Extrusion Cooking Technology: An Advance Skill for Manufacturing of Extrudate Food Products

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Abstract

The snack industry is one of the fastest growing food sectors and is an important contributor within the global convenience food market. Nowadays snacks and convenience foods are also consumed regularly in India. Properly designed convenience foods can make an important contribution to nutrition in Indian societies where social changes are altering traditional patterns of food preparation. Extrusion cooking as a popular means of preparing snack foods based on cereals and plant protein foodstuff has elicited considerable interest and attention over the past 30 years. Several studies on the extrusion of cereals and pulses, using various proportions, have been conducted because blends of cereals and pulses produce protein enriched products. Based on dough's functional properties like WAI, WSI, ER and BD, the extruded products can be classified into different group as per particular application. Therefore, this chapter is dealt with the effect of extrusion processing on product parameters, and nutritional and anti-nutritional properties of extruded product.

Keywords: extrusion processing, direct expanded snack, single screw extruder, twin-screw extruder

1. Food extrusion processing

Extrusion process is an efficient continuous process, which uniquely combines several unit operations viz.: mixing, shearing, heating, pumping, forming, and sizing. Food extruders are classified thermally as forming or cooking and geometrically as single or twin screws. Single screw forming extruders are used to manufacture pasta, processed meats, and fillings. Single screw cooking extruder (SSCE) are used to produce dry and semi moist pet foods, expanded snacks, breakfast cereals, puddings, soup and drink bases, gelatinized

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starch and texturized vegetable proteins. Twin-screw extruder applications include most SSCE products and chocolate coatings, candies, gums, enzyme modification process, etc. [1]. A food extruder is a high temperature short time bioreactor that transforms a variety of raw material/ingredients into finished product. Extrusion processing is a continuous process. The extruded products are sterile and because of complete starch gelatinization, very digestible [2].

Extrusion cooking is used for processing of starchy as well as materials since a long time. As extrusion processing is a thermally efficient process, it offers many advantages in processing of high protein based products like soy or legumes etc. Due to high temperature short time cooking of soy-cereal blend, the antinutritional factors are effectively destroyed without damage to nutritional quality of raw material [3].

2. Equipment and processing steps in making a direct expanded product

There are different processing steps involved for production of direct expanded snacks (**Figure 1**).

2.1. Mixed raw material/blender

This usually takes the form of a ribbon blender. The mixing tool inside the vessel is in the shape of a spiral ribbon which rotates through a reduction gear and electric motor. All the dry ingredients, along with liquid ingredients such as an emulsifier, lipids, and moisture (water), are loaded in measured amounts to the blender and mixed for the required time. Since the moisture content for an expanded product is low (less than 20%), it can be added to the blender with dry ingredients. This is a batch mixing process.

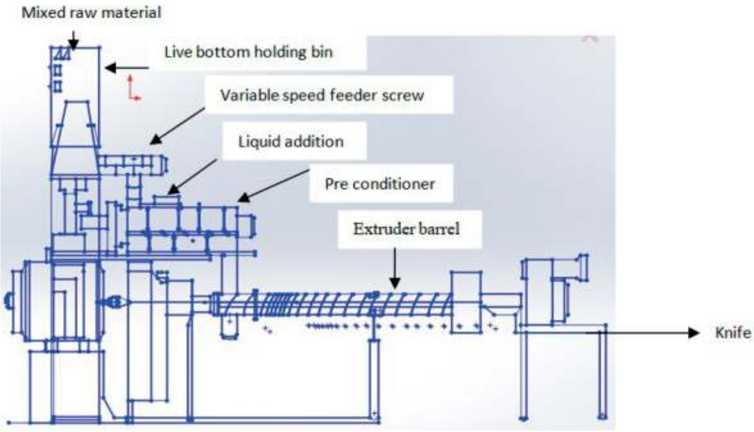

Figure 1. Layout of a typical snack food line for direct expanded products.

2.2. Variable speed feeder

This is usually in the form of an inclined screw conveyor, rotated by a geared motor, which transfers the pre blended raw-materials from the blender to the extruder hopper.

2.3. Extruder

The extruder has a hopper fitted with a horizontal auger screw run by a variable speed motor. The volumetric feeder constantly supplies a preset amount of raw-materials into the extruder inlet and over the extrusion screw running inside a grooved, electrically heated barrel. These materials are continuously moved through processing zones and forced through the die into the desired shape. Product temperature at the die exit can be as high as 190°C. Use of twin screw extruders is growing rapidly in the food industry as explained earlier. The extruder has no heating provision and the product gets sheared and temperature rises because of mechanical working of the ingredients between the plates. This extruder is almost superseded by the modern high shear cooking extruder which has versatility and immense product possibilities.

2.4. Cutters/knife

Automatic cutters are of a die-face cut variety and usually consist of a set of rotating knifes through a variable speed motor. Three dimensional cutting blades are more sophisticated and need additional knives, mounted at proper angles, to form three dimensional cut figures.

2.5. Dryer

Continuous running steel perforated belts, arranged for single or multiple passes, dry the extruded product down to 1–1.5% moisture content (wet basis). The dryer is used to produce baked collet and other products of low bulk density, whilst an additional fryer is required to produce high density products. For example, corn curls produced on a collet extruder are usually fried in a fryer to reduce the moisture level.

2.6. Coating unit

A coating unit is used to spray oil on an expanded product and to dust product with a suitable seasoning such as salt for additional mouth feel and crunch. In some units, the dryer and coating units are combined.

3. Effect of extrusion processing on product parameters

Extrusion cooking/processing of blended foods consists consideration of characteristics of starcheous and proteinaceous material i.e. gelatinization of starch and denaturation of proteinaceous material to produce quality extruded product [4]. Research carried out by different workers on effect of processing parameters on extruded snack food quality is presented below.

3.1. Expansion

The expansion is characterised on cooled and dimensionally stable products. Expansion parameters are derived both from bubble growth up until maximum size and from the ensuing contraction [5]. In a, the extrudate expansion, is a fundamentally important property during food extrusion cooking process. It is helpful in describing the product quality and also related to degree of cook. The product acceptability is based on its specific extrudate expansion. Thus, the understanding of the effects of process parameters on extrudate expansion becomes crucial for the extrusion cooking process. Several expansion theories and models have been developed to explain the characteristics of the extrudate expansion for several raw materials [6–11].

Faubion and Hoseney [12] reported that expanded volume of feed decreased with increasing amounts of proteins in the feed material, but increased with increasing starch content. In order to account for extrudates expansion upon removal from the die, longitudinal (LEI) and sectional expansion indices (SEI) proposed by Alvarez-Martinez et al. [11] were calculated.

Onwulata et al. [13] studied the effect of incorporation of whey product in extruded corn, potato and rice snacks. They concluded that the incorporation of whey protein from 0, 25 and 50%, the expansion indexes (EI) were found to be 2.4, 1.5 and 1.3, with corn flour extrudate: 2.2, 1.8 and 1.6. In case of potato flour extrudate and with rice extrudate the EI were 2.8, 2.6 and 1.8 respectively at high shear rate. Thus the effect of incorporation of whey protein with respective flours was not much as compare to flours alone. Dragnovi et al. worked fish meal, wheat gluten and soy protein blends and reported the effect of system parameters (Screw speed and barrel temperature 112–138°C) have an insignificant effect on radial expansion and in the range of 1.19–1.53. Similarly Ayse Ozer et al. [14] reported that the effect of screw speed and feed moisture on nutritious blend (Chickpea, corn, oat, corn starch, carrot powder and ground raw hazelnut) had significant effect on radial and axial expansion and were in the range of 2.36–3.08. Faubion & Hoseney [15] found that expansion of starch was greater than for wheat extrudates and decreased with increasing moisture. According to Kannadhason et al. [16], the expansion ratio of cassava and potato starch was found to decrease by 12.3 and 10.6%, respectively, with the change in net protein content from 28 to 32% wb. At higher moistures the expansion showed a maximum with respect to temperature, as reported for maize [17] and manioc starch [18]. Moraru and Kokini [9] reported that the attempt to incorporate high levels of fibre in extruded products often resulted in a compact, tough, non-crisp and undesirable texture in extrudates and reduced expansion. Falcone and Phillips [19] studied sorghum and cowpea blend and found that both temperature (175–205°C) and moisture (20.5–25%) had negative effect on expansion for most compositions. While various studies on extrusion of proteinaceous [20] and starchy [21] systems have found that puffing is directly related to temperature and inversely related to moisture. They observed that adding protein to a starchy extrusion system may interfere with expansion and also that amylopectin exerts a positive and amylose a negative influence on expansion.

Altan et al. [22] studied the effect of die temperature (140–160°C), screw speed (150–200 rpm) and pomace level (2–10%) on barley-grape pomace extrudate and found that effect of temperature had more effect. EI decreased with increasing barrel temperature and the value ranged between 0.949 and 1.747.

Ding et al. [23] studied the effect of extrusion conditions on physicochemical properties of rice based snacks and feed moisture was found to be main factor affecting the extrudate expansion. The highest expansion (3.87) was reported at 14% feed moisture, 120°C barrel temperature and screw speed at 250 rpm.

Molla [24] reported that in case of wheat extrudates, with increase in the screw speed increased from 200 to 300 rpm, initially sectional expansion index increased from 9.15 to 10.54, and then decreased to near the initial expansion. Whereas for corn extrudates no significant evolution occurred between 200 and 300 rpm, however a significant drop (39%) below the initial expansion was recorded for a speed of 500 rpm. Otherwise, the increase in screw speed induced a significant rise in the longitudinal expansion of extrudates for the two types of flour. The LEI for wheat and corn extrudates displayed an overall increase of 43 and 46%, respectively, for an increase in speed from 200 to 500 rpm.

3.2. Bulk density

The extrudate density was mainly affected by feed moisture. Screw speed and temperature also have significant effects on the density of extrudate. Increased feed moisture also promotes a sharp increase in extrudate density. However, increased screw speed and barrel temperature caused a slight decrease in the density of extrudate. Ding et al. [23] studied the effect of extrusion conditions on physicochemical properties of rice based snacks and feed moisture was found to be main factor affecting the extrudate expansion. The lowest bulk density (0.1 g/cm^3) was reported at lowest feed moisture (14%) and highest barrel temperature (140°C).

Altan et al. [22] studied the effect of die temperature (140–160°C), screw speed (150–200 rpm) and pomace level (2–10%) on barley-grape pomace extrudate and found that both (pomace level and barrel temperature) had significant effect on bulk density. The bulk density of extrudates was ranged between 0.325 and 1.18 g/cm^3. The increase in temperature from 140 to 150°C decreased the bulk density from 0.85 to 0.25 g/cm^3, whereas increase of pomace level increased the bulk density from 0.325 to 0.95 g/cm^3. The highest BD 1.18 g/cm^3 was found at 140°C and 10% pomace.

Feed moisture has been found to be the main factor affecting extrudate density and expansion [15, 25–27]. With an increased feed moisture content during extrusion due to plasticization of the melt may reduce the elasticity of the dough. This promote to in reduce SME and therefore reduced gelatinization, decreasing the expansion and increasing the density of extrudate.

It was observed that extrudate density is inversely affected with an increase in screw speed. Increase in screw speed lowers the melt viscosity of the mix increasing the elasticity of the dough, resulting in a reduction in the density of the extrudate [25]. An increase in the barrel temperature will increase the degree of superheating of water in the extruder encouraging bubble formation and also a decrease in melt viscosity [25] leading to reduced density. Similar results have been observed by Mercier and Feillet [28]. The bulk density of extrudate increased with decreasing expansion ratio. Expansion and bulk density are also related to starch gelatinization [29]. According to these authors, an increase in gelatinization increased expansion and decreased bulk density.

3.3. Water absorption index (WAI) and water solubility index (WSI)

The WAI measures the amount of water absorbed by starch and can be used as an index of starch gelatinization [23, 30, 31]. WSI, often used as an indicator of degradation of molecular components [32], measures the amount of soluble components released from the starch after extrusion. When extruded products mixed with water, this mixture will often swell. Out of that a portion of material will become soluble. Water solubility and absorption are often important in predicting the extruded material behaviour if further processed [33].

Water absorption index indicates the amount of water immobilised by the extrudate, while water solubility indicates the amount of small molecules solubilised in water so process molecular damage. Anderson et al. [30] recorded a method to estimate the amount of material that can be extracted by water from an extruded product. The materials which are soluble include gelatinized starch; undenatured globular proteins, inorganic ions and small sugars [33]. The WSI increased significantly when screw speed increased from 200 to 300 rpm for wheat extrudates and from 300 to 500 rpm for corn extrudates [34]. The WSI is indeed related to the degree of starch transformation. The unprocessed flours exhibited values of WSI less high than those of final products (for corn flours). Consequently, the WSI increased because starch granules were then more soluble in water [35].

WAI increased with extrusion temperature and feed moisture content for corn and corn-lentil extrudates [36]. The WAI measures the amount of water absorbed by starch and can be used as an index of gelatinization, since native starch does not absorb water at room temperature [30, 31, 37]. Extrusion temperature and moisture content are known to affect gelatinization during extrusion, and consequently the WAI. In high moisture soy meat analog, WAI increased with increase in extrusion temperature and feed moisture [38, 39]. Similar results were reported for corn starch extrudates, bean and chickpea extrudates [40, 41].

Furthermore, dextrinization is well known as the predominant mechanism of starch degradation during low moisture extrusion. Therefore, the decreasing trend of WSI with feed moisture content is expected and in agreement with previous reports [23, 42].

3.4. Product moisture

Product moisture was found to be directly related to feed moisture and inversely related to extrusion temperature [43]. After drying at 60°C for 12 h of starch-PDPF extrudates, the moisture content was found to be very low nearly 0.5% which expected to yield products with a high degree of crispness. After drying of extrudates the Water activity dropped down from 0.1 to 0.33 that would be advantageous with regard to the stability of the extrudate against microbial growth.

Moisture is having significant on product quality attributes such as expansion and degree of cook (absorption and solubility indices) [32]. It is necessary to adjust the water content carefully to result in expansion with whey incorporated products. Increased structural binding of water may have reduced moisture available for flash-off and consequently reduced expansion [44].

3.5. Specific mechanical energy (SME)

The specific mechanical energy (SME) is responsible for fragmentation of starch molecules [21, 45, 46]. Amylopectin molecules are broken mainly at the α–1:6 bonds due to the applied shear forces. This phenomenon was attributed to the decrease in the viscosity with the increase in water content [21, 45]. The degradation products are macromolecules in the range of 50,000–200,000 MW [46, 47].

An additional effect of SME on starch is the gelatinization process that takes place during extrusion [21, 45, 46]. The degree of gelatinization would be with the higher value of SME. In contrast to the effect of water on macromolecule fragmentation, gelatinization of starch is more intense at higher water content.

Mercier et al. [4] reviewed that SME input also depends on the exact composition of the product being extruded and increases with starch content. A general result is that SME increases when water content decreases in both single screw and twin screw [44].

3.6. Effect of extrusion on nutritional constituents

3.6.1. Proteins

Proteins are a group of highly complex organic compounds that are made up of a sequence of amino acids. Protein nutritional value is dependent on the quantity, digestibility and availability of essential amino acids [40].

Several changes occur during extrusion of which denaturation is undoubtedly the most important. Extrusion may improve protein digestibility by denaturating proteins and exposing enzyme-accessible sites [37, 48, 49]. Enzymes and enzyme inhibitors generally lose activity due to denaturation. Protein digestibility value is higher for non-extruded products. The possible cause might be the denaturation of proteins and inactivation of anti-nutritional factors that impair digestion. The extensive studies have been done and reported on the effects of extrusion on protein nutrition especially for animal feeds and for human weaning foods [50]. The extrusion operations have very little effect on the protein denaturation [51]. Maillard reactions occur during extrusion particularly at high barrel temperature, low moisture, and high shear. All processing variables have different effects on protein digestibility. High shear extrusion conditions in particular promote denaturation [52], although mass temperature and moisture are also important factors. In a model system of wheat starch, glucose and lysine, low pH favours Millard reactions, as measured by increased colour [53].

Cooking extruders for processing high-protein materials into palatable foods is very common today. Many new applications have been developed for protein extrusion during the past decade. Improvements in functional characteristics of proteins may be achieved through modification of temperature, screw speed, moisture content, and other extrusion parameters.

3.6.2. Vitamins

During extrusion process due to vast deviation of chemical structure and composition of vitamins, there is variable change in variety. The extent of degradation depends on different process parameters and storage conditions such as moisture, temperature, light, oxygen, time and pH [54, 55].

Among the fat-soluble vitamins, vitamins D and K are fairly stable [56]. In food extrusion process the thermal degradation is the major factor contributing to β-carotene losses [57].

Pham and Del Rosario [58] and Guzman-Tello and Cheftel [59] studied the effects of high temperature, short-time extrusion cooking on vitamin stability and developed different mathematical models.

In extrusion cooking there is inverse relation between the retention of vitamins and temperature, screw speed and specific energy input, whereas direct relation with moisture, feed rate and die diameter.

3.6.3. Iron and zinc

During extrusion cooking the mineral contents are generally retained well. During single screw extrusion of potato flakes with increase in barrel temperature there is increase in, iron content [60]. Total iron increased by as much as 38% due to extrusion [61]. On the other hand, after twin screw extrusion cornmeal (having low dietary fibre content) had no changes in total, elemental, or soluble iron [55].

Utilisation of iron and zinc from wheat bran and wheat in adult human volunteers was not affected by extrusion [62]. Low-shear extrusion retained dialysable iron in navy beans, lentils, chickpeas and cowpeas better than did high-shear extrusion [63]. Weaning food blends of pearl millet, cowpea and peanut had greater iron availability and protein digestibility compared to similar foods processed by roasting [64].

3.7. Antinutrient factors

3.7.1. Antinutrients

Extrusion cooking also improves the nutritional quality of foods by destroying many natural toxins and antinutrients (**Table 1**). A dilemma exists as to whether it is desirable to remove these compounds. Enzyme inhibitors, hormone-like compounds, saponins and other compounds could impair growth and development in children, but these same compounds may offer protection against chronic diseases in adults.

3.7.2. Phenolic compounds

Extrusion of soy protein concentrate and a mixture of 80:20 of cornmeal and soy protein concentrate (80:20) did not result in changes in total isoflavone content [65]. In potato peels

Compound	Foods	Factors favouring reduction
Allergens	Peanuts, soy	Increased shear; added starch
Glucosinolates	Canola	Added ammonia
Glycoalkaloids	Potato	Added thiamine
Gossypol	Cottonseed	Higher feed moisture
Mycotoxins	Grains	Increased mixing, lower temperatures; added amine sources
Protease inhibitors	Legumes, potato	Higher extrusion temperature

Table 1. Antinutrients and toxins affected by extrusion cooking.

produced by steam peeling during extrusion the total free phenolics, primarily chlorogenic acid, decreased significantly [55]. More phenolics were retained with higher barrel temperature and feed moisture. It might be possible that lost phenolics reacted with themselves or with other compounds to form larger insoluble materials. The total antioxidant activity value of samples decreased with an increase in screw speed and decrease in moisture content, while total phenolic values had insignificant (95% confidence interval) changes after extrusion. In a model breakfast cereal, containing cornmeal and sucrose, anthocyanin pigments were degraded at higher levels of added ascorbic acid, and total anthocyanins significantly decreased by extrusion [66].

Many opportunities exist for product development research in extrusion. Although several studies have been conducted on determining the effect of raw material combination and process parameters on physic-chemical characteristics of direct expanded snacks as well as their storage studies. Very little has been published on the effects of extrusion on phytochemicals and other healthful food components, in part due to the need for identification of active principles and suitable analytical procedures. Evaluations of nutrient retention by either high-moisture extrusion or by supercritical fluid extrusion have yet to be published. Improved understanding of scale-up issues in extrusion is necessary for valid interpretation of studies conducted using laboratory-scale and pilot plant extruders. Long-term animal and feeding studies are tedious and costly, yet essential for demonstrating safety and efficacy of extruded foods.

4. Conclusions

Extrusion cooking is one of the most important food processing technologies which have been used for the production of breakfast cereals, ready to eat snack foods and other textured foods. Now a days extrusion cooking is a widely used technology in the agri-food processing industry. Therefore adopting such skill can provide the good opportunity to the snack industries for developing large variety of food snacks. It is a popular unit operation for producing a variety of food products with numerous ingredients requiring a wide range of processing conditions and includes starch, protein, lipids, water and additives. There are ambiguous effects of extrusion cooking on nutritional quality of expanded snacks. Because of its beneficial effects such as destruction of antinutritional factors, increased soluble dietary fibres, reduction of lipid oxidation and contaminating microorganisms, it plays an important role in the production of a wide variety of foods and ingredients. Extrusion cooking being a complex multivariate process, to maintain the product quality requires careful control on the process. Severe extrusion conditions and improper formulation which are not suitable for process may cause nutritional destruction in the hot-screw segments. Generally, to maintain high nutritional quality, high extrusion temperature (≥200°C) and low moisture content (≤15%) of the feed should be avoided. There are many areas that require further research regarding extrusion and nutrition. Future research may be focussed on the relationships between compositional changes on product quality-both nutritional and sensory aspects, and the effects of interactions between complex extruder conditions on nutrient retention.

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