Review

High moisture food extrusion

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Summary Extrusion at higher moisture contents (> 40%), also known as wet extrusion, is relatively less investigated compared to low and intermediate moisture extrusion. Literature on high moisture food extrusion has been reviewed. Wet extrusion applications utilise twin screw extruders due to their efficient conveying capabilities. Extruders can be used as bioreactors for starch hydrolysis using thermally stable enzymes. This process is usually followed by saccharification inside or outside an extruder to produce a high DE (dextrose equivalent) syrup. Starch-based high moisture extrusion research also reports a few modelling studies. The rheological properties, torque and energy requirements of high moisture extrusion systems are different from those of low and intermediate systems. Other research reviewed includes the extrusion of low-cost plant and animal proteins to manufacture nutritious food products that imitate the texture, flavour, and mouthfeel of meat.

Keywords Extrusion, liquefaction, protein texturization, rheology, saccharification.

Introduction

This review brings together the recent literature and main research on high moisture food extrusion, and will concentrate on protein-based and starch-based foods. The intention of this review is to provide information to readers who are not necessarily specialists in this area.

Extrusion is a continuous mixing, kneading, and shaping process. Food extrusion is not new to the food industry and has been utilized to produce pasta for more than 60 years. Today, extrusion is widely used in the food industry due to its versatility, high productivity, low cost, and energy efficiency (Harper, 1981). High quality products can be manufactured by extrusion. Well-known extrusion applications in the food industry include ready-to-eat breakfast cereals, baby foods, pet foods, and confectionery products. Almost all of these applications take place at low to intermediate level moisture contents (moisture levels less than 40%). A fairly new area of extrusion utilises higher moisture levels (> 40%) combined with a twin screw extruder for making unconventional food products. Extrusion at high moisture levels, also known as 'wet extrusion', was nearly impossible about 10 years ago. However, recent developments with twin screw extruders, including sophisticated barrel designs, screws and dies, are enabling wet extrusion (Noguchi, 1989). One advantage of high moisture extrusion is more complete starch gelatinization which will be discussed later.

Applications of wet extrusion involve mainly twin screw extruders (TSE). TSE have superior conveying capabilities compared to single screw

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Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may also be suitable.

extruders (SSE), hence, they offer extended range of applications (Harper, 1981). Both SSE and TSE are drag flow devices with forward pumping action of the rotating screws. The main difference in the conveying mechanisms of SSE and TSE is that conveying in SSE is established by the friction between the barrel and the melt, and the screw and the melt. Therefore, SSE requires a grooved barrel for a good conveying action. However, in TSE the product is transferred in bulk from one screw to the other which makes the forward conveying more efficient. Extrusion at high moisture levels where there is lower friction and viscous dissipation would be difficult in an SSE.

Starch-based high moisture extrusion

Extruders as enzymatic bioreactors

Considering extruders as continuous bioreactors began in the late 1980s where materials were treated either in the presence or absence of enzymes under elevated temperature, pressure, and shear, at moisture levels as high as 70% or more (Linko *et al.*, 1983). In an extruder, enzymatic action can be coupled with thermal and mechanical breakdown, resulting in a significant reduction in the viscosity of the product. Thermomechanical liquefaction of cereals was discovered and demonstrated in the early 1970s. This process can yield a certain degree of starch breakdown with DE (dextrose equivalent) values below two (Mercier & Feillet, 1975). DE is defined as the percentage of reducing sugars present calculated as dextrose (D-glucose) on a dry solids basis, 100 corresponding to the complete hydrolysis of starch (Hebeda, 1993). The discovery in the late 1970s (Linko *et al.*, 1981) that cereal enzymes such as α-amylase can either be completely inactivated by twin screw extrusion cooking or can survive it, depending on the processing conditions, led to detailed studies of the inactivation of biologically active materials and the use of extruders as bioreactors for various applications (Linko, 1989). The early research regarding the effect of extrusion processing on enzymes and microorganisms was reviewed by Linko *et al.* (1981). The enzyme α-amylase, an endo-glucosidase, cleaves the α-1,4-glucosidic bond of the starch at internal positions to yield dextrins and oligosaccharides with the C1-OH in the α configuration (Wong, 1995). Cereal starches can be extruded with thermostable α-amylases of a bacterial origin to convert starch to dextrins in order to produce a soluble, low viscosity hydrolysate of 10–15 DE. The liquefied hydrolysate can be processed directly to a maltodextrin product or used as substrate for conversion (saccharification) to dextrose with the enzyme glucoamylase (Wong, 1995). Continuous liquefaction of various types of starch via enzymatic action has been widely reported in the literature (Linko *et al.*, 1981; Chouvel *et al.*, 1983; Hakulin *et al.*, 1983; Mattson *et al.*, 1984; Brooks & Griffin, 1987; van Zuilichem *et al.*, 1990; Tomas *et al.*, 1997). Wheat, corn, and rice starch were among the commonly used types.

There are several factors that influence the efficiency of enzymatic starch hydrolysis in a TSE. Starch needs to be gelatinized for efficient hydrolysis since gelatinized starch is more susceptible to enzymatic attack. It is important to optimize the processing conditions in the barrel for maximizing gelatinization and minimizing enzyme inactivation. The stability of α-amylase during high temperature liquefaction is also important to efficiently solubilize starch. The critical controllable factors that affect enzymatic conversion in a TSE are moisture, temperature, pH, and enzyme concentration. Moisture has a significant impact on starch liquefaction. Excess moisture in the feed results in complete starch gelatinization if combined with elevated temperatures; therefore, increasing moisture usually results in a higher degree of starch hydrolysis (Hakulin *et al.*, 1983). DE increased from 20 to 23.5 as feed moisture increased from 40 to 70% (Table 1). Lower enzyme to substrate ratios makes starch conversion more dependent on feed moisture (Chouvel *et al.*, 1983). The optimum moisture content in the feed stream was determined to be quite high, 55–60%, for efficient conversion (Colonna *et al.*, 1984). The temperature effect on conversion is two-fold. Firstly, temperature influences the starch gelatinization, and secondly enzymes function best in their optimum operating temperature range. If the temperature is outside the range of optimum enzyme activity, starch conversion would be expected to be lower. This explains the findings of Chouvel *et al.* (1983) that as temperature increased from 100 to 145 °C, DE decreased from 19.5 to 16.5 (Table 2). Tomas

Table 1 Influence of moisture, and α-amylase concentration on the extrusion-liquefaction of pregelatinized corn starch

% moisture	α-amylase added (mL kg^{-1} dry starch)	Viscosity of extrudate (*10^9 Pa.s)	DE (%) of freeze-dried extrudate
40	0	>200	0.5
40	30	20–30	20
50	30	17	19.5
60	0	—	0.3–0.4
60	30	5–10	20–21
70	0	—	0.5
70	30	3–4	23.5

Temperature = 125 °C, pH = 6 (Chouvel *et al.*, 1983)

et al. (1997) reported an almost linear increase in the DE values for rice starch as temperature increased from 70 to 100 °C. Within the experimental range studied, the highest DE was 90. This value is significantly higher than those reported in the literature for other starches. Likimani *et al.* (1991) also noted an increase in the starch hydrolysis as temperature increased from 80 to 160 °C, maximum DE being 6.43. However, Chouvel *et al.* (1983) noted a slight decrease in starch hydrolysis as the temperature increased within the range 100 to 145 °C but the maximum DE value was only 21. Initial reports indicated that α-amylase had been used at mild conditions since elevated temperatures resulted in inactivation of the enzyme. Use of thermostable amylases improved the enzyme-induced liquefaction. Neutral pH resulted in higher starch conversion compared to acid or basic pH (Chouvel *et al.*, 1983). Enzyme concentration and starch conversion are directly proportional, the higher the enzyme concentration, the higher the starch hydrolysis. However, conversion reaches saturation at a certain enzyme concentration, and beyond this point any increase in the enzyme level would have little effect on the conversion and would not be economically desirable. The enzyme action has to be terminated immediately after extrusion, otherwise starch hydrolysis continues rapidly (Reinikainen *et al.*, 1986). Direct collection of samples in a vigorously stirred, boiling 0.2 M acetate buffer of pH 3.5 was found necessary for immediate enzyme inactivation prior to DE determinations. An unsuccessful method of inactivation via 0.1% mercuric chloride, resulted in samples with 65–95% of the initial activity remaining (Linko *et al.*, 1983). Thermoamyl α-amylase is significantly inactivated at temperatures above 155 °C (Linko, 1989).

Saccharification can be partially conducted in the extruder barrel if appropriate enzymes are added or it can be a batch operation following extrusion-induced liquefaction. If it is done solely in the extruder, due to limited residence time in the barrel, the conversion rates may be significantly lower than those for batch saccharification. In order to attain reasonably higher DE values for this case, the L/D (length-to-diameter) ratio of the barrel should be > 30 (van Zuilichem *et al.*, 1990). Researches indicate that significantly higher DE values can be obtained with a longer barrel, such as a 1222 mm Werner & Pfleiderer Continua 58 barrel (Hakulin *et al.*, 1983), or a 1000 mm Creusot-Loire BC 45 barrel (Chouvel *et al.*, 1983). Literature reports that liquefaction accomplished in the extruder is usually followed by saccharification outside the extruder barrel (Linko *et al.*, 1981;1983; Reinikainen *et al.*, 1986; Linko, 1989; Govindasamy *et al.*, 1997). During the mid 1960s only acid-converted starch syrups were commercially available, with a typical DE of 42 for confectionery applications obtained by 6 minute hydrolysis with 0.03 M hydrochloric acid at 145 °C. Later on, the commercial scale availability of glucoamylase made an acid/enzyme process possible with syrup DE values as high as 94. Replacing the acid treatment with α-amylase liquefaction in an extruder followed by enzymatic

Table 2 Influence of temperature on the extrusion-liquefaction of pregelatinized corn starch

Temperature (°C)	Viscosity of extrudate (*10^9 Pa.s)	DE (%) of freeze-dried extrudate
100	30–40	19–19.5
125	24	17
145	20	16.5

Moisture = 50%, pH = 6, α-amylase = 30mL kg^{-1} dry starch (Chouvel *et al.*, 1983) saccharification resulted in production of syrups with DE values as high as 98.

The DE values accomplished by saccharification in an extruder are primarily influenced by feed moisture, temperature, pH, and enzyme concentration. High melt viscosity at high solids content results in slower hydrolysis, causing a lower percent saccharification. Die pressure can be used as an index of melt viscosity (Tadmor & Gogos, 1979). The higher the viscosity of the melt, the higher the die pressure. Samples extruded at higher moisture contents were more easily saccharified (Govindasamy *et al.*, 1997). According to van Zuilichem *et al.* (1990), concentration of glucoamylase in the extruder is by far the most important factor in saccharification. Glucoamylase concentration and conversion level was found to be approximately linear. The other commonly used enzymes for saccharification purposes are fungal α-amylase, and β-amylase (Ofoli *et al.*, 1990; Komolprasert & Ofoli, 1991; Bigelis, 1993).

Both starchy and cellulosic materials such as cereal grain or straw may be extrusion-pretreated (liquefied with α-amylase or just thermomechanically processed in the barrel) for subsequent ethanol fermentation. Saccharification and fermentation can be simultaneous since this would minimize the substrate inhibition, yielding high solids level. The glucoamylase concentration is known to have a significant effect on the fermentation rate and ethanol yield. Use of the bacterium, *Z. mobilis,* along with yeast may increase the initial rate of fermentation. Ethanol can also be produced in a column reactor by immobilized yeast in beads of calcium alginate gel, using clear glucose syrup as the substrate (Linko, 1989).

Rheological properties and modelling

High moisture extrusion systems differ from low and intermediate moisture systems due to difference in the concentration of water. Therefore, the distribution of shear, mixing, mechanical heat, and convective heat will be different in such extrusion systems (Akdogan, 1996). Higher moisture contents prevent viscous dissipation of energy in the extruder barrel due to low melt viscosity, hence, the pressure build-up in the extruder barrel is not as high as in low moisture extrusion. Lower pressure drop along the die is partly responsible for the minimal to non-existent expansion at the die. The processing conditions and ingredients utilized will have an effect on extrudate expansion. The lower the starch content of the recipe and level of gelatinization, the lower the extrudate expansion. Also lower viscosity results in the inability of the extrudate to hold expansion.

At elevated temperatures, biopolymers in foods start to lose their orderly molecular structure. On initiation of starch gelatinization, there is a rapid change in the physical properties of the biopolymer mass, due to the formation of new molecular aggregate structures by hydrogen bonding. One of the most significant changes, as far as modelling is concerned, is the rapid rise in the viscosity in the extruder. After the initial rise, viscosity starts to decline as the melt is further heated and mechanically sheared (Olkku & Hagqvist, 1983). The initial rise in viscosity is caused by gelatinization when the crystalline structure of starch molecules results in complete irreversible disappearance of birefringence (ability to rotate the plane of polarized light). Fragmentation and formation of complexes may follow gelatinization of starch in the extruder, depending on the severity of the processing conditions.

The complex physicochemical changes that take place during extrusion affect the viscosity and final product quality significantly. To enhance utilization of extrusion and extruded products, the effect of process parameters on the rheological changes of the food melt in the extruder and the resulting impact on final product quality need to be clearly understood (Akdogan *et al.*, 1997). There are two methods for analyzing and defining the rheological properties: developing a predictive rheological model based on the final measured expansion at the die and analyzing off-line; or directly measuring the rheological properties on-line by inserting a viscometer between the extruder and the die. The latter case is a preferred method since it is the extruding melt, not the extrudate, that is being analyzed. Extruder dies can be equipped with slit or capillary rheometers to measure rheological properties of the food melt continuously. Slit rheometers are most often used to measure rheological properties. This type of rheometer is based on measurements of flow rate and pressure drop along the slit die. These measurements are converted into estimates of shear rate and shear stress at the wall. The rheometer requires measurements of pressure drop for different flow rates at each operating condition to analyze the rheological properties of the melt.

Akdogan (1996) used stepwise regression analysis to determine the contribution of each extruder operating parameter (temperature, moisture, feed flow rate, screw speed) on the variance of die pressure drop, torque, and specific mechanical energy. An important aspect of this project was that temperature was determined to be the most important parameter influencing the rheological properties of the melt. Temperature accounts for more than half of the variance in the responses mentioned above. Moisture, feed flow rate, and screw speed, in decreasing order, also affected the responses. Moisture is usually the most effective extruder parameter influencing the rheological behaviour of the melt for low and intermediate moisture extrusion. Since viscosity of a high moisture extruding system is considerably lower, viscous dissipation in such systems is less. Therefore, the energy required for working the melt in the screw channel would rely mostly on thermal input through the barrel walls rather than friction between molecules.

Several extrusion models for low and intermediate moisture (15–40%) starch-based dough exist in the published literature (Cervone & Harper, 1978; Remsen & Clark, 1978; Harper, 1981; Bhattacharya & Hanna, 1986; Mackey, 1989; Morgan *et al.*, 1989; Lai & Kokini, 1990; Wang *et al.*, 1990; Altomare *et al.*, 1992). However, modelling studies for high moisture extrusion systems are quite scarce in the literature (van Zuilichem *et al.*, 1990; Akdogan & Rumsey, 1996; Akdogan *et al.*, 1997). These models were either purely empirical or semi-empirical statistical models which gave limited insight into structural and physicochemical changes. Also, such models are useful only within the experimental range of the variables and extrapolation is not advised. High moisture extrusion can certainly benefit from a more general numerical model derived from fundamental equations of motion incorporating also the structural changes of the melt. This type of model may need modifications for starch and protein-based high moisture extrusion systems to account for the molecular and functional characteristics of starch and protein. Akdogan *et al.* (1997) presented a simplified approach to evaluate the rheological responses of a twin screw extruder at high moisture contents (57–65% wb), based on viscometry principles, including only extruder operating conditions as independent variables. A semi-empirical modified Harper's model for viscosity was developed by incorporating moisture in the feed stream, temperature, shear rate, and screw speed variables. The model considered power law dependency of shear rate, and an exponential dependency on temperature, moisture, and screw speed. A multiple linear regression analysis was performed to determine the predicted viscosity values within the experimental range studied. The predicted apparent viscosity values were found to be in good agreement with the experimental viscosity. van Zuilichem *et al.* (1990) developed a Gaussian regression algorithm to determine the constants of an equation for the enzymatic conversion of cracked corn into a fermentation substrate. Thermamyl α-amylase during extrusion and glucoamylase during saccharification were utilized at a moisture range of 60–80%. A response surface methodology (RSM) calculation on the calculated constants described the initial conversion rate and final conversion rate. These two constants were included in the proposed DE model describing the saccharification process. The independent variables included in the algorithm were α-amylase concentration, glucoamylase concentration, substrate concentration, and temperature. Tomas *et al.* (1997) presented a model incorporating the integrated effect of moisture content, temperature, shear rate, and enzyme concentration to describe the viscosity of extruding rice flour in the presence of α-amylase for 55–65% moisture. The predicted and observed viscosity of rice flour were found to be in good agreement.

Steady state models can predict the performance of an extruder according to a set of operating conditions and material properties. When this set of operating variables changes to a new set of values, the extruder moves towards a new steady state. The path followed between two different steady states cannot be predicted by steady state models. On the other hand, dynamic models offer an understanding of the transient states, the rate at which this change occurs, and provide

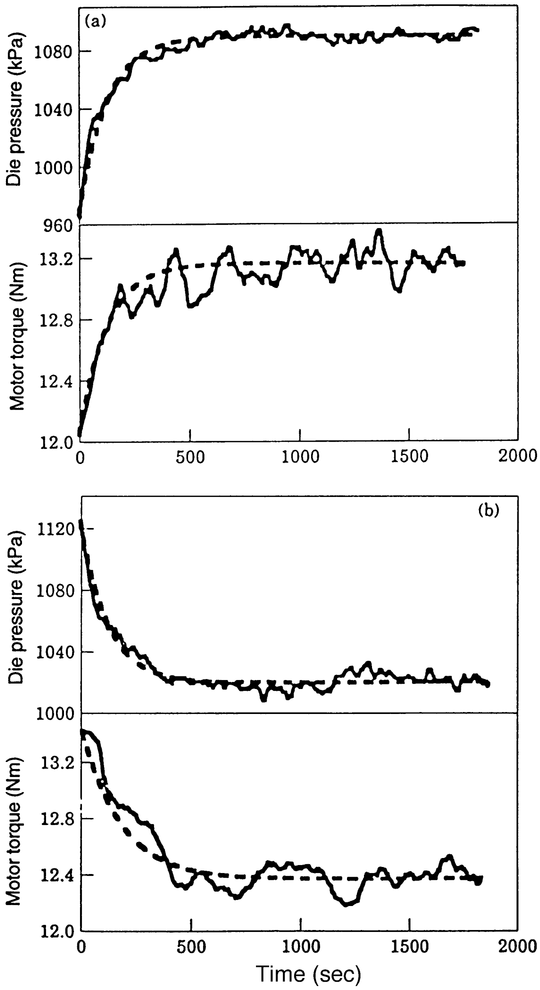

Figure 1 Dynamic response of die pressure and motor torque to a step change in feed rate (screw speed = 175 rpm). (———) experimental, (– – –) model. Feed rate changes: (a) 3.8–4.5 kg h^{-1}; (b) 4.5–3.8 kg h^{-1} (Akdogan & Rumsey, 1996).

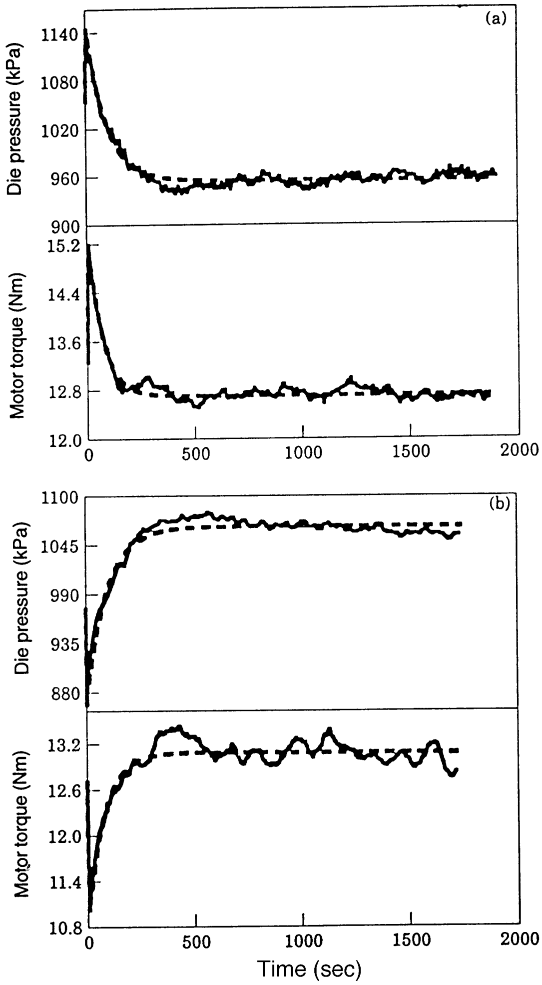

Figure 2 Dynamic response of die pressure and motor torque to a step change in screw speed (feed rate = 3.8 kg h^{-1}). (———) experimental, (– – –) model. Screw speed changes: (a) 175–225 rpm; (b) 225–175 rpm (Akdogan & Rumsey, 1996).

valuable tools for designing model-based control systems for extruders. Dynamic analysis of extrusion has been widely reported in the plastics extrusion literature, however there is only one published food related study in the high moisture extrusion area. In this, Akdogan & Rumsey (1996) studied the dynamic responses of a lab-size co-rotating twin screw extruder (APV) at a constant temperature (80 °C) and moisture (60%), applied to a rice starch system. Die pressure and motor torque were found to respond in the same manner. Responses to a step change in mass flow rate were modelled with a first order transfer function (Fig. 1), and step changes in the screw speed (Fig. 2) and screw speed-flow rate simultaneously were modelled by an inverse response. Upon changing the screw speed from 175 to 225 rpm (Fig. 2a), extruder throughput suddenly increases; thereby, resulting in an increase in the pressure and torque responses. Throughput returns to its original value after the system recovers. A new steady state is reached at which pressure and torque stabilises at lower values than initially. Figure 2(b) shows the similar but opposite effect of a sudden decrease in screw speed. Changing both the screw speed and flow rate simultaneously also resulted in inverse response. Future work is needed to investigate the effects of other operating conditions and quality attributes such as density, textural properties, and colour as related to the dynamic responses of an extruder operating at high moisture levels.

Protein-based high moisture extrusion

Wet extrusion has made possible unconventional products such as texturized proteins. Some of these products have already been commercialized in Japan, China, and USA. Examples include extruded crab analog made from Alaska pollack surimi with egg white and 1% starch, and texturized soybean foods such as 'fupi' (Shen & Wang, 1992). Texturization processes via extrusion can make products that imitate the texture, taste, and appearance of meat or seafood with high nutritional value (Cheftel *et al.*, 1992).

Plant protein-based high moisture extrusion

The idea of producing meat analogs from inexpensive vegetable proteins has received considerable attention, not only in academic research but also in industrial research by major food processing companies such as Central Soya, General Foods, General Mills, Nestle, Pillsbury, Proctor and Gamble, Quaker Oats, and Ralston Purina. This has led to patents for meat analogs or meat extenders (Valentas *et al.*, 1991). Millions of tons of soy every year are being transformed and consumed directly, or incorporated into new or traditional foodstuffs by extrusion into texturized vegetable proteins. Without this transformation, this soy protein source would not be used as human food on this scale (Areas, 1992).

It is possible to use extruders to restructure vegetable-based proteins to form fibrous structures that resemble the texture of meat tissues. 'Texturization' can be described by the processes illustrated in Fig. 3. Soybean protein isolates and concentrates, and flours are the most widely used raw materials for this purpose (Dahl & Villota, 1991). Usually, one of the above mentioned soy products is extruded, sometimes blended with other ingredients, at moisture contents equal or higher than 60% at temperatures of 100 to 150 °C. The dry material is fed to the barrel by a screw type of feeder and water is directly injected by a pump through the barrel wall.

Protein reactions during texturization

During extrusion, protein structures are disrupted

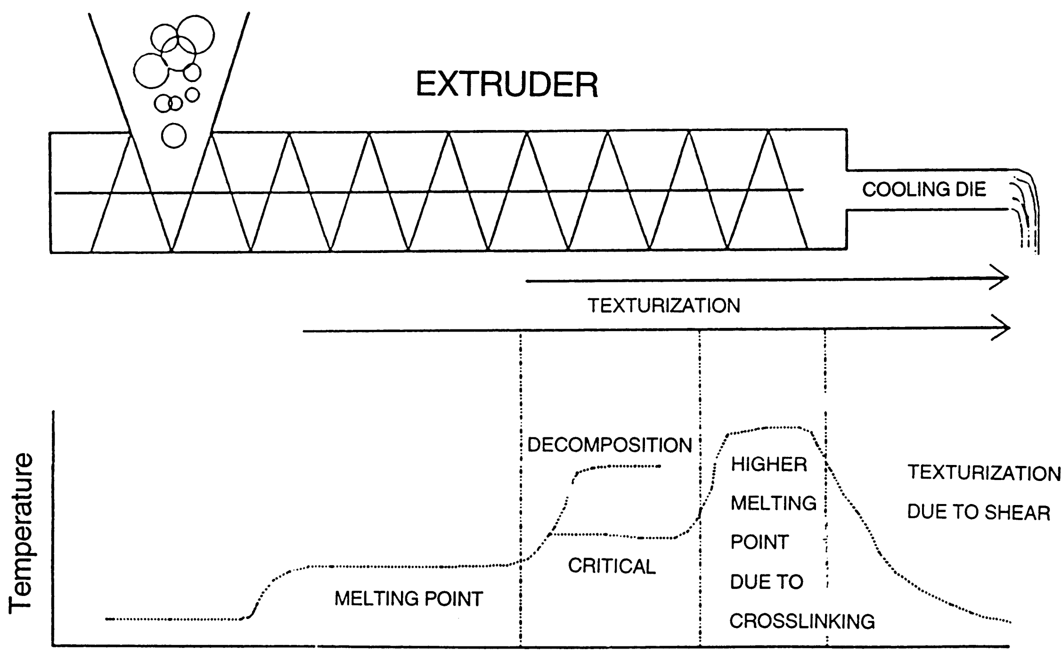

Figure 3 Texturization of wet proteinaceous foods in an extruder (Reprinted with permission from AACC; Noguchi, 1989).

and altered under high shear, pressure, and temperature (Harper, 1981). Protein solubility decreases and cross-linking reactions occur. Possibly, some covalent bonds form at high temperatures (Areas, 1992). Thermal plastification of the protein mix at high moisture contents (60%) is possible at relatively high extrusion temperatures (>150 °C). At moisture levels lower than 60%, plastification requires higher temperatures. Cheftel *et al.* (1992) suggested that a minimum of 150 sec of residence time in the barrel is necessary for protein plastification. Using a barrel with a high L/D ratio, reducing the screw speed and feed rate, or using a more aggressive screw configuration (i.e. more kneading blocks or reverse screw elements) would increase the residence time in the barrel. Moreover, an aggressive screw configuration would increase the heat transfer to the melt and hence, would contribute to protein plastification (Cheftel *et al.*, 1992). Protein type and additives to the mix have an impact on texturization. Fibre formation can be enhanced by the addition of some polysaccharides such as starch, soy arabinogalactans, or maltodextrins in the food mix before extrusion. During extrusion polysaccharides form a separate phase which appears to enhance protein aggregation in the direction of extrusion and reduce it in the direction perpendicular to extrusion.

The type of ingredients may enhance or inhibit the desired texture. For instance, the presence of lipids does not support fibre formation since the lubricating effect of lipids decreases the shear effects and particle alignment. The addition of more than 5% of oil to the mix before extrusion usually leads to a marked decrease in the longitudinal resistance to stretching. If the recipe includes large amounts of oil, the die needs to be longer to increase the friction between the material and the die wall. Figure 4 shows the influence of fat addition. Lengthwise strength (F_L) decreased abruptly whereas changes in crosswise strength (F_V) were not as much. With 15% or more oil addition, F_V was greater than F_L, indicating a reverse orientation of protein filaments (Noguchi, 1989). Also, additives such as calcium caseinate are not as easily texturized as fibrillar proteins.

Protein reactions, including both non-covalent and disulfide bonds, form upon cooling.

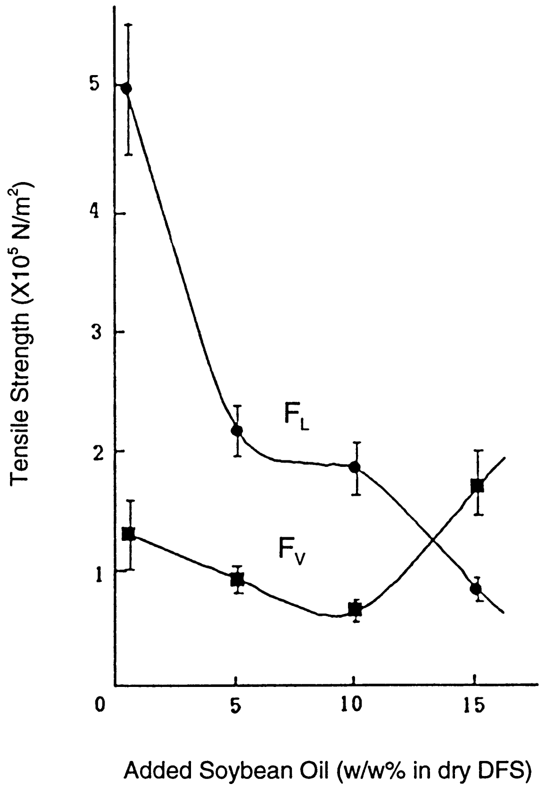

Figure 4 Influence of soybean oil added to defatted soy flour on tensile strength of textured product from a Clextral BC-45 twin screw extruder. Feed rate = 15 kg h^{-1}; screw speed = 60 rpm; moisture content = 60%. The tensile strength data are the means of five measurement. Soybean oil was added into the first barrel using a peristaltic pump. F_L = lengthwise strength F_V = crosswise strength. (Reprinted with permission from AACC; Noguchi, 1989).

Protein–protein interactions may be enhanced by decreased temperature and by macromolecular alignment. Crystalline aggregation leads to parallel fibre formation of varying length and thickness. A wide range of interaction energy is possible for protein cross-linking with protein and other molecules due to the diversity of the amino acid. Therefore, hydrophobic, cation–mediated electrostatic interactions, and covalent bonds also contribute to the stabilization of the three dimensional network formed after extrusion (Areas, 1992). Earlier research claimed that new peptide bonds were responsible for extrudate structure and disulfide bonds had insignificant impact on it (Burgess & Stanley, 1976). However, recent research attributes disulfide bonds, non-specific hydrophobic and electrostatic interactions as mainly responsible for protein texturization by extrusion (Areas, 1992).

Properties of the protein extrudates are strongly influenced by the extruder operating conditions, pH, and ingredients (Noguchi, 1989; Thiebaud *et al.*, 1996). Hayashi *et al.* (1992) reported that extruder barrel temperature was the most important parameter for the texturization of the dehulled whole soybean. Melt temperature is a critical factor in protein cross-linking reactions. Increasing temperature from 140 to 180 °C results in a proportional decrease in disulfide linkages formed in extruded soy protein isolates (Areas, 1992). Temperatures lower than 90 °C hinder the expansion and layer formation (Cheftel *et al.*, 1992). Figure 5 shows the influence of barrel temperature on the tensile strength of an extrudate made on Clextral BC-45 at pH 7. The lengthwise strength, F_L, was always larger than the crosswise strength, F_V and was affected by the extrusion temperature more than F_V. The ratio of F_L to F_V was always greater than 1, suggesting the existence of an aligned structure. At a given temperature, higher moisture contents resulted in softer and less texturized extrudates due to reduced protein–protein interactions and lower viscosity. At relatively lower moisture contents, higher barrel temperatures (140 to 180 °C) resulted in better textures. At higher moisture levels, temperature needs to be decreased as moisture flash-off may cause considerable water loss if a cooling die is not used. Screw speed and flow rate are also likely to influence the texturization by affecting the degree of barrel fill and mean residence time in the barrel (Thiebaud *et al.*, 1996). Alkaline and acid pH reduce the extrudate strength drastically. The maximum strength was found to be obtained at neutral pH (Noguchi, 1989). The type of protein has also an impact on texturization. Cheftel *et al.* (1992) noted that it is easier to extrude and texturize soybean concentrates compared to soy protein isolates under the same extrusion conditions. Soy protein isolates presented a homogenous structure while those that contain only soy protein concentrate displayed an anisotropic structure with layers or coarse fibres in the direction of flow through the die. Addition of wheat gluten to soy protein isolates even enhanced this type of fibre formation.

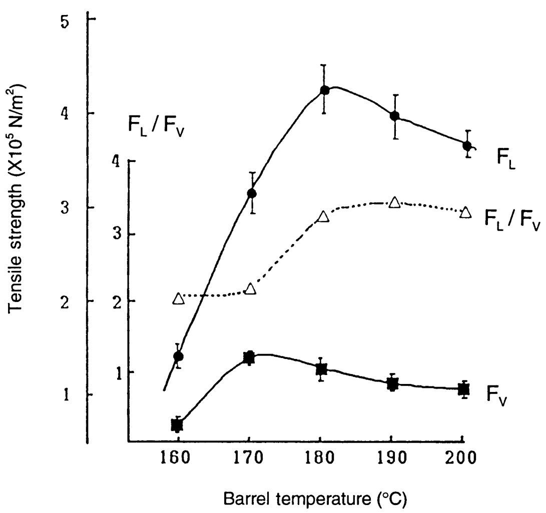

Figure 5 Influence of barrel temperature on tensile strength of samples (pH 7) extruded from Clextral BC-45 twin screw extruder. Feed rate = 15 kg/h; screw speed = 60 rpm; moisture content = 60%. The tensile strength data are the means of five measurement. F_L = lengthwise strength F_V = crosswise strength (Reprinted with permission from AACC; Noguchi, 1989).

Importance of die in texturization

The die is a major component in the extruder apparatus. It not only stabilises the flow coming out of the barrel but also shapes the dough into a desirable product (Akdogan *et al.*, 1997). Therefore, the design of the die is an important factor on the quality of the extrudates. The high moisture levels combined with elevated temperatures yield extrudates that are very soft and not self-supporting after the die. However, a specially designed die which provides cooling at this section will increase the viscosity of the hot extrudate before exiting, contributing to the correct elasticity and fluidity required for texturization (Noguchi, 1989). The temperature at which the solidification occurs is related to the plastification temperature. However, it is important to keep in mind that when water and lipid contents of the mix increase, the plastification temperature decreases. Harper (1981) noted that a cooled die allows the protein matrix to contain longitudinally oriented bubbles, which gives a product similar to the layered characteristics of meat. The nearly solidified layers of extrudate in contact with the two cooled metallic surfaces move at a lower speed than the hotter and more fluid internal region.

Laminar flow exists from the screw head to the die entrance and is necessary to achieve proper texture. Velocity gradients and shear forces developed in the peripheral zones permit the orientation and alignment of the unfolded protein macromolecules and result in formation of parallel layers of great length. The lowest shear stress occurs at the middle section of the die so the proteins would not be as well aligned in the extrusion direction. A homogenous distribution of melt and melt pressure across the die section can be provided by using attachments with multiple holes between the barrel and the die. These breaker plates also help initiate the stream alignment of protein molecules.

Another factor influencing the protein texturization is the size of the die opening. This has significant impact on melt velocity. Melt velocity and shear stress at the wall would significantly increase as the size of the die opening decreases. Noguchi (1989) reported extrusion of defatted soy flour at 60% moisture by a Mitsubishi FT-60N twin screw extruder with three different die openings of 1, 3, and 5 mm. The 5 mm die produced tough and smooth extrudates with higher crosswise and lengthwise strength. On the other hand, the 1 and 3 mm die openings gave very fragile products with low extrudate strength. This can be attributed to the excessive shear stress at the wall causing the destruction of the product when using a very narrow die opening. Therefore, optimizing the die size is important from a quality standpoint.

Animal protein-based high moisture extrusion

High moisture extrusion cooking of animal tissues, either alone or in combination with plant materials, has been used to upgrade protein animal by-products (Ba-Jaber *et al*., 1992). It is possible to texturize hand-boned or mechanically deboned meat such as chicken, turkey, beef, and pork by extrusion cooking. The product is usually a gelled band with a multilayer structure. The use of cooling dies at a temperature of 10 °C after texturization of this type is also common practice.

The binding of meat pieces can be enhanced by the addition of non-meat proteins and/or polysaccharides (Lawrie, 1991). These ingredients are also called non-meat binders. Ingredient binders include wheat flour, corn starch, soy protein isolate, hydrolyzed vegetable proteins, gums, or maltodextrin. Fish such as sardine, Alaska pollack, and salmon may also be texturized into animal meat analogs after blending with non-meat binders at ratios as high as 6–4.

The moisture content of fish and meat can be as high as 75%. However, texturization by extrusion requires a lower moisture level. One method for reducing the moisture in the feed is to dehydrate the meat before extrusion, which is difficult to accomplish, or to increase the level of non-meat binders in the recipe (Alvarez *et al*., 1990; Isobe *et al*., 1990; Hsieh *et al*., 1991; Thiebaud *et al*., 1996). Non-meat binders also affect the final protein content of the feed, which usually varies between 15 to 40%. The final protein content depends on the type of the non-meat binders and on the ratio of the meat or fish to non-meat binders in the formula.

Non-meat binders affect the extrudate properties. Comer (1979) noted that most non-meat binders decreased extrudate firmness. Cheftel *et al*. (1992) reported that extrudates with corn starch as a part of the recipe were superior to those made with soy protein isolate or wheat gluten. Corn starch contributed to cohesiveness, hence, the extrudates did not crumble. Samples containing added corn starch exhibited increased tensile strength compared with corn gluten or soy protein isolate added samples. Samples containing 15% added corn starch exhibited higher tensile strength than 10% added corn starch samples. Higher extrusion temperatures enhanced this effect (Alvarez *et al*., 1990). If starch or flour are used as binders, both starch gelatinization and protein denaturation contribute to the texture, appearance, and physical properties of the animal-protein based extrudates (Alvarez *et al*., 1990). Increased gelatinization also enhances the extrudate expansion (Chauhan & Bains, 1985).

Extruder operating conditions significantly affect the extrudate texture (Foegeding & Lanier, 1987; Alvarez *et al*., 1990). Extrusion temperatures need to be high enough to affect new protein states in the binders in order for them to have an impact on texture. Thiebaud *et al*. (1996) found that barrel temperature significantly affected the colour of the extrudates, darkening occurring at high barrel temperatures (> 180 °C), possibly through Maillard reactions. Hardness of extrudates was found to be decreased as temperature increased from 85 to 105 °C (Ba-Jaber *et al.*, 1992). Extrusion temperature has also an effect on the nutritional value of the extrudates. Chicken diets extruded with full-fat soybeans at 122 and 126 °C contributed to maximum growth in broiler chickens, whereas diets extruded at 118 and 120 °C resulted in significantly lower body weights (Perilla *et al.*, 1997). This might be attributed to the inactivation of antinutritional compounds such as trypsin inhibitors and protease inhibitors at temperatures over 120 °C. Temperatures above 126 °C resulted in overheating of soybeans which might have adversely affected the bioavailability of some amino acids. Higher screw speeds usually result in a better dispersion, hence, improve the textural characteristics. However, residence time in the barrel shortens at higher screw speeds and decreases the reaction time. This could be compensated with a more aggressive screw configuration, including spacers, reverse screw elements, and/or kneading blocks. Sasamoto *et al.* (1987) found that extrudates resistance to stretching is directly correlated to barrel temperature and screw speed. Excessive moisture may lead to poor texture by making 'melting' incomplete due to dilution effect. Aoki *et al.* (1989) reported an increase in the longitudinal stretching of the extrudates by lowering moisture levels to 60 from 67% at temperatures between 160 and 180 °C. When moisture in the feed increases, the protein concentration per unit mass decreases, which leads to a lower number of fibres per unit of cross sectional area because of reduced protein–protein interactions (Thiebaud *et al.*, 1996).

Other wet extrusion applications

Twin screw extrusion of a larval diet for mass rearing of the pink bollworm moth, by using a long barrel Continua 37 extruder (L/D = 39.7), was developed by Edwards *et al.* (1996). The diet is mainly composed of soy flour, wheat germ, and agar at a moisture level of 63%, and a temperature of 150 °C and screw speed of 275 rpm was used. The screw profile was composed of several kneading blocks to improve mixing, heat transfer, and residence time in the barrel. This process is now in operation at a Pink Bollworm Rearing Facility at Phoenix, Arizona.

Cheese analogs from caseinate and butter oil, and fat analogs from whey protein isolates can be made through wet extrusion. The firmness of the cheese analogs is highly influenced by water and fat content. The higher the fat and water contents in the recipe, the softer the extrudate. Higher screw speeds and lower moisture (50%) may improve smoothness. The extruded cheese analogs could be used in pizza, hamburger, and sauces (Cheftel *et al.*, 1992). The pH had a significant effect on the firmness and smoothness of these products. Improved smoothness and firmness would necessitate a pH between 3.5 and 3.9 for fat analogs, and a pH as high as 5 for cheese analogs. For cheese analogs, extruder operating temperatures are lower than for other high moisture extrusion applications (< 60 °C) and moisture levels vary from 60 to 75%. Larger die orifices are preferred for this application. The coagulation of skim milk powder to insoluble acid casein and the conversion of acid casein to sodium caseinates are also possible by extrusion, offering a productive and time-saving alternative to batch mixing.

Conclusions

Literature on high moisture food extrusion has been reviewed and compiled. Temperature has the dominant influence on the rheological behaviour in the extruder for high moisture starch-based systems. This finding differs from low and intermediate moisture extrusion, where moisture is the most influential extrusion parameter. Twin screw extruders used as enzymatic bioreactors for the liquefaction and subsequent saccharification of starch, to produce high maltose syrup, have gained attention by many researchers.

Applications of high moisture protein extrusion include texturization, especially for soy proteins and soy concentrates, and various types of fish and animal meats. Various meat analogs have been produced by utilizing twin screw extruders at high moisture levels. Although wet extrusion is not as well explored as low moisture extrusion, it has been used for manufacturing many novel food products and possesses the potential for replacing conventional methods of food processing.

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