Chapter 12
Food Extrusion

Zeki Berk

Abstract Food extrusion is an increasingly important and widely applied process in the industry, and at the same time is a subject of extensive scientific and engineering research activity. The complexity of the extrusion process is prompting research in areas such as fluid dynamics, rheology and chemical reactions. The introduction of the twin-screw co-rotating extruder with flexible screw configuration is a marked improvement in the process. In addition to its use as an efficient tool for the production of pasta, snacks, ready-to-eat (RTE) cereals, texturized proteins and animal feed, the extruder is a valuable high-temperature-short-time (HTST) reactor. Extruded food products are safe, nutritious and of high organoleptic quality. Progress in extrusion technology is expected to contribute to the global food supply.

Keywords Cooking extrusion · Single-screw extruder · Twin-screw extruder · Flow pattern · Mixing · Residence time distribution · High moisture extrusion · Co-extrusion · Reactive extrusion · Texturization · Pellets · Direct expansion · Cold extrusion · Nutritional aspects · Food safety · Food availability

12.1 Introduction

Food extrusion is an increasingly important and widely applied process in the industry, and at the same time is a subject of extensive scientific and engineering research activity. Industrially, extrusion is the central process in the production of pasta products, expanded and filled snacks and ready-to-eat (RTE) breakfast items, pre-cooked cereals and legumes, infant foods, pet foods, texturized meat analogs and numerous confectionery items including chocolate, edible films, modified starch, starch hydrolysates, ice cream and more (Frame 1994; Riaz 2000; Guy 2001). From a scientific perspective, the complex nature of the extrusion process has driven and continues to drive extensive research in areas such as fluid dynamics, rheology and chemical reactions.

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Literally, the word "extrusion" means the action of pushing out material through a narrow opening (from the Latin *extrūdere*, *ex* = out + *trudere* = push, thrust). This definition fits well with the operation of extrusion in processing metals, plastic polymers, most pasta products and animal feed pellets, whereby the principal role of the extruder is to impart to the product a certain shape, depending on the cross section of the opening and the cutting device, without otherwise affecting the physical and chemical properties of the extruded material. Without underestimating the importance of such applications of "forming extrusion", one can say that the type of extrusion that has had the most significant impact on the food industry is the thermomechanical process known as "extrusion cooking", whereby significant modifications in the chemical composition and physical properties of the extruded product are induced. In extrusion cooking, the combined action of mechanisms such as heat transfer (both heating and cooling), mass transfer, shear, compression and expansion results in effects such as cooking, thermal processing, stabilization, mixing, kneading, melting, cooling, freezing (ice cream), chemical reactions (protein denaturation, starch gelatinization, sugar caramelization), texturization, coating, puffing, kneading and forming, all in one operation.

Long before its application in foods, industrial extrusion was widely used in metallurgy and in the processing of plastic polymers. The first extrusion patent for making lead pipe was issued in 1797 (Kazemzadeh 2012). Production of pasta products by continuous extrusion started in the late 1930s (Mercier and Cantarelli 1986), and cooking extruders for making puffed snacks were developed in the 1940s (Harper 1989). In the 1960s, simple low-cost extruders were developed for on-farm cooking of soybeans, used as animal feed. A decade later, low-cost extruder-cooker (LEC) technology was adopted and promoted by international agencies and governments for the production of low-cost infant foods based on oilseed–cereal mixtures (Crowley 1979). Extrusion cooking has been used for the texturization of proteinaceous materials of vegetable origin to produce meat-like structures (Berk 2013), which continues to be one of the principal applications of extrusion cooking. Recently, extrusion has been applied to the development of biodegradable and nanocomposite films with interesting barrier characteristics (Kumar et al. 2010; Li et al. 2011).

The first food extruder-cookers were single-screw machines. Twin-screw extruders for foods were introduced in the 1970s, widening the scope of food extrusion cooking considerably.

The rapid expansion of cooking extrusion in the food processing industry may be explained in light of the specific advantages of this process over other processes serving the same purpose. Some of these specific advantages are listed below:

- Extrusion is a continuous, single-pass process.
- Extrusion is a multi-functional process. A number of effects may be achieved simultaneously in the same extruder.
- The same extruder, with certain modifications, may be used with different materials, for different purposes, resulting in a vast variety of different products.
- For its production capacity, the extruder is relatively compact and requires little plant space.

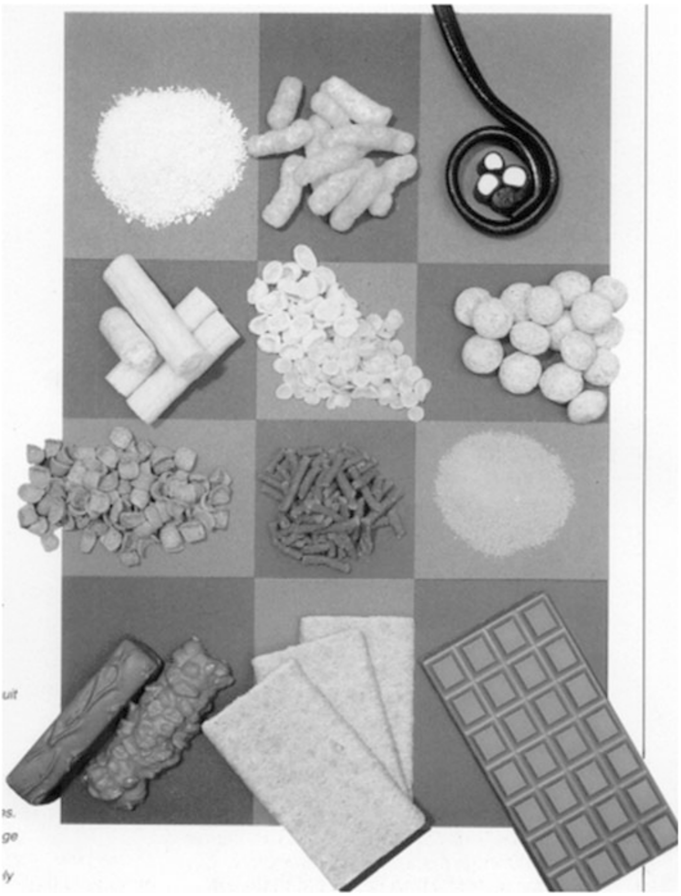


Fig. 12.1 Some extruded products (Courtesy of Baker Perkins Limited)

- Extrusion easily lends itself to automation and control. It requires little labor or supervision.
- The average retention time in extruders is usually short, and the retention time distribution is fairly narrow.

These advantages explain the rapid expansion of extrusion processes in the food industry. A limited array of foods produced by extrusion is presented in Fig. 12.1.

12.2 The Extruder

Harper (1978) describes the food extruder as consisting of "a flighted Archimedes screw which rotates in a tight fitting cylindrical barrel". While this description may have corresponded to the structure of some of the earliest single-screw extruders, the present-day extruder is physically much more complex. The first use of single-screw extruders in food processing for continuous extrusion of pasta dates back to 1935 (Bruin et al. 1978).

12.2.1 *The Single-Screw Extruder*

(a) **Basic structure**

The single-screw extruder has a simple basic structure, consisting of the following components (Fig. 12.2):

- A hollow cylindrical shell, called the "barrel". The barrel can be either smooth or grooved. Extruders with conical barrels exist (Meuser and Wiedmann 1989), but they are not used in food processing.
- A flighted *screw* (also known as the "worm"), with a thick shaft (also known as the "screw root") and shallow flights, turning inside the barrel. The flights of the rotating screw convey the material along a helicoidal path (known as the "flow channel") formed between the flights, the screw root and the barrel. The width of the flow channel, resulting from the screw pitch, is considerably larger than its thickness, resulting from the distance between the root and the surface of the barrel. To maintain the positive displacement capacity of the extruder, the gap between the screw tip and the barrel surface is made as narrow as possible.
- At the feed end of the extruder, a feeding device such as a gravity hopper or an auger.
- At the exit end of the extruder, a restricted outlet, known as the die. The die serves as both a pressure release valve and a shape-forming element, imparting to the extrudate the desired shape, determined by the cross section of the aperture(s). The die is sometimes preceded by a perforated breaker plate, the function of which is to distribute the compressed material evenly across the die.
- A cutter for cutting the extrudate emerging from the die into pieces of known size. The cutter can simply be a blade rotating in a plane perpendicular to the exit direction.
- Additional elements for heating or cooling the barrel (steam or water jackets, electrical resistance heaters, induction heaters, etc.) These elements, external to the barrel, may be divided into individual segments in order to impose different temperature profiles at different sections of the extruder.

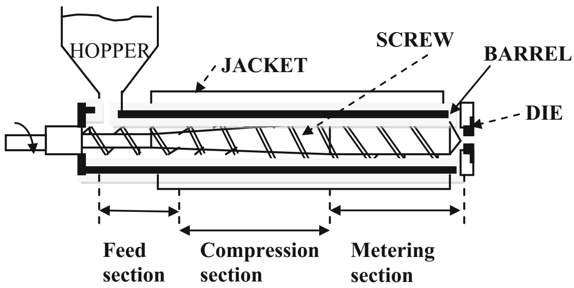


Fig. 12.2 Basic structure of a single-screw extruder

- At selected positions of the barrel, openings or ports for the introduction of steam, water and additional feed materials, as needed for the process.
- Ports for pressure release.
- Sensors for measuring and controlling temperature and pressure.
- A powerful motor and a drive, with speed and direction variation capability and appropriate protection devices.

(b) **Operation**

The feed materials processed in cooker-extruders are typically particulate solids (flours, powders, meals, etc.) at a certain water content. Prior to extrusion, the feed material may be subjected to "conditioning" operations such as water equilibration, pre-mixing or pre-heating. The feed is then introduced into the machine through the hopper by gravity or by an auger. Additional water or other fluids may be fed directly to the extruder through appropriate ports. As the screw rotates, the flights drag the material forward towards the die end of the extruder. Friction with the moving material occurs on both the screw and barrel surfaces. Preferably, friction with the barrel surface is stronger than friction with the screw. In the opposite case, occurring if the water content of the material is high, the melt sticks to the screw and turns with it without advancing. This undesirable effect is known as "cylindering", and is less likely to occur in extruders with slotted barrels. Due to friction, a large part of the mechanical energy is internally converted to heat, and the temperature of the material rises significantly. Additional heat may be supplied by externally heated barrels. As a result of shear and high temperature, the particulate structure of the material disappears, and the mass is converted to a viscous dough. Similar to that produced in the extrusion of plastic polymers, this viscous mass is called "melt". At the same time, chemical reactions such as protein denaturation, starch gelatinization and partial hydrolysis take place (Camire 1998). The kinetics of these reactions was reviewed by Zhao et al. (2011).

The screw and barrel are constructed in such a way as to progressively reduce the cross section of the flow channels. As a result, the material is increasingly compressed as it moves down the extruder. The "compression ratio" of a screw is defined as the ratio of the cross-sectional area of the flow channel at the feed end to that at the exit end. Compression can be achieved by several types of screw configurations. The most

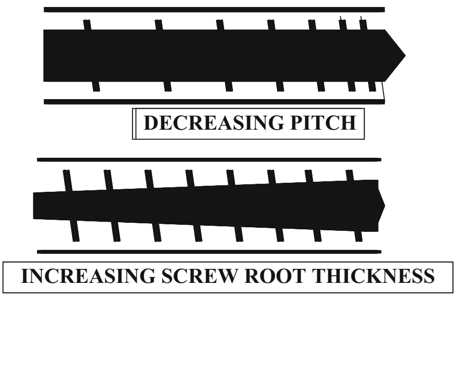


Fig. 12.3 Two methods of increasing compression ratio

common methods of compression call for either progressively decreasing screw pitch, progressively increasing root thickness, or both (Fig. 12.3). Screw configurations resulting in compression ratios between 1.5 and 4 are the most common.

In most single-screw extruders, screw configuration is not uniform over the entire length of the machine. The extruder can typically be divided into three sections, each with different screw structures (Fig. 12.2), as follows:

- Feed section: In this section, the screw pitch and root diameter are constant. The material coming from the feed hopper is simply conveyed forward, as in a screw conveyor, almost without compression or texture modification.
- Transition section (compression section): In this section, the mass is heated and compressed.
- Metering section: Here, the cross-sectional area of the flow channel is nearly constant. Therefore, there is almost no compression, but most of the effects of extrusion (melting, texturization, kneading, chemical reactions, etc.) occur in this section as a result of extensive shearing and mixing. At the end of the metering section, the melt is delivered to the die assembly.

As mentioned above, most of the mechanical energy used for turning the screw is dissipated into the material as heat. This is heat generated in situ and not supplied through heat transfer. Additional heat may be supplied by the externally heated barrel surface or by direct injection of live steam. In single-screw extruders, the heat generated by viscous dissipation constitutes the major portion of the energy input. Consequently, heating in a single-screw cooking extruder is extremely rapid.

Instantaneous puffing at the exit from the die is another important effect of extrusion cooking. As a result of compression, the melt may reach pressure of up to 20 MPa (Bruin et al. 1978). At such high pressure, the moist melt does not boil, despite its moisture content and temperatures as high as 180–200 °C. However, as the pressure is suddenly released into the atmosphere at the exit from the die, some of the water in the product is instantaneously evaporated, and as a result the product is puffed. Air bubbles inevitably entrapped in the melt through mixing in the extruder also contribute to puffing (Cisneros and Kokini 2002). An interesting alternative to puffing by flash evaporation of water makes use of supercritical fluid carbon dioxide. Supercritical CO_2 is injected into the melt in the extruder and penetrates the melt by diffusion. As the pressure drops at the exit from the die, gaseous CO_2 is desorbed and puffing occurs. Puffing by this method is reported to be less explosive, resulting in a product with improved porous structure, smooth surface and light color (Ferdinand et al. 1990; Mulvaney and Rizvi 1993; Ayoub and Rizvi 2011; Sauceau et al. 2011; Wang and Ryu 2013).

The extent of puffing can be controlled by releasing some of the pressure through an appropriate port at the metering section and/or by lowering the temperature of the melt just before the die.

Energy consumption in extrusion is an important technological and commercial factor. It is usually expressed as "specific mechanical energy (SME)", which is the actual net mechanical energy invested per unit mass of product. The net mechanical energy input is calculated by multiplying the torque by the angular speed of the screw and dividing the result by the mass flow rate of the extruder.

(c) **Flow patterns, extruder throughput**

Since the development of the extruder, numerous efforts have been devoted to the study of the flow patterns inside the machine (Carley et al. 1953; Pinto and Tadmor 1970; Bigg and Middelman 1974; Bruin et al. 1978; Tadmor and Gogos 1979; Harper 1980; Bounié 1988; Tayeb et al. 1992). Most of these studies have dealt with extruders for processing plastic polymers in plasticators, and later applied with varying degrees of success to cooking extruders for food materials by simulation. The interest in studying flow inside the extruder stems from the need to understand the mechanisms of mixing and residence time distribution (RTD) and to develop viable theories for the prediction of material throughput rates, pressure drop and power consumption (Bruin et al. 1978). Numerous mechanical models have been proposed for analysis of the complex flow patterns in the extruder. In the most common early models, the helicoidal flow channel is mentally "peeled off" the screw and laid flat (Harper 1980), so as to have a straight flow channel of rectangular cross section. Most commonly, only the metering section, where there is no compression and no acceleration due to a gradual decrease in the cross section, is considered. For convenience, the screw is considered static and movement is attributed to the barrel. In most studies, it is assumed that the melt is a Newtonian fluid.

The movement of the melt inside the flow channel is defined by the components of its velocity in the direction of the axes x, y and z, corresponding to the width, depth and length of the channel, respectively. Flow in the x direction contributes to mixing, and flow in the y direction is usually negligible. Net movement in the z direction (direction of the extruder axis) determines the material flow rate. Two different flow elements occur in the z direction. The material is pushed forward by the turning flights. This is "drag flow", and it depends on the velocity component in the z direction and the cross section of the flow channel. The velocity in the z direction, v_z, depends on the screw diameter D, rotation speed N and lead angle of the screw θ.

$$v_z = \pi DN \cos \theta$$

It follows that the drag flow rate F_{drag} is given by:

$$F_{\mathrm{drag}} = \pi DN \cos \theta \, WH/2$$

where W and H are the width and height of the channel. The drag flow rate represents the positive displacement capability of the extruder.

The second flow element in the longitudinal direction is the "backflow" or "pressure flow". As a result of gradual compression, a pressure gradient is created in a direction opposite that of the drag. The effect of this gradient $\mathrm{d}P/\mathrm{d}z$ is the flow element F_{pressure} given by:

$$F_{\text{pressure}} = \left[\frac{WH^3}{12\mu}\left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)\right]$$

where μ is the apparent viscosity of the melt, assuming Newtonian rheology.

The pressure flow rate can be regarded as the deviation of the extruder from true positive displacement pump behavior. The ratio of pressure flow to drag flow is a parameter of extruder performance (Harper 1980). Subtracting the pressure flow from the drag flow, one obtains the net volumetric throughput Q of the extruder, subject to the simplifying assumption made:

$$Q = \left[\frac{(\pi DN\,\cos\theta)WH}{2}\right] - \left[\frac{WH^3}{12\mu}\left(\frac{P_2 - P_1}{L}\right)\right]$$

where P_1 and P_2 are the pressure at the feed end and exit end, respectively, and L is the length of the extruder.

The above development is only approximate and cannot serve for design purposes because of the complex nature of flow in the extruder, and even more so because of the complex rheology of the food materials extruded. Model systems assuming non-Newtonian (e.g. power law) rheology, more suitable for polymer melts but not food doughs, have also been studied. Bruin et al. (1978) carried out a detailed experimental study with biopolymers (corn grits, soybean flour, modified amylopectin). At the conclusion of their extensive study, the authors wrote: "The prediction of flow rates during extrusion of biopolymers in single screw extruders is at present not well possible. An important reason is the lack of rheological data for materials under extrusion conditions. A second important reason is that most biopolymers undergo chemical reactions during extrusion cooking." However, the following qualitative approximate relationships may be concluded from the above analysis:

- Extruder output increases with screw diameter, speed of rotation, flow channel cross section and the area of die aperture.
- The backflow is strongly influenced by melt viscosity. Lower viscosity (e.g. due to higher moisture content) results in an increase in backflow and a corresponding decrease in net throughput.

(d) **Mixing**

One of the important functions of the extruder is mixing, with the objective of increasing the homogeneity of the contents. The basic mechanism of mixing consists in moving parts of the material in relation to each other. In the single-screw extruder, the movement of parts of the fluid in different directions occurs mainly because of the existence of the pressure flow (back flow), and to a lesser extent because of the transversal flow (in the x direction) within the flow channel (Fig. 12.4). Consequently, any factor capable of reducing the backflow (higher melt viscosity, smaller longitudinal pressure gradient, larger die opening) may be expected to diminish mixing efficiency.

Twin-screw extruders are better "mixers" than their single-screw counterparts due to specific screw configurations, to be described later.

(e) **Residence time and residence time distribution**

Important chemical reactions, such as gelatinization of starch, hydrolysis of carbohydrates and peptides, denaturation of proteins and Maillard reactions, take place during extrusion cooking. One branch of extrusion studies, reactive extrusion, deals specifically with extrusion-driven chemical reactions (Kokini 1993; Manoi and Rizvi 2009; Steinmacher et al. 2012; deMesa-Stonestreet et al. 2012). At any rate, the extruder can be viewed as a reactor, and as with any reactor, residence time (RT) and—even more so—RTD become important process parameters. RT and RTD refer primarily to the length of time during which the processed material or portions of it are subjected to a certain treatment (Bimbenet et al. 2002). The pathway of every particle of material in a continuous reactor is too complex for analytical treatment. Therefore, simplified models of reactor behavior have been developed (Berk 2013). Two of these models (Fig. 12.5) and their variations have been proposed for predicting RT and RTD in extruders:

- The plug flow reactor (PFR): In this model, as its name indicates, the material moves as a block or plug. Flow velocity is uniform throughout, and there is no mixing within the fluid. Therefore, the RT is the same for every portion of the fluid. The RTD curve is flat.
- The continuous stirred tank reactor (CSTR): This type of reactor simulates a perfectly agitated tank or vessel, continuously fed and discharged. The assumption of perfect mixing dictates that the composition and all other conditions at a given time are uniform at all points within the reactor. The

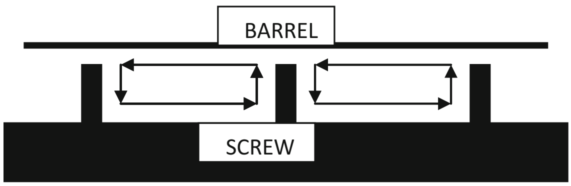


Fig. 12.4 Mixing by cross-flow

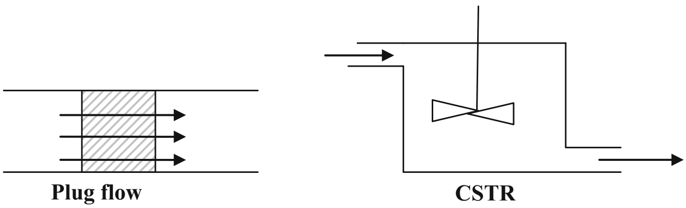


Fig. 12.5 Two reactor models

composition of the fluid discharged is the same as that of the bulk material in the reactor at the same instant.

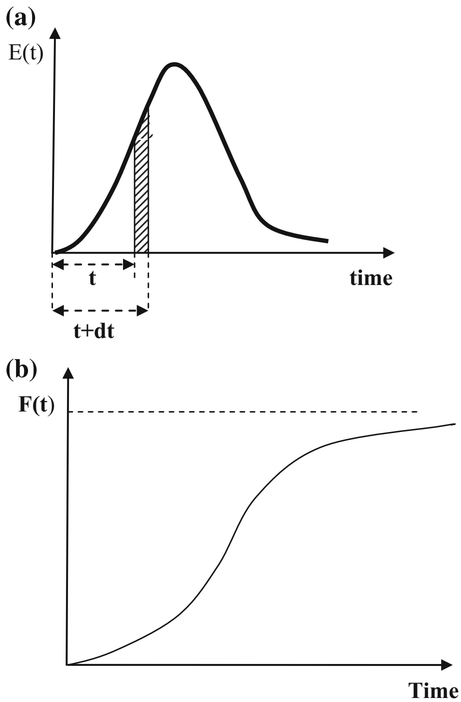
Real reactors do not behave like the idealized models. RT is usually not the same for each portion of the material, hence the need to consider the RTD. In cooking extrusion, a narrow RTD is obviously preferred. RTD can be evaluated experimentally and modeled using statistical functions and parameters as described below.

- The RDT function $E(t)$, known as the frequency density function, refers to the probability of a given particle to reside in the reactor for a time equal to t. Figure 12.6a shows a hypothetical plot of the $E(t)$ function versus t. The area of the shaded strip in this plot represents the mass fraction of the fluid that has spent a time between t and $t + \Delta t$ in the reactor.
- The RDT function $F(t)$, referred to as the cumulative distribution function, represents the mass fraction of the material that has spent time t or less in the reactor. Figure 12.6b shows a hypothetical plot of the $F(t)$ function versus t.

The mean RT t_m is:

$$t_m = \int_0^\infty t \,.\, E(t) \,.\, dt$$

Fig. 12.6 **a** Hypothetical plot of E_t versus t. **b** Hypothetical plot of F_t versus t



The mean RT is equal to the mean travel time through the reactor (space time), τ, given approximately by:

$$t_{\mathrm{m}} \approx \tau = \frac{V}{Q}$$

where V is the active volume of the reactor (the extruder, in our case) and Q is the volumetric flow rate.

RTD can be evaluated experimentally, most commonly by the *pulse injection* method (Fig. 12.7). At time 0, a small quantity of a tracer, such as a radioactive substance, is fed into the reactor. The concentration of the tracer (e.g. radioactivity) at the exit from the reactor is measured and recorded as a function of time. If C is the concentration of the tracer at the exit, $E(t)$ is given by:

$$E(t) = \frac{C}{\int_0^\infty C\mathrm{d}t}$$

A sharp peak with little tailing on either side indicates uniform RTD.

RTD in single-screw extruders has been studied extensively (Pinto and Tadmor 1970; van Zuilichem et al. 1973; Bigg and Middleman 1974; Bruin et al. 1978), both theoretically (according to velocity profiles) and experimentally. Relatively good fit between the predictions and the experimental results have been observed, particularly when working with Newtonian fluids. In general, RT is shortened by increasing the feed rate or the screw speed. Increasing the screw speed widens the RTD. Increasing the pressure flow causes the extruder to behave more like a PFR (Bruin et al. 1978). Working with rice flour, Yeh and Jaw (1998) found that a model consisting of a PFR in series with a CSTR fit well with the experimental data.

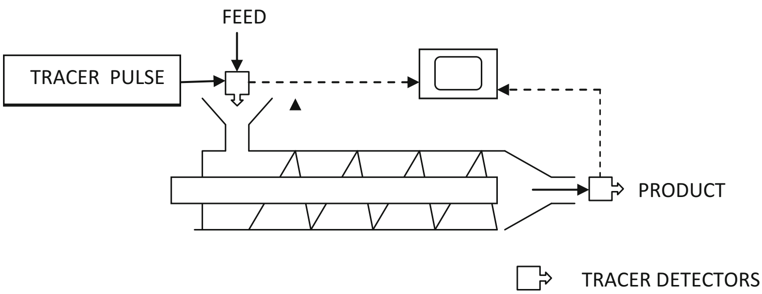


Fig. 12.7 Basic setup for the pulse injection method

12.2.2 The Twin-Screw Extruder

Suggestions to add a second screw to the extruder, with the objective of overcoming the problem of adhesion of highly viscous materials to the screw shaft (self-cleaning), were made already at the end of the nineteenth century (Ullrich 2008). Many patents were accorded, but the improvement of the concept, the practical application and the building of industrial machines was a lengthy process, and twin-screw extruders became available to the chemical and polymer industry only in the early 1940s. Their introduction to the food industry for extrusion cooking dates from the mid-1970s (Yacu 1985).

The twin-screw cooking extruder is not just a single-screw machine to which a second screw has been added, but a totally different machine in structure, operation, behavior and results. Harper (1992) lists the comparative advantages of the twin-screw extruder over its single-screw counterpart:

- Pumping efficiency is better and less dependent on the flow properties (viscosity, stickiness) of the processed material.
- Mixing is more complete.
- The rate of heat exchange rate from the barrel surface to the material is faster and more uniform.
- RTD is more uniform.
- The possibility of flexible modular configuration of the screw and the barrel makes the twin-screw extruder a much more versatile machine.
- High-moisture and sticky materials can be handled. This is probably the most important advantage, because it enables processing of materials that could not be handled previously by single-screw extruders. The introduction of twin-screw technology has resulted in the most significant expansion of the application of extrusion to foods and the spectrum of extruded products.
- Self-wiping reduces the risk of residue buildup.
- Feeding problems with cohesive materials are less serious.

Because of these and other advantages, the use of twin-screw extruders in the food industry grew rapidly, at the expense of the single-screw extruder. On the other hand, for equal output, a twin-screw extruder is considerably more expensive than a single-screw machine. The operating and maintenance costs are also higher. The mechanical complexity of the twin-screw extruder makes it less robust and more sensitive to abuse, and it requires more skilled supervision.

(a) **Basic structure**

Twin-screw extruders feature a pair of parallel screws rotating inside an enclosure or barrel with a figure-8-shaped cross section. At the entrance end there is a feeding device such as a gravity hopper or an auger-type conveyor. The hopper may be vibrated if the feed material is not free-flowing. At the exit end, each half of the barrel converges into a short conical section, each with a die at the apex (Fig. 12.8).

Alternatively, the barrel may converge into a single conical section ending in a single common die. Multi-die extruders are also available.

The screws can be co-rotating or counter-rotating (Fig. 12.9), closely intermeshing or distant. The co-rotating, closely intermeshing (self-wiping) extruders constitute the type most commonly employed in the food industry (Harper 1989). In the following discussion, we shall refer only to this type of extruder.

One of the important advances that accompanied the twin-screw extruder was the "tailor-made" screw, imparting to the extruder a degree of versatility not available to the older fixed-screw machines. The screws can be assembled by the user according to the desired configuration by sliding different screw elements on splinted shafts (Fig. 12.10). The short screw elements supplied by the manufacturer comprise leading, restricting, mixing, kneading, reverse-flow and many other types

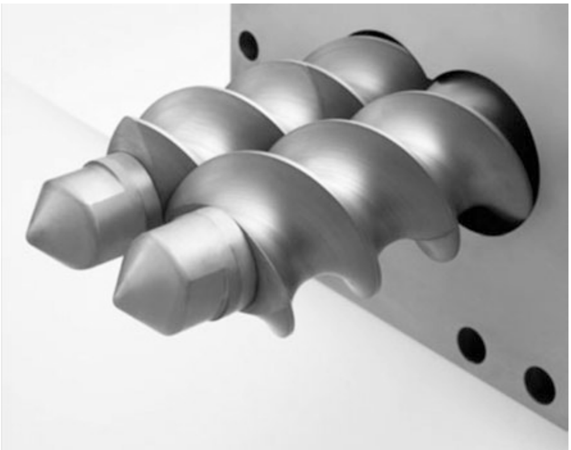


Fig. 12.8 Die end of twin screws (Courtesy of Baker Perkins Limited)

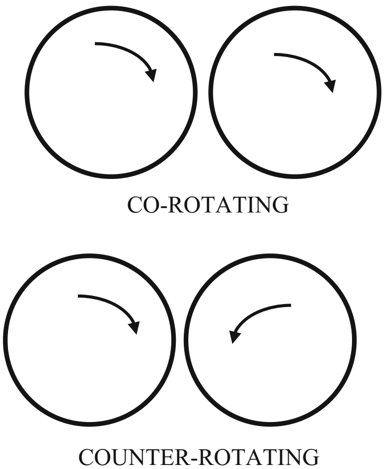


Fig. 12.9 Rotation directions in twin-screw extruder

Fig. 12.10 Twin screws for flexible configuration

Fig. 12.11 Screw elements for assembly on splinted shaft

of pieces with different pitch lengths (Fig. 12.11). The barrels are also different. In some models, the barrel is split into two halves longitudinally (clamshell barrel), allowing easy opening for removing and changing screws, inspection and cleaning. In other models (modular barrel), the barrel consists of short, separable sections or modules (Fig. 12.12).

(b) **Operation**

In the feed section, the material is rapidly conveyed forward by the two rotating screws. Typically, conveying screw elements with large lead angles are installed on the screw shaft in this section. As twin-screw extruders are usually starve-fed (Yacu 1985) and rapidly evacuated, the feed section is only partially full. The feeding section acts essentially as a fairly long heated screw conveyor with two screws. Due to the low holdup, the material is rapidly heated almost up to the temperature of the barrel surface. If needed, a short length of mixing elements can be included in the

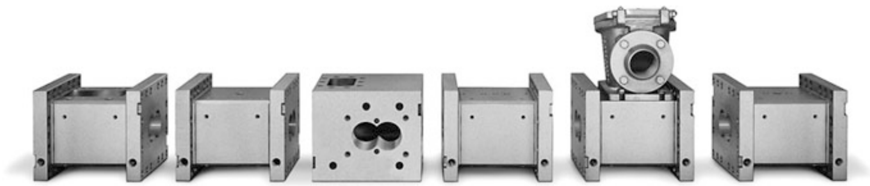


Fig. 12.12 Modular barrel

screw configuration at the end of the section, with the objective of giving the feed additional mixing.

Further down the barrel, in the melting and metering section, flow-restricting screw elements such as reverse-pitch units and barrel valves provide compression, promote heating and melting, and increase the filling ratio. The filling ratio in this section increases gradually towards the die.

Due to the dragging action of the second screw, friction is less than in single-screw extruders. Therefore, the proportion of mechanical energy converted to heat is lower, and heating depends primarily on heat transfer from the externally heated barrel. Most of the mechanical power is used for conveying. Cylindering is less likely to occur even with high-moisture feeds. Consequently, the positive displacement capability of the twin-screw conveyor is considerably higher.

(c) **Flow patterns, mixing and RTD**

Patterns of material flow, mixing, viscous dissipation of mechanical energy, degree of filling and RT are much more complex and difficult to model in twin-screw extruders because of the extreme variability in screw configurations in the "tailor-made screw" technology. The effect of screw configuration and operating conditions on mixing and RTD has been studied extensively (Altomare and Ghossi 1986; Choudhury and Gautam 1998). Shear and thermal effects in a co-rotating twin-screw extruder were investigated by Chang and Halek (1991). Attempts to model and predict the effects of the screw configuration on these and other performance parameters have met with limited success, but directional indications are available from experimental studies.

Unlike the single-screw extruder, there is no continuous flow channel. The material passes from one screw to the other, and changes direction with each revolution (Fig. 12.13). Most of the material moves in C-shaped chambers delimited by the two screws and the barrel (Fig. 12.14). At any given time, different parts of the screw surface fulfill different functions (Sastrohartono et al. 1992). The part of the screw surfaces close to the surface of the barrel performs the action of translation, while mixing occurs in the intermeshing section between the screws. However, a good part of the mixing is done by special mixing and kneading

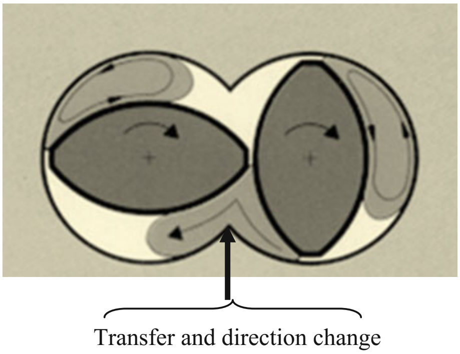


Fig. 12.13 Transfer of material from one screw to the other in twin-screw extruder

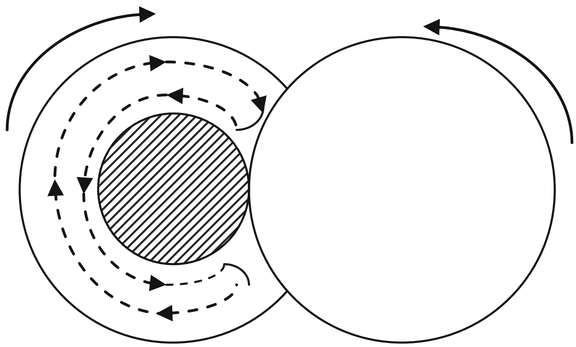


Fig. 12.14 Movement in C-shaped chambers (Adapted from Harper 1989)

elements on the screw, and depends on the number, length and spacing of the mixing regions. These elements are flat paddles without a significant restriction effect. Restriction is achieved mainly by gates and reverse-flow elements.

12.3 Food Extrusion Technologies

In this section, some of the commercially important and scientifically interesting food extrusion technologies are discussed.

12.3.1 Cold Extrusion—Pasta

Here we shall refer only to dry pasta, which is the principal industrial pasta product. Dry pasta is made by mixing wheat (preferably durum) semolina (Wiseman 2001) with water and other optional ingredients (eggs, tomato, spinach, vitamins, etc.), kneading the mixture to obtain a homogeneous dough, extruding this dough through die openings of the desired shape and drying the extrudate (Kill 2001; Brockway 2001). The most significant recent advances in pasta technology have been in the area of drying (which is outside the scope of the present chapter) and in the introduction of non-traditional ingredients into pasta products (e.g. Yalia and Manthey 2006; Marti et al. 2013).

The ingredients are pre-mixed in a screw or ribbon mixer. Sufficient water is added to bring the moisture content of the dough to about 30 %. The mixture is fed to the extruder, and a vacuum is applied to expel the air and prevent air bubbles in the product. The role of the extruder is twofold: kneading the dough and forming the product at the die (Dawe 2001). In contrast to cooking extrusion, cold extrusion is used for making pasta. Both single-screw and twin-screw extruders are used. The barrel is water-cooled so as to maintain the temperature of the dough around 40 °C. A lower temperature results in high dough viscosity, which makes passage through the die difficult. A higher temperature results in degradation of the gluten and lower cooking quality (Abecassis et al. 1994). Pasta made by the older lamination technique is said to have a better texture, but most dry pasta today is made by extrusion.

12.3.2 Frozen Extrusion—Extruded Ice Cream

The application of extrusion to the production of ice cream in the late 1980s (Eisner 2006) is probably the most innovative recent development in food extrusion technology. Based on the research work of Windhab at ETH (Windhab and Wildmoser 2002), and further developed by Bollinger (Bollinger et al. 2000), this so-called low-temperature extrusion (LTE) ice cream technology is now being used by most leading manufacturers of ice cream. The mix is prepared, pasteurized and aged as usual, then partially frozen in a conventional ice cream freezer such as a swept-surface heat exchanger with air injection. A screw extruder with a strongly cooled barrel is used as a second freezer. Shear and heat transfer are controlled so as to promote the formation of very small ice crystals, in order to prevent the formation of large crystals and to distribute the fat evenly. The resulting ice cream is smooth and creamy. The material is extruded through dies of desired shapes and cuts. Thus, the LTE ice cream process not only produces ice cream of superior quality, but also helps form the final shape, such as bars or cone balls, without molds. The formed units are coated and sent to the final freezer for hardening.

12.3.3 Co-extrusion

Co-extrusion is the simultaneous extrusion of two or more materials of different properties (texture, flavor, color, etc.) in order to obtain a multi-phase product such as a filled breakfast cereal or snack (deCindio et al. 2002). Co-extrusion has been practiced in the polymer industry for many years, but its application in the food industry dates only from the 1980s. The two materials can come from two extruders. More commonly, one of the materials, usually a cereal-based mixture, is processed in a cooking extruder and constitutes the outer shell. The second material, usually a filling such as cheese, cream, jam or chocolate, is injected into the center of the cooked mass stream at the specially designed co-extrusion die (Figs. 12.15 and 12.16). A pump assembly (Fig. 12.17), is used to inject the filling at the appropriate pressure. The cereal-based shell material expands, while the colder filling does not. Down the production line, the malleable extrudate is crimped and cut. The choice of shell and filler materials is important. For example, in order to maintain the crispiness of the relatively hygroscopic shell, the moisture content of the filling must be low. Matching the viscosities of the dough and filling is necessary in order to minimize flow instabilities at the die.

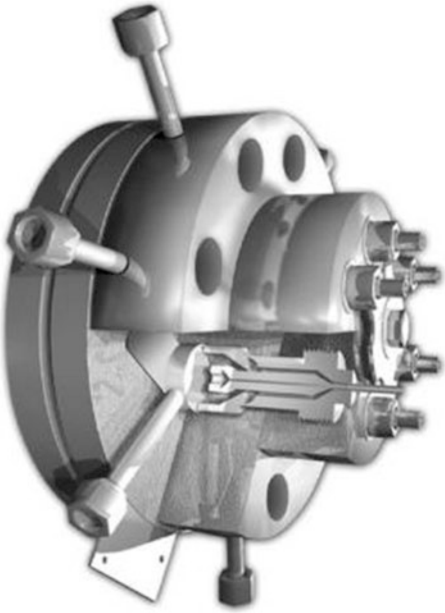


Fig. 12.15 Co-extrusion die (Courtesy of Baker Perkins Limited)

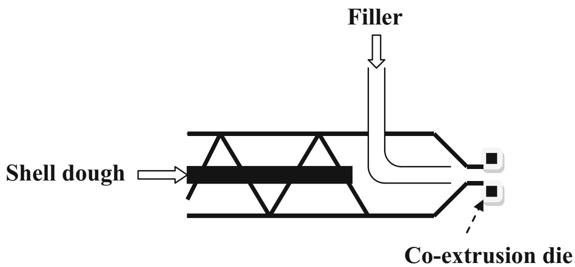


Fig. 12.16 Basic principle of co-extrusion

A special case of co-extrusion is co-injection, whereby a material of much lower viscosity (e.g. a food colorant in solution) is injected into the dough in order to incorporate ornamental patterns into the product (Morales-Alvarez and Rao 2012).

An interesting application of co-extrusion is the production of sausage by extrusion. Here, the outer shell material is a collagen gel, and the inner phase is extrusion-processed sausage meat. At the die, the collagen gel coats the cylinder of extruded meat as a thin film. A brine bath causes the collagen film to solidify and form an edible casing around the sausage "rope", which is cut to proper size and packaged. The casing can also be formed by a film of alginate, hardened by a calcium salt.

Fig. 12.17 Pump assembly for filler (Courtesy of Baker Perkins Limited)

12.3.4 Reactive Extrusion

Reactive extrusion refers to the use of extruders to carry out chemical or biochemical reactions. The advantages of the extruder as a continuous reactor with outstanding mixing capability led the chemical industry to consider it as a successful substitute for batch reactors, particularly for polymerization and polymer modification (Mani et al. 1999). The main food-related applications of reactive extrusion are hydrolysis and modification of starch (Linko 1992; Akdogan 1999; Xie et al. 2006). Reactive extrusion is particularly suited for the treatment of highly viscous media. Co-rotating twin-screw extruders are preferred for reactive extrusion, due to their efficient mixing, short and uniformly distributed RT and, above all, their ability to handle feeds with high water content (Akdogan 1999). Due to the high temperature, the efficient mixing and the relatively high concentration of the reactants, the reactions are very rapid and correspond well to the short RT in the extruder (Linko 1992).

Starch-related processes include gelatinization, liquefaction, saccharification and chemical modification (e.g. esterification). Gelatinization is essential for the solubilization of starch and for increasing the susceptibility of starch to enzymatic amylolysis. High temperature and sufficient water are necessary for gelatinization. In conventional processing, starch gelatinization requires water content of 35–40 %. Although gelatinization has been achieved by extrusion cooking at a moisture level as low as 10 % (Linko 1992), the process is accelerated by higher moisture, hence the advantage of the twin-screw extruder. Liquefaction refers to the initial stage of hydrolysis whereby the viscosity of starch paste is greatly reduced, producing non-sweet (low DE) syrups. The thermomechanical action of cooking extrusion, with or without enzymes, can be used for the continuous liquefaction of starch (Davidson et al. 1984; Cheftel 1986; Colonna et al. 1989; Linko 1992; Karathanos and Saravacos 1992). The enzyme most commonly investigated in connection with starch liquefaction by reactive extrusion is thermostable α-amylase. Complete saccharification by extrusion alone is difficult, and the recommended procedure is extruder liquefaction in the presence of thermostable α-amylase, followed by post-extrusion hydrolysis by the enzyme glucoamylase.

Extrusion has been found to be a useful tool for carrying out starch-based reactions for the production of edible or biodegradable films (Carr 1991; Shogren 1996; Mani et al. 1999; Miladinov and Hanna 2000; Xie et al. 2006; Raquez et al. 2008; Li et al. 2011).

12.3.5 Texturization, Meat Analogs

Texturization of protein-rich vegetable sources to produce meat analogs was one of the first objectives of food extrusion (Clarck 1978). Texturized vegetable protein (TVP®, a trademark of the Archer Daniels Midland Company, USA) is made by extrusion cooking of defatted soybean flour. It is a sponge-like product with a lamellar structure. When rehydrated, it becomes chewable. In the late 1960s, TVP was widely used as a meat extender in a variety of products, and its consumption grew considerably after it was adopted by school lunch programs. It was also produced and distributed in a number of developing countries, with the objective of improving the protein nutrition of the population. In the beginning, single-screw extruders were used. TVP made of defatted soy flour has some of the characteristic beany flavor of the raw material. A better product was able to be made by texturizing soy protein concentrate (70 % protein) or isolated soybean protein (94–96 % protein). The flour or concentrate was extruded at a moisture content of about 20 % and temperature of 160–180 °C. After extrusion through a die of appropriate shape, the product was cut and dried (Berk 1992). The product was quite successful as a meat extender but not as a true meat analog, because it lacked the juiciness and fibrous structure of meat. Incidentally, a material similar to TVP was prepared by a non-extrusion process consisting of static compression, heating and pressure release, which led to the conclusion that "the working and kneading of the extrusion screw is not a prerequisite for the formation of texture" (Taranto et al. 1978). This view was contradicted by Holay and Harper (1982).

In the late 1980s, a process for making a better meat analog by extrusion was developed in Japan. Soybean protein isolate or concentrate is cooked in a twin-screw extruder at a moisture content of 60 % or higher and temperature of 100–150 ° C. (Noguchi 1989; Akdogan 1999). The material is extruded through a long, cooled die, which is essential for obtaining a fibrous structure. The addition of starchy components enhances fiber formation. According to Tolstoguzov et al. (1985), fiber formation is a consequence of protein aggregation following phase separation. Moisture content has a stronger influence on product characteristics than cooking temperature (Lin et al. 2002; Chen et al. 2010b). Water performs several functions in the extrusion process. It acts as a lubricant, plasticizer and reaction reagent, lowers the glass transition temperature and causes different energy conversion ratios. As such, it affects the structure of the extrudate (Chen et al. 2010a). The molecular background of protein texturization has been investigated (Burgess and Stanley 1976; Aréas 1992; Ledward and Tester 1994). Based on the solubility of the extruded protein in various media, Prudencio-Ferrera and Arias (1993) concluded that disulfide bonds and non-covalent interactions are mainly responsible for the texture.

Soybean products are the principal but not the only material texturized by extrusion. Other protein-rich plant and animal sources have been treated by this process (Mégard et al. 1985; Hagan et al. 1986; Manoi and Rizvi 2009; Adhikari et al. 2009; Onwulata et al. 2010).

12.3.6 Direct Expanded Products

In terms of production volume, expanded snacks and breakfast cereals constitute the most widespread extruded food products, after pasta. Figure 12.18 shows a limited array of extruded snacks and breakfast cereals. Snacks and RTE breakfast cereals differ only in their formulation; their production processes are essentially the same.

Extruded foods, expanded by virtue of the pressure drop at the die exit, are known as second-generation or direct expanded products. Those obtained by thermal expansion during frying, oven or microwave heating of pellets (to be discussed in the next section) are called third-generation or indirect expanded products.

The standard production process of direct expanded foods is as follows:

The principal raw materials are cereal flours and starches. Optional additives are sugars, flavorings, colorants and fat. The raw materials and water are pre-mixed and fed into the extruder. Twin-screw extruders (Fig. 12.19) are used almost exclusively. Additional liquids may be added directly to the extruder. The mass is cooked at 160–180 °C and extruded through a die insert of appropriate shape. Expansion, both sectional and longitudinal, occurs at the exit from the die. The extrudate is cut to the desired length. At this point the product is still moist and soft. To make it crisp or crunchy, it must be dried. Heat-sensitive flavorings, vitamins and some fat may be added after extrusion. Some products are coated with sugar or cocoa and some are powdered or flaked.

The degree of expansion depends on the extrusion conditions as well as the properties of the raw materials. Literature on this matter up to 1989 was reviewed by Colonna et al. (1989). Starch is the principal factor in expansion. Nearly complete melting of the starch in the metering section is essential for expansion, and the viscosity of the melt at the die affects the degree of expansion. The amylose-to-amylopectin ratio is also important. The screw configuration has no marked effect on puffing (Sokheye et al. 1994). Payne et al. (1989) investigated the puffing of biological products in general, and classified the puffing processes into

Fig. 12.18 Some expanded snacks and breakfast cereals (Courtesy of Baker Perkins Limited)

Fig. 12.19 Pellet extruder (Courtesy of Baker Perkins Limited)

four categories based on the mechanism responsible for gas evolution: phase change, absorption, adsorption and chemical reaction. They defined an explosive expansion rate *E*, and concluded that *E* must be in the range of 0.05–12 m^3/s kg to puff biological products.

In addition to the production of snacks and breakfast cereals, extrusion expansion is being exploited for the production of fish feed (Oliveira et al. 1992). The possibility of producing sinking or floating particles by controlling the degree of expansion is attractive to manufacturers of feed for pisciculture.

12.3.7 Pellets—Products for Post-extrusion Expansion

One of the shortcomings of direct expanded snacks and breakfast cereals is their low bulk density, requiring expensive packaging and large storage space. Extrusion cooking is the first step in the production of pellets for subsequent puffing. Pellets are essentially non-porous particles of pre-cooked starchy materials. The raw materials are again starchy substances, optional additives, and water in sufficient quantity to permit starch gelatinization and adequate viscosity for regular transport in the extruder and through the die. Here, the only function of extrusion is cooking and forming. Expansion is avoided by pressure release and cooling before the die. The shape of the extrudate is determined by the die insert selected and the cutting device used. After extrusion, the pellets are stabilized by drying to a moisture content that warrants long-term conservation but leaves sufficient moisture (about

5–8 %) for puffing the pellet when exposed to high temperature. At a later stage, and often in a different location, the pellets are thermally puffed by frying, baking, roasting or microwave heating.

An important application of extrusion cooking without puffing is the production of raw materials for flaked breakfast cereals. In the production of the familiar corn flakes, for example, milled corn is moistened, then extrusion-cooked with other ingredients and extruded without expansion in the form of large particles. These granules are then flaked and toasted to produce corn flakes.

12.4 Nutrition, Safety, Availability

12.4.1 Effect of Extrusion on the Nutritional Characteristics of Foods

Chemical changes of nutritional significance in extrusion cooking have been extensively researched, and in-depth reviews of the voluminous literature on the subject are available (Cheftel 1986; Asp and Björck 1989; Singh et al. 2007). Extrusion cooking is essentially a thermal process. Consequently, any effect on the nutritional value depends primarily on the composition of the feed and the time–temperature history of the mass in the extruder. Design parameters and operating conditions such as the diameter and length of the extruder, screw configuration, mass flow rate, rotation speed and die geometry may have an effect on the nutritional properties in the measure that they affect the time–temperature profile. Thermal processes such as pasteurization, sterilization, cooking, roasting, frying, baking, blanching and drying are essential in the preparation of food industrially or at home. Therefore, the effect of extrusion cooking on nutrition should be evaluated in comparison to alternative thermal processes. Extrusion cooking is a high-temperature-short-time (HTST) process, and as a rule, HTST processes produce organoleptically and nutritionally superior food.

(a) Proteins: In general, extrusion improves the digestibility of proteins. This is attributed in great part to the inactivation of inhibitors of proteolysis in the GI tract (Asp and Björck 1989; Alonso et al. 2000). Acceleration of the Maillard reaction resulting in the depression of lysine availability is of concern, but can be minimized by extruding at moderate temperatures, below 180 °C (Cheftel 1986), and excluding reducing sugars.
(b) Digestible carbohydrates: These include mono-, di- and some oligosaccharides, dextrins and starch. Nutrition-wise, the most important change is the gelatinization of starch, which is efficiently performed by extrusion cooking, even at low moisture content. Gelatinization facilitates starch digestion by amylases in the GI tract.
(c) Non-digestible carbohydrates: These include cellulose, hemicelluloses, pectin and some polysaccharides. Many of these are components of the large and

nutritionally important group known as dietary fiber. Most raw materials subjected to extrusion cooking, such as cereal flours, are important sources of dietary fiber (Brennan et al. 2008) Extrusion cooking at moderate conditions does not significantly alter the dietary fiber content, but solubilizes some of it (Singh et al. 2007). Extrusion destroys some of the flatulence-inducing non-digestible oligosaccharides such as raffinose and stachyose (Asp and Björck 1989).

(d) Lipids: High fat content is generally avoided in the formulation of extruded foods, mainly because of the excessive lubrication and the resulting cylindering effect of fats. Extrusion cooking may induce slight and nutritionally insignificant chemical changes in characteristics such as unsaturated/saturated ratio and *trans* fatty acid content (Asp and Björck 1989).

(e) Vitamins: Heat-labile vitamins such as thiamine and ascorbic acid are degraded to a considerable extent by extrusion cooking. The rate of degradation is comparable to that caused by similar thermal processes. The most common practice for replacing the lost vitamins in products where vitamin content is important (e.g. RTE breakfast cereals) is post-extrusion incorporation.

12.4.2 Safety and Stability of Extruded Foods

As an HTST thermal process, extrusion should be considered as one of the most efficient food stabilization processes. The time–temperature profile of extrusion cooking, even under "moderate" conditions, is sufficient for the inactivation of most spoilage enzymes. The same is true for microorganisms and their spores (van de Velde et al. 1984). In a study investigating the destruction of one of the most heat-resistant spoilage microorganisms, *Bacillus stearothermophilus* (used for the validation of sterilization cycles in autoclaves, and now renamed *Geobacillus stearothermophilus*) (Bouveresse et al. 1982), no living spores were left after extrusion at 165 °C, provided that the average RT was at least 80 s. Cheftel (1989) calculated that the time–temperature profile of typical extrusion processes exceeded the thermal treatment needed to achieve commercial sterilization in foods. It is interesting to note that one of the reasons for suggesting extrusion cooking as a replacement for the lengthy process of conching (Aguilar et al. 1995) was the ability of extrusion to pasteurize the cocoa mass.

Extrusion cooking destroys many antinutritional and toxic factors that are frequently present in the raw materials treated. Inactivation of trypsin inhibitors in full-fat soybean flour was demonstrated by Mustakas et al. (1964). Destruction of antinutritional factors in animal feeds was one of the objectives in developing low-cost extruders in the 1960s. Trypsin inhibitors and lectins in pulses are also efficiently inactivated by extrusion (Cheftel 1989). Reduction of flatus-inducing sugars was mentioned in a previous section.

Mycotoxins are relatively heat-resistant toxic substances produced by molds. Kabak (2009) discusses the destruction of mycotoxins by extrusion. Cooking extrusion causes considerable degradation of aflatoxin in corn and peanuts (Saalia and Phillips 2011a, b), without adversely affecting the nutritional quality of the meal.

On the negative side, as far as food safety is concerned, the risk of the formation of toxic factors as a result of heating amino acids to high temperatures should be considered. The risk of acrylamide formation is of particular concern (Sharp 2003; Singh et al. 2007). Acrylamide, a by-product of the Maillard reaction, is a "probable human carcinogen", produced when certain foods are heated to high temperatures. The main precursor is the amino acid asparagine, in the presence of carbohydrates. Acrylamide is produced by industrial and home cooking alike, when asparagine-rich foods (such as potatoes) are subjected to high temperatures (such as frying). Acrylamide is present in potato and cereal foods produced by extrusion cooking (Singh et al. 2007; Mulla et al. 2011) and in extruded pellets fried for post-extrusion expansion. It is not yet known whether the concentrations of acrylamide typically found in extruded foods constitute a health risk for humans. At present, there are no guidelines or regulations concerning acrylamide in food. Techniques for reducing acrylamide levels in foods are available or in development, most of which are based on the enzymatic decomposition of asparagine.

12.4.3 Food Availability

The process of extrusion is probably the best example of the significant contribution of food engineering to the global availability of food. Pasta products are the backbone of nutrition in Italy and a significant factor in food availability elsewhere. RTE breakfast cereals are indispensable components of the diet of modern society, where convenience is the chief parameter for the selection of foods. For populations and individuals who cannot afford meat or would like to reduce their meat consumption for economic, religious or environmental reasons, texturized vegetable proteins offer a valuable solution.

Extrusion cooking has been suggested as a means of transforming underutilized plants and animals, by-products and waste material into potential food resources and as a way of reducing production costs. The use of extrusion cooking for the production of tarhana, a traditional Turkish staple based on wheat and yogurt, offers economic advantages (Ibanoğlu and Ainsworth 2010). Nixtamal is the lime-treated corn used for making tortillas. The tedious process of nixtamal production from corn can be replaced by extrusion cooking to save time and energy (Mensah-Agyapong and Horner 1992). Certain kinds of pulses are not fully utilized because they are difficult to cook. Extrusion cooking has been suggested as a solution to the problem (Ruiz-Ruiz et al. 2008). Sources of animal protein that can be upgraded by extrusion include fish (Bhattacharya et al. 1992; Choudhury and Gogoi 1995) and poultry (Mégard et al. 1985).

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