Extrusion Techniques for Meat Analogues

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ABSTRACT

Extrusion processing has been utilized for creating textured substrates for many years. Early extrusion systems relied on simple ingredients and equipment, but the demand for high-quality consumer goods has increased the range of raw materials that can be used, and the complexity of extrusion processes has changed dramatically. Today, there are three primary extrusion-based methods utilized for production of texturized proteins: dry extrusion, wet extrusion, and thermal extrusion. This article examines the basic principles of each process, outlines differences in the processes used in creating a textured substrate, and describes the limitations and challenges of each method.

Extrusion is a widely accepted process for manufacturing protein-based foodstuffs that are used in a variety of textured convenience foods. Extrusion has been used for many years to produce texturized proteins, including spun soy protein isolates and extruded meat analogs, while other technologies, such as 3D printing of proteins, have only recently been introduced. Commercial feasibility has supported the development of three extrusion-based methods for production of texturized proteins: dry extrusion, wet extrusion, and thermal extrusion. The development of each technology has been driven by consumer needs and demands for product texture, nutrition, and quality.

Extrusion allows a wide range of protein sources to be continuously cooked using a combination of mechanical and thermal energy. The macromolecules in proteinaceous ingredients lose their native, organized structure and form a continuous, viscoelastic mass. As they pass through the extruder barrel and die, they are aligned in the direction of flow. This realignment exposes bonding sites that lead to cross-linking and a reformed, expandable structure (2) that is responsible for the chewy, meat-like texture in plant-based alternatives (Figs. 1 and 2).

In addition to texturizing and restructuring plant proteins, the extrusion cooking process performs several other important functions, including

- **Denaturing protein**—Proteins are effectively denatured during the moist, thermal process of extrusion. Denaturation of protein "lowers solubility, renders it digestible while destroying the biological activity of enzymes and toxic proteins" (3).
- **Deactivating residual heat-labile growth inhibitors**—Growth inhibitors are inherent in some vegetable proteins and can exert harmful physiological effects on humans or animals, as revealed by growth and metabolism studies. By deactivating these growth inhibitors, the harmful physiological effects can be dramatically reduced or eliminated altogether.
- **Controlling raw or bitter flavors**—Many undesirable raw or bitter flavors are volatile and are eliminated through the extrusion and decompression of the protein at the extruder die. The use of preconditioning and atmospheric venting devices in the design of an extrusion system also assists in volatilization and removal of off-flavors.
- **Providing a homogeneous, irreversible, bonded dispersion of all micro-ingredients throughout a protein matrix**—Dispersion not only ensures uniformity of all ingredients, such as dyes, throughout the product, but also provides a means whereby minor ingredients can be intimately associated with potential reaction sites, promoting cross-linking or other desirable chemical and physical modifications.

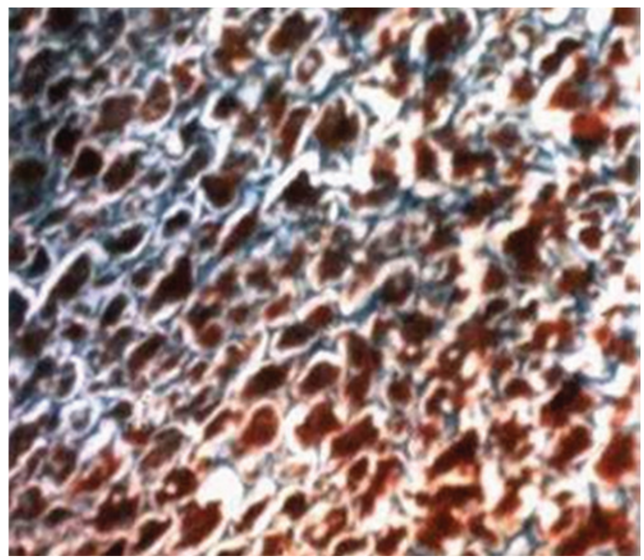

Fig. 1. Raw protein globules.

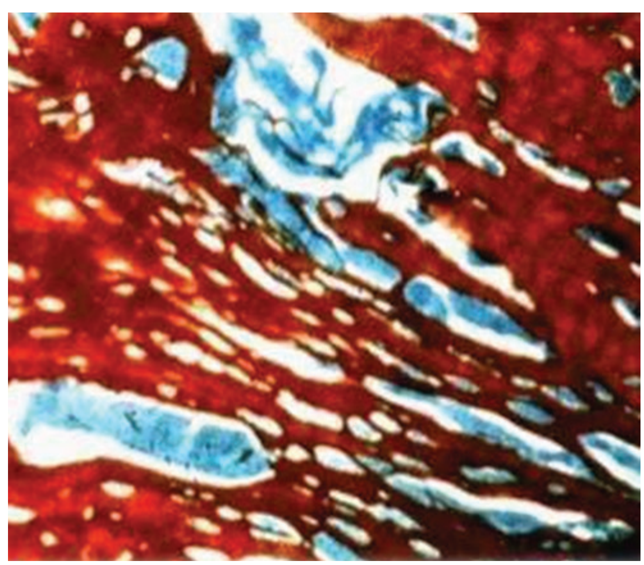

Fig. 2. Texturized and aligned protein.

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- **Shaping and sizing of the final extruded product**—Shaping and sizing of final products creates textured vegetable protein products that are convenient and available in transportable portions for packaging in retail or institutional marketplaces.

Raw Materials

Extrusion was first utilized for texturization of products in the late 1960s. At that time, the most popular raw material for production of textured plant-based protein was solvent-extracted defatted soy flour with approximately 50% protein. Soy flour allows for controllable production of texturized proteins, both in chunk and minced forms, that can then be added to meat as an extender or reformed into consumer-ready plant-based meat analog products. For more than 30 years, soy flour was the preferred ingredient for extrusion because of its availability, price, and nutritional density.

As new protein sources, such as wheat gluten and pea protein, were introduced into the marketplace, a greater emphasis was placed on understanding the properties that allow for successful extrusion processing. These include protein level, protein quality, oil level, fiber level, carbohydrate level, and particle size.

The protein level in a raw material is the most important property in terms of the characteristics of the product made from that raw material and the process required to transform the raw material into a texturized intermediate. Raw materials with higher protein levels are more easily texturized and tend to result in products with stronger and firmer textures. When processed further into consumer products, they tend to be more resilient and retain a meat-like texture and mouthfeel.

Protein quality is also very important. For soy-based raw materials, protein quality can be measured by the protein dispersibility index(PDI) or nitrogen solubility index (NSI) (1). Both the PDI and NSI tests measure the level of protein solubility, which reflects the heat treatment history of the raw material preparation process. Higher levels of heat treatment result in lower PDI and NSI values. In general, the PDI test will give lower results than the NSI test. If the raw materials have a lower PDI, more mechanical energy often is required to effectively texturize the material. Although the PDI test can be utilized for other raw material sources, such as pea and chickpea, it does not fully capture the ability of a protein to gel and be texturized.

Another method that can be utilized in characterizing protein quality is a gel test. A protein is hydrated with a predetermined amount of water (normally 3 parts water to 1 part protein) and heated in a water bath to set and denature the protein. After cooling, the gel strength is determined using a texture analyzer. As seen in Figure 3 protein gels can have very different properties, ranging from rubbery, firm textures to soft, breakable textures without cohesiveness. The soy concentrate on the left is extremely soft and easy to cut, while the soy isolate on the right has a much tougher and firmer, almost rubbery, texture. The gel strengths for a variety of plant proteins are listed in Table I. As illustrated by the final two entries in the table, materials that are classified the same, such as a soy isolate, can have significantly different gel strengths due to their processing histories.

Additional information, such as the slope of the rise in cutting force and the length of time to cut through the material, can also be collected and compared as shown in Figure 4. The data allow different proteins to be compared to give product developers an idea of how the proteins will react during extrusion.

In any extrusion process, the particle size of the raw material is a vital characteristic. Large particles are difficult to hydrate and may require additional preconditioning or additional mechanical energy input to plasticize and disperse the entire particle. In some cases, very fine, floury particles can be detrimen-

Fig. 3. Gels from different plant proteins (left to right: soy concentrate, lentil concentrate, soy isolate).

Table I. Gel strength values of various plant proteins

Product	Gel Strength (g)
Soy concentrate	178
Lentil protein concentrate	204
Soy flour	218
Pea protein isolate	304
Air-separated bean protein	348
Chickpea protein concentrate	1,246
Soy isolate A	1,031
Soy isolate B	1,400

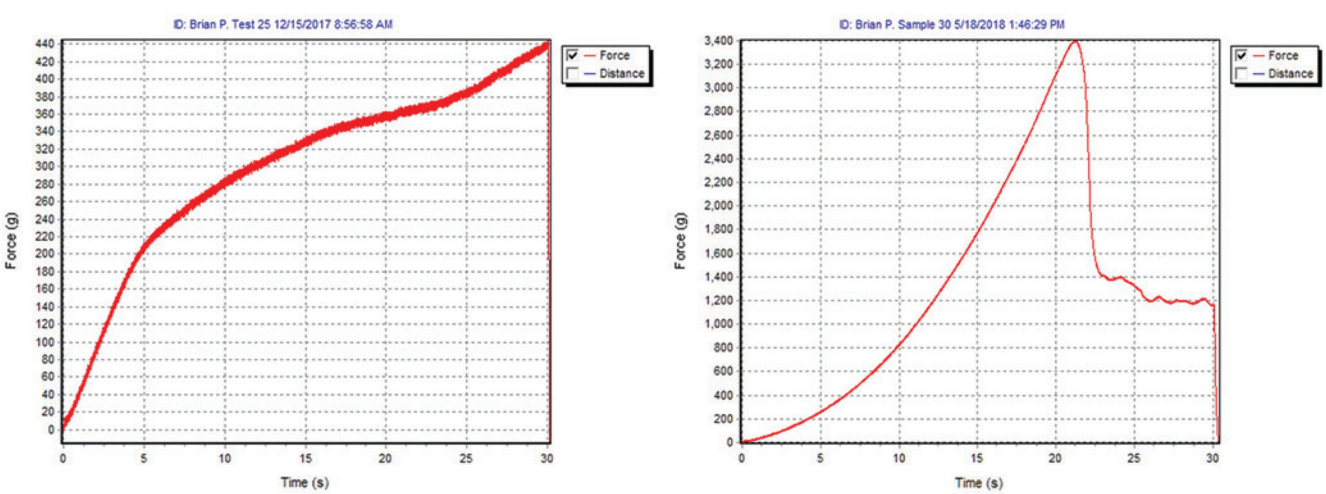

Fig. 4. Texture profile analysis of protein gels: soy concentrate (left) and soy isolate (right).

tal because they tend to agglomerate during preconditioning, and these agglomerates are then difficult to redisperse in the extruder barrel. Not only does the average particle size need to be considered, but care must also be taken to limit particle size distribution. The particle size range of a soy flour is shown in Figure 5. The flour was sieved after grinding and ranged in particle size from grit larger than 30 mesh to fine flour that passed through an 80 mesh sieve. When a particle size range is this wide, all the water is absorbed by the fine flour, and the larger particles that are not hydrated are very abrasive to the extruder components, causing rapid wear on the extrusion system.

The whole grains from which many protein sources are derived usually contain some level of oil. Whole soybeans, for example, contain about 20% oil, while other legumes contain much lower levels. In the extrusion process, oil acts as a lubricant within the extruder barrel and interferes with the addition of mechanical energy to the product. Raw materials containing higher oil levels often require an alteration of the extruder screw and die configuration to effectively texturize the product. In addition to the lubrication effect, a higher residual oil level dilutes the protein level.

Whole grain sources of raw materials can also contain significant levels of fiber, usually concentrated in the seed hull or pericarp. Fiber interferes with texturization by diluting the protein level and causing discontinuities in the texturized matrix. Fiber levels exceeding 3–4% often result in a product with a rough texture, and an increased quantity of fines is created during extrusion and drying of the textured protein.

Carbohydrates in the form of starches or sugars are present in most cereal grains and legumes. If they are not removed from raw materials, they can act as diluents and lower the overall protein content. Starches also can expand during extrusion and affect the lamination of proteins, resulting in softer final products and noncontinuous fiber structures. For these reasons, they are often removed from raw materials.

Fig. 5. Particle size distribution in a ground soy flour.

Extrusion Process

The raw materials are often the most important and costly portion of the texturization process. If the proper materials are not identified and the formula designed appropriately, it can be extremely difficult to create a properly texturized material.

Once the raw materials have been identified, the next important step is to determine the extrusion process that will be utilized. There are three basic extrusion techniques for producing texturized plant proteins:

1) Dry extrusion processing
2) High-moisture (wet) extrusion processing
3) Thermal extrusion (PowerHeater) processing

Dry extrusion processing is the most common method utilized to create texturized proteins, for several reasons, including the fact that it allows the widest range of raw materials, has the broadest flexibility in creating textures, and is the most cost-effective method for production of high volumes of product. Typically, this process will operate with an extrusion moisture level of 20 to 35% followed by drying to create a shelf-stable moisture content in the final product. A diagram of a typical dry extrusion process flow used to produce texturized vegetable proteins is shown in Figure 6.

Raw materials generally are supplied either in bulk or bags. After mixing, the raw materials are conveyed to the processing step. The extrusion portion of the system includes a feed bin with integral feeder, preconditioner, extrusion cooker, and die-knife assembly (Fig. 7). The design of each of these components is engineered to accomplish a specific function in the process of texturizing vegetable food proteins. Within the design features, the operating conditions are adjusted to vary and control the texture of the finished product.

Feeder. The feed bin and feeder provide a means of uniformly metering raw materials, whether they be granular or floury in

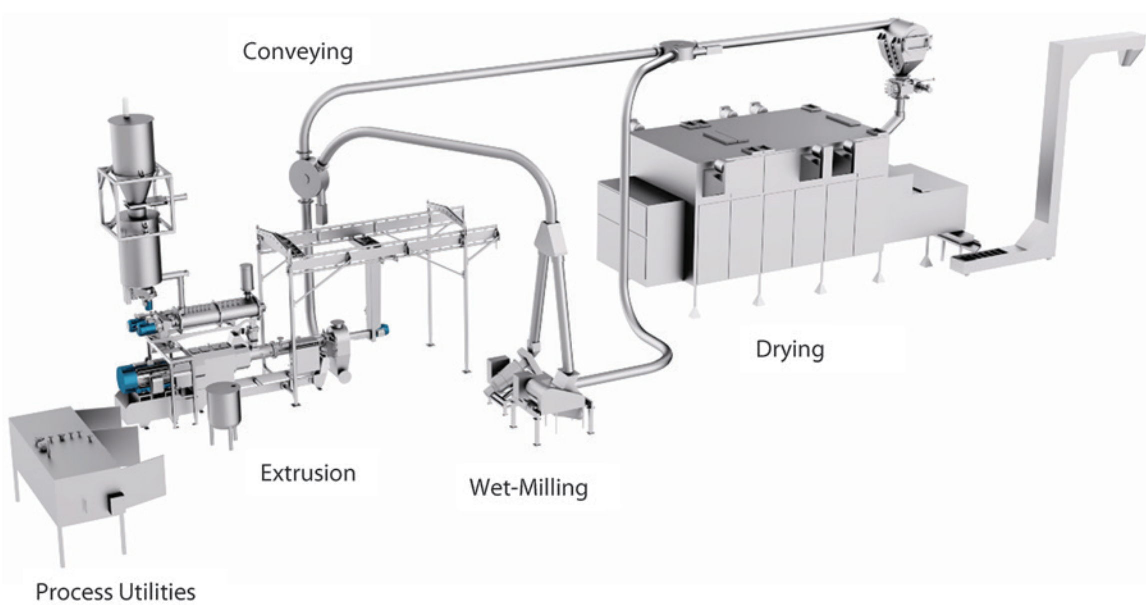

Fig. 6. Dry extrusion and drying process flow for texturized protein production.

nature, into the preconditioner and subsequently into the extruder. The design of the feeder needs to enable control of the flow of raw materials. Some materials can be problematic to handle due to their hydroscopic nature or fine particle size. Thus, it is important that the feeder is designed to meter raw materials in a continuous flow and at a controlled rate into the preconditioner or extruder. These feeders can be simple single-screw augers or more complex twin-screw feeders and are chosen based on the flow properties of the raw materials.

Preconditioner. Without preconditioning it can be challenging to produce texturized vegetable protein with good laminar structure. Vegetable proteins that are not preconditioned have a strong tendency to expand rather than laminate due to nonuniform moisture penetration that does not allow alignment of protein molecules.

Uniform and complete moisture penetration of raw ingredients significantly improves the stability of the extruder and final product quality. In addition, by completely plasticizing the raw material particles prior to their introduction into the extruder barrel, extruder wear caused by abrasive raw material particles is greatly reduced.

During the preconditioning step, moisture is uniformly applied in the form of water and/or live steam to achieve a moisture content of 18 to 25%. Water is introduced through a series of spray nozzles that atomize the water stream and, thereby, reduce the mixing load on the preconditioner. Steam is added through a manifold to the preconditioner. The plumbing for the steam supply must be designed to supply a continuous flow of condensate-free steam. If the steam added to the preconditioner contains pockets of condensate, an unstable extrusion process will result due to rapidly varying moisture content. Flavorants, coloring agents, and other liquid additives may be introduced at this phase of the process to ensure thorough and continuous mixing of all the foodstuffs entering the extruder barrel.

Extrusion processes that do not utilize effective preconditioners often operate at lower capacities and require larger main drive motors for the extruder and longer length to diameter ratios to create comparable textures.

Extruder. The preconditioner discharges directly into the extruder assembly, which consists of the barrel and screw configuration. The major transformation of raw preconditioned vegetable proteins occurs in the extruder, which ultimately determines the final product structure.

Extruders used for the manufacture of texturized vegetable proteins are either single-screw or twin-screw in design. In both cases, the final product texture is produced by the screw and barrel profile, screw speed, processing conditions (e.g., temperature, moisture), raw material characteristics, and die selection. Meat extenders successfully produced from defatted soy protein using single-screw extruders were the first products introduced in the early 1970s, and single-screw extruders continued to be the dominant extrusion technology utilized for many years. As additional proteins became available and markets began to extend into value-added products, twin-screw extruders predominated because they are very flexible systems and can be configured to produce a wide range of final products.

Recent analysis of the production costs of single-screw versus twin-screw extruders has shown that although twin-screw extruders have higher capital investment costs, their long-term operating costs are similar to single-screw extruders. Coupling this effect with greater up time and process stability results in twin-screw extruders being the more cost-efficient option for most producers.

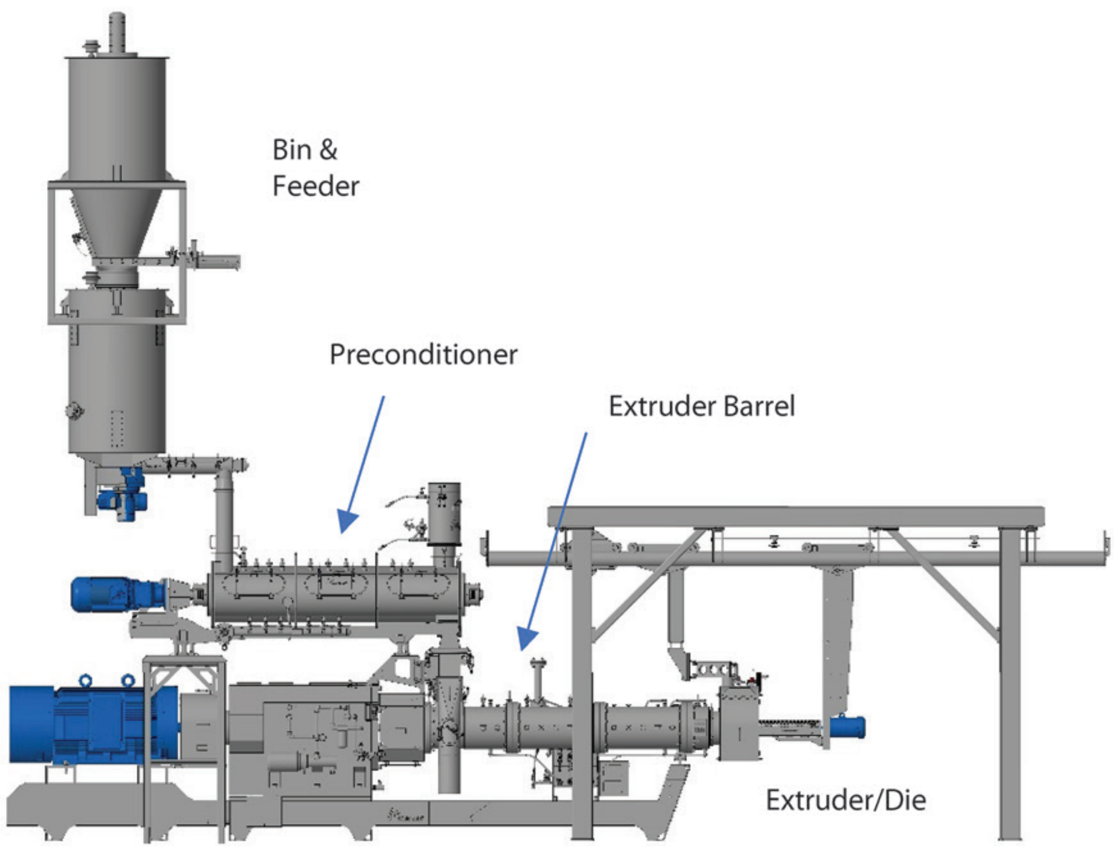

Fig. 7. Extrusion system.

The initial section of the extruder barrel is designed to act as a feeding or metering zone to simply convey the preconditioned vegetable protein into the center of the extruder barrel, where the amorphous, free-flowing vegetable protein is worked into a colloidal dough. The compression ratio of the screw profile is increased in this stage to assist in blending water or steam with the raw material. The temperature of the moist proteinaceous dough is rapidly elevated in the final 2–5 sec of dwell time within the extruder barrel.

The temperature rise in the extruder barrel is primarily generated by mechanical energy dissipated through the rotating screws and may be assisted by the direct injection of steam or external thermal energy sources. The screw profile may be altered by utilizing screw elements of different pitch, with interrupted flighting, or by adding mixing lobes configured to convey either in a reverse or forward direction. All of these processing factors increase the dough temperature until the protein reaches its reaction temperature and is texturized. Each plant protein has an ideal processing temperature at which the highest quality texture is created. This temperature can range from 120 to 160°C, but optimal temperatures for plant proteins typically range from 130 to 135°C

At these temperatures, the long and twisted protein molecules completely unravel. As the material exits the extruder and flows through the final die, the protein strands are stretched and aligned. The combination of shear, temperature, and retention time causes cross-linking between the protein fibers and ultimately yields a texturized product that is layered and resistant to disintegration upon rehydration. This thermal denaturation or cross-linking is an irreversible endothermic chemical reaction. The extent of cross-linking seems to be a function of time, temperature, and moisture history, which can be related to changes in the apparent viscosity of the extrudate.

The proper exposure to shearing action as the protein molecules align themselves for cross-linking during the extrusion process is important. Although adequate shear rates are necessary to enhance the cross-linking effects of protein molecules, over-shearing after the cross-linking step has begun may disrupt the layered structure of the protein molecules, resulting in decreased water-holding capacity. This is demonstrated by the data illustrated in Figure 8, which relate the water-absorbing ability of a texturized soy concentrate to the level of mechanical energy input. As the mechanical energy increases, there is a resulting rise in water absorption. After a certain level of mechanical energy input, however, water absorption begins to decline, indicating over-shearing of the protein.

Die. The extrusion chamber is capped with a final die, which serves two major functions. First, the die restricts product flow, thereby causing the extruder to develop the required pressure and shear. Second, the final die shapes the extrudate. The plasticized material is extruded through the die openings, and expansion occurs as the product is released to ambient pressure. As a consequence, final product density has been shown to correlate with extrusion temperature and moisture.

Dies utilized for texturized vegetable proteins are usually one of two types: face dies or peripheral dies. The openings of face dies are positioned such that the extrudate exits the die in the same axial direction as the overall flow through the extruder. In the case of peripheral dies, the extrudate exits the die at right angles to the direction of the overall flow through the extruder. The choice of which type of die to use for a particular product and process depends entirely on the nature of the product and the raw materials used to produce it.

In cases in which high die restriction is required to increase mechanical energy input but large amounts of open area are required in the final die for proper product shaping, a venturi die concept may be used. This allows restriction to be added to the extruder by the venturi die, and then a streamlined spacer is used to channel the material to the final shaping die (Fig. 9).

Regardless of the type, dies utilized for texturized vegetable proteins should promote smooth streamlined flows that do not disrupt or cause shearing effects in the already laminated and cross-linked protein molecules.

Postextrusion Processing

Texturized vegetable protein is discharged from the die and carried by a belt conveyor or pneumatic conveying line either directly to the dryer or to a wet-milling device. A wet-milling

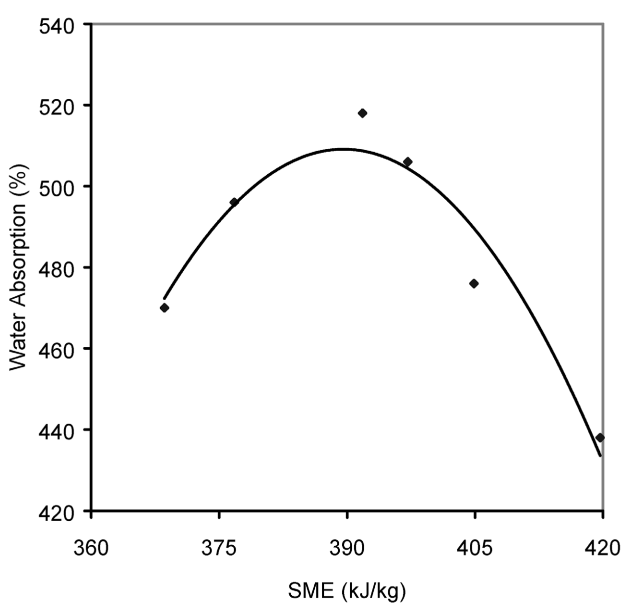

Fig. 8. Effect of mechanical energy input on water absorption of texturized soy concentrate. SME = specific mechanical energy.

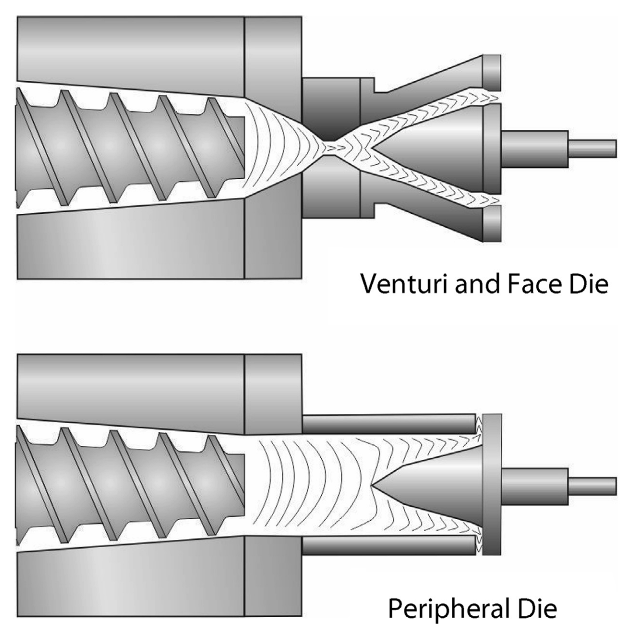

Fig. 9. Streamlined die design.

device creates products with a flaked appearance or more of a sliced, minced cut. The style of cut affects the final texture and mouthfeel and should be chosen based on the final product application (Fig. 10). After wet-milling the product is conveyed to the dryer.

Drying. The dryer used for texturized vegetable products is usually a conveyor-style dryer in which the drying air is heated either with steam or a combustion burner (Fig. 11). In a horizontal conveyor dryer, the product is spread on a belt that moves through zones where heated air is passed through the product. After the air is circulated through the product, a portion of it is exhausted to carry away the water removed from the product, and the remainder is mixed with fresh incoming air, reheated, and then passed through the product again. These dryers can be single or multiple pass in design, depending on the configuration required to fit the plant location and to adequately dry the product. A horizontal conveyor dryer provides excellent control of retention time and results in uniform drying.

There are several product factors that determine how the product will dry. The moisture content, size, shape, and density of the incoming product all alter its characteristic drying curve. Temperature, time, bed depth, and air velocity are all controlled within the dryer to accomplish both complete and uniform drying.

Drying characteristics can vary significantly depending on the raw material used and the denseness of the protein structure. Examples of these differences are shown in Figure 12. Each of these products has a different starting moisture level as a result of their processing requirements in the extruder. In addition, due to differing product structures, each of these products releases moisture at a different rate, resulting in different drying times. In the case of the examples shown in Figure 12, the soy flour chunk and wet-milled concentrate both require about 5 min of drying time to reach 10% moisture. Even though the wet-milled concentrate starts at a significantly higher moisture content, its product size and shape allow water to be released more quickly compared with the soy flour chunk. In contrast, the dense meat analog requires a drying time that is about 19 min longer than the other products, both due to its higher incoming moisture content and the slow release of water due to its dense structure.

After drying, the product is cooled, fines are removed, and the product is segregated into the appropriate size ranges and sent to holding bins prior to packaging. This intermediate product is subsequently used in downstream processing by the food service industry to create meat alternative solutions or replacements.

High-Moisture Processing

The second extrusion processing method used for making texturized products is high-moisture processing and is often referred to as HME (high-moisture extrusion), HMEC (high-moisture extrusion cooking), or HMMA (high-moisture meat analogues).

The technology was first investigated in the late 1970s with the development of an extrusion system called UNITEX. The UNITEX system was made using two single-screw extruders—the first for cooking and the second for aligning and laminating the fiber structure (Fig. 13). As shown by the product displayed in the upper left corner of Figure 13, the UNITEX process produced a very distinct layered structure that mimicked natural cuts of meat. The process was not fully commercialized until the 1990s when it was simplified from dual single-screw cooking

Fig. 10. Chunk and minced texturized protein products.

Fig. 11. Conveyor-style dryer.

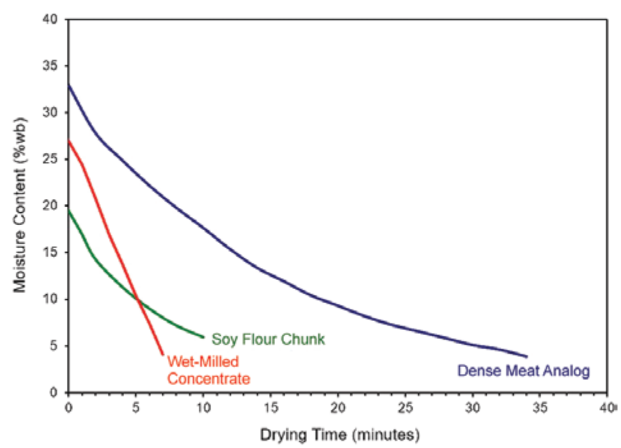

Fig. 12. Drying curves for different texturized protein products.

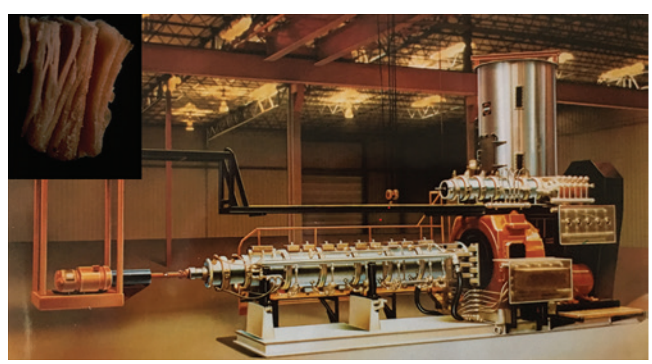

Fig. 13. UNITEX extrusion process.

extruders to a twin-screw extruder for cooking the proteins and the addition of a long cooling die to develop the desired fibrous and laminar texture. A commercial version of this technology is shown in Figure 14.

Today, the type of ingredients and mixing system used are very similar to what is used for dry extrusion. As the material enters the preconditioner, the process begins to differ. The moisture content of the dry material is hydrated to approximately 35–45% moisture to fully hydrate the proteins. This material then enters the extruder, and additional water and mechanical shear are added to produce a high-temperature melt with moisture levels in the 55–70% range.

As the hot material exits the extruder, it is pushed into a long cooling die that allows the material to texturize and fibrate, creating a dense, layered structure (Fig. 15). The streamlined drag flow created by the cooled walls of the die allows fibers to stretch and align, creating a meat-like texture.

The product leaves the die at a temperature that is less than 100°C to prevent expansion and separation of the fiber structure. It is then cut and milled into smaller pieces (Fig. 16). Due to the high moisture level, the material is handled via a cold chain process in which flavors and binders are mixed with the extruded intermediate and then the textured protein is formed into final consumer products and flash frozen or chilled.

The high-moisture process allows premium products to be created that have the look and mouthfeel of real meat, but due to the lower outputs for similar sized extrusion systems, their products will always entail a higher production cost than dry texturized materials.

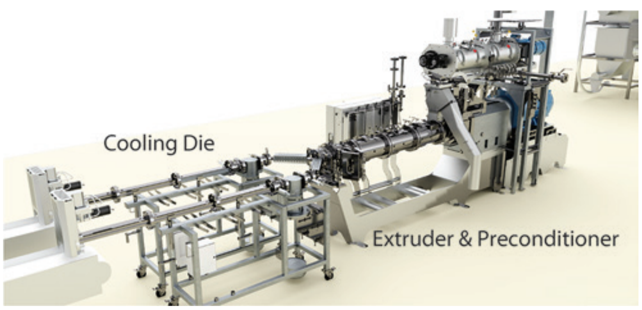

Fig. 14. High-moisture texturization system.

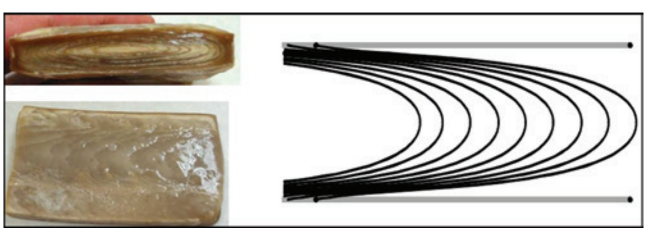

Fig. 15. Fiber creation in cooling dies.

Fig. 16. High-moisture extruded products.

PowerHeater Process

The third extrusion-based technology that is utilized for creating plant-based alternatives is the thermal extrusion system called the PowerHeater. This technology, which was originally developed for cooking and texturizing meat products, has found application in vegetarian and plant-based products as well.

The PowerHeater process is based on transferring indirect thermal energy into an emulsion to coagulate the proteins. It transforms simple protein-based formulas into texturized meat-like products. The ingredients used to create plant-based products from this process are very similar to those used for the cooking extrusion processes previously discussed.

Unlike the previously discussed cooking extrusion processes, the PowerHeater system is an entirely wet process (Fig. 17). Dry protein, carbohydrate, fiber, and fat are combined with oil and water in a bowl chopper and mixer to create a hydrated emulsion. The emulsion is then pumped through the PowerHeater, where it is heated by indirect thermal energy to set the structure. As it exits the die, the material is laminated, creating a fibrous structure.

Once texturized, the material can be cut and shaped into crumbles, cubes, and stripes or reformed into consumer-ready goods such as burgers (Fig. 18). Because the products have high moisture contents (60–75%), they need to be handled via a cold chain process, similar to the high-moisture extrusion process.

Although the PowerHeater system has many similarities to the cooking extrusion process, there are some unique differences between the processes. First, the PowerHeater is a wet process and requires the processor to be able to handle and create emulsions prior to extrusion. Second, most of the energy comes from indirect thermal heat rather than from a combina-

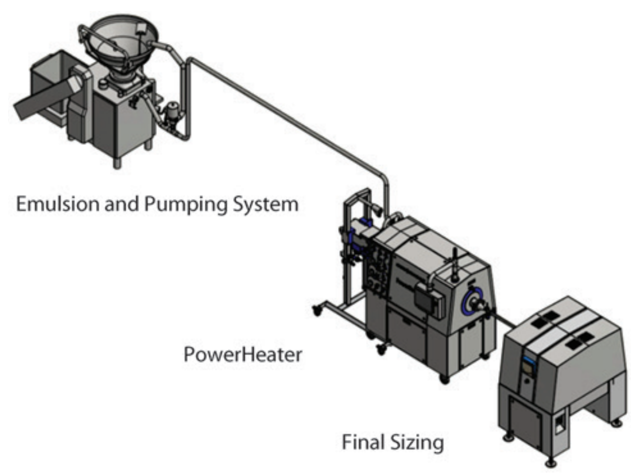

Fig. 17. PowerHeater process.

Fig. 18. Final crumble and burger products created from PowerHeater texturates.

tion of mechanical and thermal energy. When scaling up products made in a PowerHeater system to a higher capacity, multiple units are installed rather than larger diameter machines.

Conclusions

The products that are made using the three extrusion-based processes described have similarities, in that very simple products such as plant-based burgers and sausages can be made with the intermediate products created by all three methods. The differences in the technologies are primarily due to the differences in the textures desired for developing specific culinary products. All three technologies play an important role in creating intermediate ingredients for the manufacture of mainstream products that meet the demands of modern consumers—be it vegan, vegetarian, flexitarian, or reducetarian.

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