

11. Mitchell, J.R., and J.A.G. Areas, Structural Changes in Biopolymers During Extrusion, *in Food Extrusion Science and Technology*, edited by J.L. Kokini, C. Ho, and M.V. Karwe, Marcel Dekker, Inc., New York, 1992, pp. 345-360.

12. Alcocer, M.J.C., and J.A.G. Areas, Lipid Composition and Hydration Characteristics of Lung Protein Isolated by Several Solvents, *J. Food Sci. 55*:19-22 (1990).

13. Faubion, J.M., and R.C. Hoseney, High-Temperature Short-Time Extrusion Cooking of Wheat Starch and Flour. I. Effect of Moisture and Flour Type on Extrudate Properties, *Cereal Chem. 59*:529-533 (1982).

14. Troutt, E.S., M.C. Hunt, D.E. Johnson, J.R. Claus, C.L. Kastner, D.H. Kropf, and S. Stroda,. Chemical, Physical, and Sensory Characterization of Ground Beef Containing 5 to 30 Percent Fat, *J. Food Sci. 57*:25-29 (1992).

Table 1. Compositional and Chemical Analyses of Extruded-Expelled Soybean Flour

Sample Code[a]	PDI	Residual Oil, % mfb	Times Expelled	Crude Protein, % mfb
38/8/1	37.7	7.7	1	51.3
35/6/2	35.3	5.5	2	52.4
45/8/1	45.4	7.7	1	50.9
67/10/2	67.2	9.5	2	50.5
71/13/1	70.7	12.7	1	49.1
55/13/1	55.3	12.6	1	50.0
58/6/2	58.4	5.5	2	52.0
57/8/1	57.3	7.6	1	50.6
40/12/1	39.8	11.5	1	49.3
70/11/1	70.4	10.5	1	49.5

[a] Denotes PDI/residual oil content/times expelled.

Table 2. Water-Holding Capacities and Bulk Densities of Texturized Soy Protein from Extruded-Expelled Soybean Flour[a]

Sample Code[b]	Water-Holding Capacity, %	Bulk Density, g/cc
38/8/1	364^{c}	0.231^{ab}
35/6/2	335^{bc}	0.254^{b}
45/8/1	367^{c}	0.229^{a}
67/10/2	312^{ab}	0.264^{b}
71/13/1	293^{a}	0.264^{b}
55/13/1	324^{b}	0.245^{ab}
58/6/2	323^{b}	0.264^{b}
57/8/1	365^{c}	0.223^{a}
40/12/1	309^{ab}	0.255^{b}
70/11/1	339^{bc}	0.236^{ab}
ADM118	319^{ab}	0.382^{c}

[a] Means within each column with different superscripts are significantly different at $P<0.05$.

[b] Denotes PDI/residual oil content/times expelled.

Table 3. Extruder Conditions During Texturization of Extruded-Expelled Soybean Flour[a]

Sample Code[b]	Torque[c]	Pressure, psi
38/8/1	30.0^{bc}	470^{b}
35/6/2	33.0^{c}	517^{c}
45/8/1	30.7^{bc}	477^{b}
67/10/2	26.7^{ab}	467^{b}
71/13/1	25.0^{a}	433^{a}
55/13/1	26.0^{ab}	437^{a}
58/6/2	29.0^{b}	463^{b}
57/8/1	29.0^{b}	470^{b}
40/12/1	26.0^{ab}	447^{ab}
70/11/1	25.3^{ab}	437^{a}

[a] Means within each column with the different superscripts are significantly different at $P<0.05$.

[b] Denotes PDI/residual oil content/times expelled.

[c] Torque is given as % of maximum load of extruder drive motor.

Table 4. Texture Properties of Hydrated Texturized Soy Protein[a]

Sample Code[b]	Hardness, N[c]	Springiness[c]	Cohesiveness[c]	Chewiness, N[c]
38/8/1	10.5^{bc}	0.870^{ab}	0.563^{a}	5.1^{bc}
35/6/2	10.0^{b}	0.870^{ab}	0.602^{b}	5.2^{bc}
45/8/1	9.8^{b}	0.903^{b}	0.595^{b}	5.2^{bc}
67/10/2	7.6^{a}	0.854^{ab}	0.610^{b}	3.9^{a}
71/13/1	7.0^{a}	0.863^{ab}	0.577^{ab}	3.5^{a}
55/13/1	8.0^{ab}	0.837^{a}	0.573^{ab}	3.9^{a}
58/6/2	10.6^{bc}	0.884^{ab}	0.643^{c}	6.0^{c}
57/8/1	9.4^{b}	0.884^{ab}	0.592^{b}	4.9^{b}
40/12/1	7.5^{a}	0.866^{ab}	0.598^{b}	4.0^{ab}
70/11/1	7.9^{a}	0.859^{ab}	0.568^{ab}	3.9^{a}
ADM118	11.4^{c}	0.844^{a}	0.566^{a}	5.9^{c}

[a] Means within each column with different superscripts are significantly different at $P<0.05$.

[b] Denotes PDI/residual oil content/times expelled.

[c] Hardness and Chewiness values are given in Newtons; Springiness and Cohesiveness are unitless.

Table 5. Texture Properties of Texturized Soy Protein-Extended Hamburger Patties[a]

Sample Code[b]	Hardness, N[c]	Springiness[c]	Cohesiveness[c]	Chewiness, N[c]
38/8/1	112.9^{ab}	0.780^{ab}	0.539^{a}	47.4^{ab}
35/6/2	105.3^{ab}	0.779^{ab}	0.543^{a}	43.9^{ab}
45/8/1	123.7^{b}	0.763^{ab}	0.539^{a}	50.9^{b}
67/10/2	96.1^{a}	0.763^{ab}	0.558^{a}	40.7^{a}
71/13/1	110.4^{ab}	0.772^{ab}	0.571^{a}	48.6^{b}
55/13/1	131.8^{b}	0.773^{ab}	0.529^{a}	52.2^{b}
58/6/2	105.8^{ab}	0.776^{ab}	0.561^{a}	45.7^{ab}
57/8/1	119.8^{b}	0.792^{b}	0.554^{a}	52.5^{b}
40/12/1	100.9^{a}	0.744^{a}	0.560^{a}	42.1^{a}
70/11/1	111.1^{ab}	0.795^{b}	0.532^{a}	46.6^{ab}
ADM118	105.5^{ab}	0.800^{b}	0.537^{a}	45.3^{ab}
Control 7%	127.7^{b}	0.772^{ab}	0.499^{a}	50.0^{b}
Control 19%	98.8^{a}	0.802^{b}	0.566^{a}	44.1^{a}

[a] Means within each column with different superscripts are significantly different at $P<0.05$.

[b] Denotes PDI/residual oil content/times expelled.

[c] Hardness and Chewiness values are given in Newtons; Springiness and Cohessiveness are unitless.

Table 6. Cooking Losses of Texturized Soy Protein-Extended Hamburger Patties[a]

Sample Code[b]	Cooking Loss, %
38/8/1	21.2^{b}
35/6/2	22.3^{bc}
45/8/1	25.3^{cd}
67/10/2	21.7^{b}
71/13/1	22.8^{bc}
55/13/1	24.9^{cd}
58/6/2	21.7^{b}
57/8/1	24.1^{bcd}
40/12/1	21.9^{b}
70/11/1	22.7^{bc}
ADM118	24.3^{bc}
Control 7%	19.3^{a}
Control 19%	28.2^{d}

[a] Means within the column with different superscripts are significantly different at $P<0.05$.

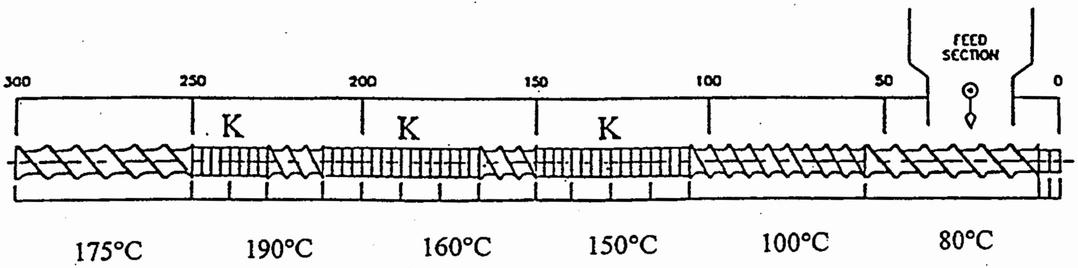
[b] Denotes PDI/residual oil content/times expelled.

Table 7. Sensory Properties of Texturized Soy Protein-Extended Ground Beef Patties[a]

Sample Code[b]	Hardness	Cohesiveness	Chewiness	Soy Flavor	Overall Flavor
35/6/2	7.3^{b}	7.4^{b}	7.6^{b}	2.0^{ab}	11.1^{ab}
45/8/1	8.0^{b}	7.2^{b}	8.2^{b}	5.0^{d}	7.9^{b}
71/13/1	7.2^{b}	5.8^{a}	7.7^{b}	8.7^{e}	3.3^{c}
58/6/2	7.9^{b}	6.8^{b}	8.1^{b}	3.1^{bc}	9.8^{ab}
40/12/1	7.9^{b}	7.3^{b}	8.6^{b}	4.7^{cd}	8.3^{b}
ADM118	4.5^{a}	5.5^{a}	4.8^{a}	4.4^{cd}	9.1^{ab}
19% Control	6.6^{ab}	7.0^{b}	8.7^{b}	0.7^{a}	11.7^{a}

[a] Means within each column with different superscripts are significantly different at $P<0.05$.

[b] Denotes PDI/residual oil content/times expelled.



✓ Fig. 1. Extrusion screw configuration and temperature profile.

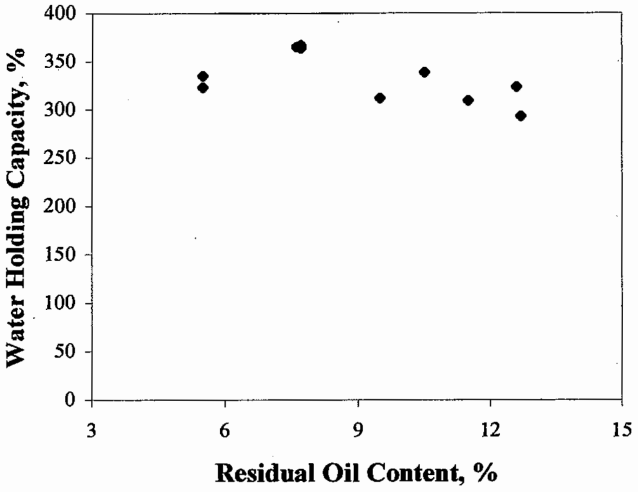


Fig. 2. Relationship between water holding capacity and residual oil content of texturized soy protein.

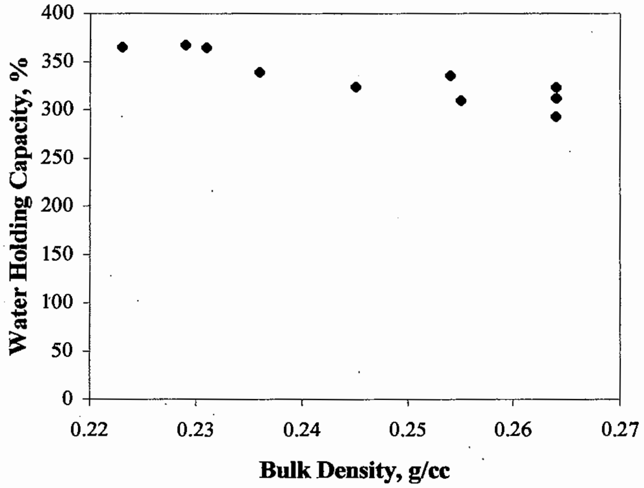


Fig. 3. Relationship between water holding capacity and bulk density of texturized soy protein.

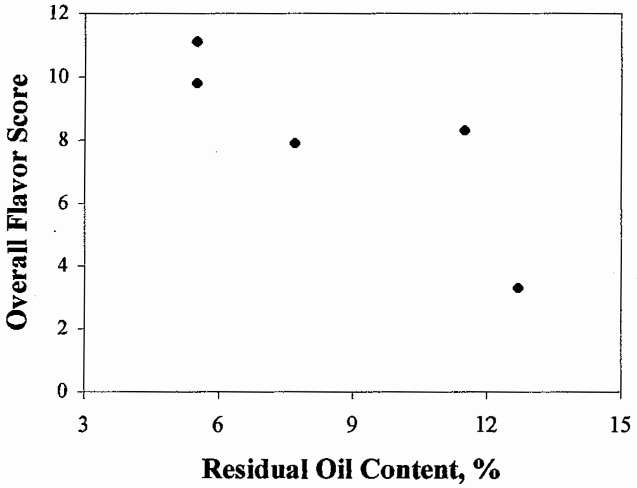


Fig. 4. Relationship between overall flavor score and residual oil content of texturized soy protein.

CHAPTER 5. GENERAL CONCLUSIONS

This study had two broad objectives: 1) to determine the range of soy flour properties possible by E-E processing of dehulled soybeans; and 2) to determine if E-E partially defatted soy flour can be extruded to produce TSP. Both of these objectives were met with results fully described within the body of this work.

For the first objective, partially defatted soy flours with a wide range of residual oil contents and PDI, 4.7-12.7% and 12.5-69.1, respectively, were produced at a commercial facility (Iowa Soy Specialties, Vinton, IA) using extruder and expeller configurations which are easily replicated at other E-E mini-mills with little or no change in infrastructure. These flours had higher oil contents and lower PDI values than flours commonly utilized for producing of TSP. The publication of these data along with the E-E parameters used to produce these partially defatted soy flours will benefit both food processors and scientists as there is currently almost no literature available regarding this subject.

For the second objective, selected E-E partially defatted soy flours (n = 10) were successfully re-extruded to produce TSP. Although soybean flours and flakes are widely used in the production of TSP, the conditions necessary for extrusion-texturization of E-E partially defatted soy flour have not been previously reported. In addition, because of the unique characteristics of E-E partially defatted soy flour (e.g., high residual oil and low PDI), it was unknown whether texturization was feasible. Extrusion conditions for production of TSP were optimized for the median residual oil versus PDI partially defatted soy flour, and identical parameters were used to texturize the nine remaining partially defatted soy flours. Texture characteristics of hydrated TSP from the E-E partially defatted soy flours were similar to those measured in a commercial product. When incorporated into a low-fat (7%) TSP-extended ground beef system, many of the extrudates exhibited textural and flavor attributes similar to the higher fat (19%) ground beef control, with reduced cooking loss. These data indicate that TSP produced from E-E partially defatted soy flour has the functional and flavor characteristics necessary for use in human food applications. Production TSP from partially defatted soy flour for use as meat extenders may provide an important market option for E-E mini-mills.

REFERENCES CITED

Areas, J.A.G., Extrusion of Food Proteins, *Crit. Rev. Food Sci. Nutr. 32*:365-392 (1992).

Armstrong, D.L., and Stanley, D.W., Functional Properties of Microwave-Heated Soybean Proteins, in *Functionality and Protein Structure*, edited by A. Pour-El, American Chemical Society, Washington, D. C., 1979, pp.146-172.

Bernhardt, E.C., *Processing of Thermoplastic Materials*, Reinhold Publishing, New York, 1962.

Cheftel, J.C., Cuq, J.L., and Lorient, D., Amino Acids, Peptides and Proteins, in *Food Chemistry 2nd Ed.*, edited by O. Fennema, Marcel Dekker, Inc., New York, 1985, pp. 245-369.

Cheftel, J.C., Kitagawa, M., and Queguiner, C., New Protein Texturization Processes by Extrusion Cooking at High Moisture Levels, *Food Rev. Int. 8*:235-275 (1992).

Crocco, S.E., Better Texture for Vegetable Protein Foods, *Food Eng. 48*:15-19 (1976).

Faubion, J.M., and Hoseney, R.C.,High-temperature short-time extrusion cooking of wheat starch and flour. I. Effect of moisture and flour type on extrudate properties, *Cereal Chem. 59*:529-533 (1982).

Frame, N.D., Operational Characteristics of the Co-rotating Twin-screw Extruder, in *The Technology of Extrusion Cooking*, edited by N. D. Frame, Blackie Academic & Professional, Bishopbriggs, Glasgow, 1994, pp. 1-51.

Guy, R.C.E., Raw Materials for Extrusion Cooking Processes, in *The Technology of Extrusion Cooking*, edited by N. D. Frame, Blakcie Academic & Professional, Bishopbriggs, Glasgow, 1994, pp. 52-72.

Harper, J.M., Food Extrusion, *Crit. Rev. Food Sci. Nutr. 11*:155-215 (1979).

Harper, J.M., *Extrusion of Foods*, CRC Press, Boca Raton, Florida, 1981.

Harper, J.M., Extrusion Texturization of Foods, *Food Tech. 40*:70-76 (1986).

Harper, J.M., Food Extruders and Their Applications, in *Extrusion Cooking*, edited by C. Mercier, P. Linko and J.M. Harper, American Association of Cereal Chemists, St. Paul, MN, 1989, pp. 1-15.

Harper, J.M., A Comparative Analysis of Single- and Twin-Screw Extruders, in *Food Extrusion Science and Technology*, edited by J.L. Kokini, C. Ho and M.V. Karwe, Marcel Dekker, Inc., New York, 1992, pp. 139-148.

Holay, S.H., and Harper, J.M., Influence of the Extrusion Shear Environment on Plant Protein Texturization, *J. Food Sci. 47*:1869-1875 (1982).

Jeunink, J., and Cheftel, J.C., Chemical and Physiochemical Changes in Field Bean and Soy Proteins Texturized by Extrusion, *J. Food Sci. 44*:1322-1325, 1328 (1979).

Kearns, J.P., Rokey, G.J., and Huber, G.R.,Extrusion of Texturized Proteins, in *Proceedings of the World Congress on Vegetable Protein Utilization in Human Foods and Animal Feedstuffs*, edited by T.H. Applewhite, American Oil Chemists' Society, 1988, pp. 353-362.

Kinsella, J.E., Texturized Proteins: Fabrication, Flavoring, and Nutrition, 1978.

Kokini, J.L., Chang, C.N., and Lai, L.S., The Role of Rheological Properties on Extrudate Expansion, in *Food Extrusion Science and Technology*, edited by J.L. Kokini, C. Ho and M.V. Karwe, Marcel Dekker, Inc., New York, 1992, pp. 631-652.

Lusas, E., and Riaz, M., Texturised Food Proteins from Fullfat Soybeans at Low Cost, *Extrusion Comm. 9*:15-18 (1996).

Mercier, C., and Feillet, P., Modification of Carbohydrate Components by Extrusion Cooking of Cereal Products, *Cereal Chem. 52*:283-290 (1975).

Meuser, V.F., van Lengerich, B., and Kohler, F., The Influence of Extrusion Parameters on the Functional Properties of Wheat Starch, *Starke 34*:366-372 (1982).

Meuser, F., Gimmler, N., and Lengerich, B.V., A Systems Analytical Approach to Extrusion, in *Food Extrusion Science and Technology*, edited by J.L. Kokini, C. Ho and M.V. Karwe, Marcel Dekker, Inc., New York, 1992, pp. 619-630.

Nelson, A.I., Wijeratne, W.B., Yeh, S.W., Wei, T.M., and Wei, L.S., Dry Extrusion as an Aid to Mechanical Expelling of Oil from Soybeans, *J. Am. Oil Chem. Soc. 64*:1341-1347 (1987).

Otterburn, M., Healy, M., and Sinclair, W., The Formation, Isolation and Importance of Isopeptides in Heated Protein, in *Symposium on Protein Crosslinking*, edited by M. Friedman, Plenum Press, San Francisco, CA, 1977, pp. 239-262.

Rhee, K.C., Kuo, C.K., and Lusas, E.W., Texturization. in *Protein Functionality in Foods*, edited by J.P. Cherry, ACS Symposium Series, 1981, pp. 51-87.

Said, N., *Personal Communication*, Triple "F"/Insta-Pro, Des Moines, IA (1999).

Seib, P.A., *An Introduction to Food Extrusion,* Department of Grain Science and Industry, Kansas State University, Manhattan, KS, 1976.

Shimada, K., and Cheftel, J.C., Determination of Sulfhydryl Groups and Disulfide Bonds in Heat-Induced Gels of Soy Protein Isolate, *J. Agric. Food Chem.36*:147-153 (1988).

Smith, O.B., Textures by Extrusion Processing, in *Fabricated Foods* edited by G.E. Inglett, The AVI Publishing Company, Inc., Westport, CN, 1975 pp. 89-108.

Stanley, D.W., Protein Reactions During Extrusion Cooking, in *Extrusion Cooking*, edited by C. Mercier, P. Linko and J.M. Harper, American Association of Cereal Chemists, St. Paul, MN, 1989, pp. 321-341.

Utsumi, S., and Kinsella, J.E., Forces Involved in Soy Protein Gelation: Effects of Various Reagents on the Formation, Hardness and Solubility of Heat-Induced Gels Made from 7S, 11S, and Soy Isolate, *J. Food Sci. 50*:1278-1283 (1985).

Van Dyne, D., *Economic Analysis of Three Different Size Soybean Processing Plants,* Department of Agricultural Economics, University of Missouri, Columbia, MO, 1997.

van Lengerich, B., Meuser F., and Pfaller, W., Extrusion Cooking of Wheat Products. in *Wheat Is Unique*, edited by Y. Pomeranz, American Association of Cereal Chemists, St. Paul, MN, 1989, pp. 395-429.

Williams, M.A.,Ingredient and Feed Processing: Adjustable Jaw Expanders, *Feed Management 44*:25-26 (1993).

Williams, M.A.,Extrusion Preparation for Oil Extraction, *INFORM 6*:289-293 (1995).