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REVIEW ARTICLE

# Extrusion Cooking Technology for Foods: A Review

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## Abstract

Extrusion-cooking is increasing popularity in the global agro-food processing industry, particularly in the food and feed sectors. Extrusion cooking is a high-temperature, short-time process in which moistened, expansive, starchy and protenacious raw material is used. Food materials are plasticised and cooked in a minute by a combination of moisture, pressure, temperature and mechanical shear, resulting in molecular transformation and chemical reactions. It is reduces the microbial count and inactivates the enzymes. It is a multi-step, multi-function thermal or mechanical process, has permitted a large number of food applications. Beneficial changes in the bioavailability as well as in the content of nutrients may take place during extrusion. The mechanisms underlying these changes as well as the influence of process conditions and food mix composition. Special importance is placed on the physico-chemical and chemical modifications of protein, starch and dietary fibre. Extrude product can be categorized for a particular application depending on their functional properties such as water absorption and water solubility index, expansion ratio, bulk density and viscosity of the dough.

**Keywords:** Extrusion system, Raw Ingredients, Extruded foods, Packaging and storage.

## 1. Introduction

Extrusion cooking technology, a high temperature short time (HTST) processing being used increasingly in the food industries for the development of new products such as cereal based snacks, including dietary fiber, baby foods, breakfast cereals and modified starch from cereals (Sebio and Chang, 2000; Pardeshi and Chattopadhyay, 2014; Pawar *et al.*, 2014). As it is a HTST process, which reduces microbial contamination and inactivates enzymes, the main method of preservation of both hot and cold extruded foods is by the low water activity of product (0.1-0.4) (Bordoloi and Ganguly, 2014). The thermal energy generated by viscous dissipation extruded with combination of shearing effect cooks quickly the raw mixture so that the properties of the materials are modified by physicochemical changes of the biopolymers (Thymi *et al.*, 2005).

This technology becomes a widely used in the agri-food processing industry, where it is referred to as extrusion-cooking (Moscicki and Zuilichem, 2011). 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. Extrusion of starchy foods resulted in gelatinization of starch, denaturation of protein and formation of complexes between starch: lipids and between proteins:lipids (Mercier and Feillet, 1975). Changes in the properties of starchy foods caused by the addition of lipids are attributed to the formation of complexes between amylase and lipids. The complexes between starches and lipids are due to the ability of the amylase fraction of starches to bind lipids such as fatty acids (Bhatnagar and Hanna, 1994). The extrusion cooking, especially used in the production of precooked and modified starches, ready to eat cereals, infant formulae and snack foods has increased recently. The native starch undergoes substantial changes leading to a greater molecular disorganization during extrusion cooking. As per the perspective of finished product texture is concern, the starch loses its relative crystallinity, undergoes molecular fragmentation and often complexes with lipids in the mixture.

The role of shear, temperature, moisture and feed composition are significant in the transformation of starch by extrusion (Harper, 1986). It has become an important technique in an increasing variety of food processes. The benefits of this technology are it is a low cost, variability of product shape, high quality production of new foods, higher productivity, inactivation of anti-nutritional factors etc (Chakraborty *et al.,* 2009). Feed moisture is one of the most critical processing variables for extrusion cooking because it contributes to thermo-mechanical liquefaction and gelatinization of starch (Gomez and Aguilera, 1984). Cereals and tuber starches undergo several physicochemical changes during extrusion cooking (Mercier and Feillet, 1975). The extent of molecular degradation of starch is a function of extrusion parameters like temperature, moisture, feed rate, screw speed (Davidson *et al.,* 1984) and feed composition (Faubian and Hoseney, 1982). In cereal-based products, the degree of starch processing is all important for major quality aspects such as taste, digestibility, texture and appearance. Low pressure extrusion, at temperature below 100°C, is used to produce fish paste, surimi and pet foods. Extrusion cooking is a continuous process with high production capacity, versatility and low cost per product unit (Colonna *et al.,* 1984).

## 2. Types of Extrusion System

The use of thermoplastic extrusion in food processing is facilitated by the dynamism of extruders, which can be divided into two types: single-screw and twin-screw extruders (Riaz, 2000). A variety of extruders with different configurations and performances have been developed and they are categorised based on their applications, design and configurations.

Extruders are composed of five main parts: (i) the pre-conditioning system; (ii) the feeding system; (iii) the screw or worm; (iv) the barrel; (v) the die and the cutting mechanism. They can vary with respect to screw, barrel and die configuration. The selection of each of these items will depend on the raw material used and the final product desired (Riaz, 2000). Fig 1 shows the schematic representation of an extruder including its main parts and zones. The food (melt) is fed at one end of a tubular structure housing the screw. Inside this housing the melt is worked upon to form a semi solid mass. The semi solid mass is forced through a restricted opening (die) at discharge end of the screw. The food comes out expands as it touches the atmosphere. This expansion is because of the bubble growth in the semi solid mass because of the moisture that it contains (Kokini *et al.,* 1992). The expanded product is the extrudates can be consumed as it is, or after desirous processing. Fig 2 shows the bubble growth in the melts at the die exit.

Single-screw extruders are the most common extruders applied in the food industry. The classification of single-screw extruders can be defined based on process or equipment parameters such as: moisture content (dry or wet) conditioning, solid or segmented screw, desired degree of shear and heat source. From a practical point of view, the main classification used considers the degree of shear and the heat source (Riaz, 2000). The screw configuration comprises there are screws made up of only one piece or screws of multiple pieces.

Twin-screw extruders are composed of two axis that rotate inside a single barrel, usually the internal surface of the barrel of twin-screw extruders is smooth. Depending on the position of the screws and their direction of rotation, four different types of configurations are possible: (i) co-rotating intermeshing screws; (ii) co-rotating non-intermeshing screws; (iii) counter-rotating intermeshing screws; and (iv) counter-rotating non-intermeshing screws. Although intermeshing screws result in greater residence time of the material in the extruder, non-intermeshing screws cause greater degrees of shear, especially if they rotate in opposite directions. However, twin screw type of extruder is little used in the food industry, even though they present more efficient displacement properties (Steel *et al.,* 2012).

### 2.1 Extruder Variables

Screw speed, barrel temperature, screw and barrel configuration, die opening and feed rate are some of the parameters that affect the extruded performance. Extruder operation depends on pressure build up in the barrel (prior to exiting the die), slip at the barrel wall (transportation), and the degree of filling. The screw speed is responsible for the rate of shear development and the mean residence time of the feed. The heat dissipation from the mechanical energy input to dough depends on screw speed, which in turn influences dough viscosity. The feed zone temperature must be low to avoid plugging and back flow of material travel down the screw. The barrel temperature has positive effect on the degree of starch gelatinisation and extruded expansion whereas it has a negative effect on product colour especially at elevated temperature. Several studies have indicated that elevated temperature leads to more moisture evaporation when exiting the die and thus results in more expanded products (Muthukumarappan and Karunanithy, 2012). Extruder feedrate depends on the types of screw element, screw speed, type of feeding element and feed moisture. The federate has an influence on residence time, torque requirement, barrel pressure and dough temperature.

### 2.2 Feed Ingredient Variables

Feed composition, moisture content and particle size have the greatest effect on extrusion. The typical composition of any blend consists of starch, protein, -

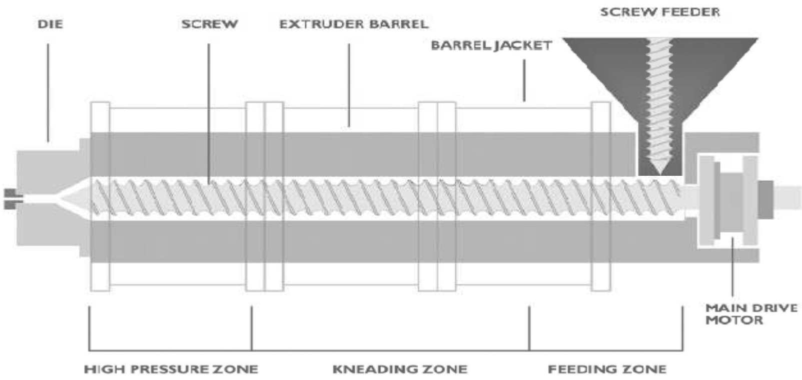
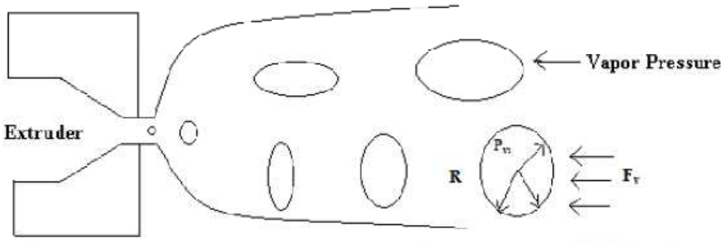



Fig 1: Schematic representation of an extruder including its main parts and zones.




$P_{vs}$ = vapor pressure, $F_v$ = residence due to melt viscosity and R=bubble radius

Fig 2: Bubble growth in the melt at the die exit.

lipid/fat and fiber which contribute the product quality. The starch degradation usually reduces products expansion. The infant and weaning foods have high starch digestibility which is largely dependent on full gelatinisation (Camire, 2000). The lipid levels over 5-6% acts as a lubricant, reducing the slip within the barrel and resulting in poor product expansion. The fibers are the non interacting component that contributes to low expansion, cohesiveness, durability and water stability. Higher fiber content usually results in high screw wear.

The moisture is critical variable that has multiple fractions in starch gelatinization, protein denaturation, barrel lubrication and the final product quality. A dry extruder can process materials with 8-22% moisture with no additional drying of extrudates. Most extrudates snacks have moisture content between 8-12% and require additional drying to impart desired texture and mouthfeel (Rokey, 2000).

General rule of thumb that the extruder feed should not have particles larger than one third the diameter of die holes. Particle size also plays an important role in moisture distribution, heat transfer, viscosity and final product. Quality course ingredient particles have more effect on wear than fine particles. A product composed of fine particles will have good water stability, water absorption index, expansion (Riaz, 2000).

### 2.3 Sources of Raw Material in Extrusion Cooking

The most used raw materials in the extrusion process are starch and protein based materials. This technique has been widely used with raw materials such as corn, wheat, rice and soybean. Natural biopolymers of raw materials such as cereals or tuber flours are rich in starch, or oilseed legumes and other protein rich sources. Most commonly used materials are wheat and corn flours, but many other materials are also used such as rice flour, potato, rye, barley, oats, sorghum, cassava, tapioca, buckwheat and pea flour. The protein rich materials such as pressed oilseed cake from soya, sunflower, rape, field bean, fava beans or separated proteins from cereals such as wheat (guten) (Guy, 2001). Expanded (Ready to Eat) RTE cereals are manufactured from mixtures of cereal flours and starches combined with small amounts of malt, fat, sugars, emulsifiers, and salt. The raw materials in the extrusion cooking processes cover various combinations of ingredients including: cereals, grains and starches, tubers, legumes, oil seeds, cereals as well as animal fat and proteins (Ilo *et al.*, 2000). The main characteristics of the raw material for extrusion cooking are type of material, moisture content, physical state, chemical composition (quantity and type of starch, proteins, fats and sugars) and pH of the material. Most raw materials used in food extrusion are solid (Steel *et al.*, 2012). The structure of the extruded products may be formed from starch or protein polymers. Most products, such as breakfast cereals, snacks and biscuits are formed from starch, while protein is used to produce products that have meat-like characteristics and that are used either as full or partial replacements for meat in ready meals, dried foods and many pet food products (Guy, 2001). Typical raw materials used in the popular extruded products, each of which offers a wide variety of functions: structure-forming, facilitating physical transformation during the extrusion-cooking, affecting the viscosity of the material and its plasticization, facilitating homogeneity of the dough ingredients, accelerating starch melting and gelatinization and improving the taste and colour of products (Moscicki, 2011). Further, ready to eat breakfast was successfully developed using the low-amylose rice flour incorporated with seeded banana powder in a single-screw extruder (Borah *et al.*, 2015). Dhumal *et al.* (2014) developed cold extrudate, microwave puffed and oven toasted low fat ready to eat fasting foods successfully using potato and barnyard millet. Table 1 shows the sources of raw materials used by the different researches for extrusion Cooking.

### 2.4 Role of Starch in Extrusion Cooking

Extrusion cooking may have both beneficial and undesirable effects on nutritional value. Beneficial effects include gelatinisation of starch, destruction of antinutritional factors, increased soluble dietary fibres, reduction of lipid oxidation and contaminating microorganisms and retains natural colours and flavours of foods (Nikmaram *et al.*, 2015). Among all flour components, starches play a key role during extrusion cooking. Starch undergoes several significant structural changes, which include gelatinization, melting, and fragmentation (Lai and Kokini, 1991). Starch is a carbohydrate composed of chain of glucose molecule. Potato, corn and rice are the major sources for starch but they are also used as a food (Karmakar *et al.*, 2014). Roots contain starch ranging from 73.7 to 84.9 % of the root dry weight. Starch is one of the most important raw materials in the food industry because of its properties are a low gelatinization temperature (71°C), a low tendency to retrograde, no residual proteinaceous materials or soil residues, non cereal flavor, high viscosity, high water binding capacity, bland taste, translucent paste and relatively good stability (Sriburi *et al.*, 1999). Native starch undergoes substantial changes leading to greater molecular disorganization during extrusion cooking. Most importantly from the perspective of finished product texture, the starch loses its relative crystallinity, undergoes molecular fragmentation, and often complexes with lipids in the feed texture. The role of shear, temperature, moisture and feed composition are significant in the transformation of starch by extrusion (Gonzalez and Perez, 2002). The starch granule consists of two different glucose polymers: amylose and amylopectin, which are responsible for its physicochemical and functional properties. Inside the extruder, starch undergoes through several stages. First, the initial moisture content is very important to define the desired product type. Inside the extruder have relatively high temperatures, the starch granules melt and become soft, besides changing their structure that is compressed to a flattened form (Guy, 2001). The application of heat, the action of shear on the starch granule and water content destroy the organized molecular structure, also resulting in molecular hydrolysis of the material (Mercier *et al.*, 1998). The final expanded product presents air cells that are formed due to superheated water vapour pressure. When the temperature of the extrudate is reduced below its glass transition temperature, it solidifies and maintains its expanded form (Riaz, 2000). The main parameters that influence these reactions, such as shear forces, residence time and shear rate. They defined by the geometry of the extruder as well as the processing variables, such as temperature, screw speed, feed composition (such as amy1ose:amylopectin ratio) and moisture content (Meuser and van Lengerich, 1984a-b). Order-disorder transitions usually occur over a range of temperatures. As dough's temperature exceeds the transition threshold temperature, the starch molecules begin to undergo various disordering reactions that affect their size and shape. Since rheological properties are related to the size and shape of a fluid's molecules. It seems logical to assume that these molecular changes within starch will greatly affect their rheological properties (Lai and Kokini, 1991).

## 3. Feed Constituents or Ingredients Used in Extrusion Cooking

### 3.1 Starch

Starch is the main component; it provides the underlying structure (Guy, 2001). Starch granules are gelatinized and dispersed during extrusion, resulting in the formation of a continuous phase of the melt inside –

Table 1: Raw material used by different researchers for extrusion cooking

| S. No. | Raw material | Researcher (s) |
|---|---|---|
| 1 | Cassava, maize and wheat flour | Fayose *et al.* (2015) |
| 2 | Wheat, mungbean and groundnut | Pathania *et al.* (2013) |
| 3 | Water yam starches | Oke *et al.* (2013) |
| 4 | Rice-Sweet potato and rice-yam | Hazarika *et al.* (2013) |
| 5 | Broken rice flour, pineapple waste pulp powder and red gram powder | Kothakota *et al.* (2013) |
| 6 | African yam bean and cassava flour | Omeire (2012) |
| 7 | Pearl millet | Singh and Devi (2011) |
| 8 | Tef, corn and soy protein isolated blends | Forsido and Ramaswamy (2011) |
| 9 | Corn, millet and soybean | Semasaka *et al.* (2010) |
| 10 | Carrot pomace, rice flour and pulse powder | Kumar *et al.* (2010) |
| 11 | Arrowroot starch | Jyoti *et al.* (2009) |
| 12 | Barnyard millet and red gram | Chakraborty (2008) |
| 13 | Defatted soy flour and rice | Garg (2005) |
| 14 | Corn grits | Arhaliass *et al.* (2003) |
| 15 | Lentil based snacks | Banerjee *et al.* (2003) |
| 16 | Cassava starch | Chang and Dash (2003) |
| 17 | Rice and moong flour | Jha and Prasad (2003) |
| 18 | Faba bean and rice | Singh (2003) |
| 19 | Soy and maize | Singh *et al.* (2003) |
| 20 | Lentil starches | Gonzalez and Perez (2002) |
| 21 | Defatted chick pea, corn and bovine lung flour | Cardosa *et al.* (2001) |
| 22 | Full fat soy flour (FFSF) and cereal or pulse flour | Deshpande *et al.* (2001) |
| 23 | Broken rice and corn grits | Boonyasirikool and Charunch (2000) |
| 24 | Mustered oil and rice grits | Kaur *et al.* (2000) |
| 25 | Faba beans | Rajawat *et al.* (2000) |
| 26 | Yam flour | Sebio and Chang (2000) |
| 27 | Potato and wheat flour | Bhattacharya *et al.* (1999) |
| 28 | Rice flour and amaranth | Llo *et al.* (1999) |
| 29 | Soy flour and maize | Adesina *et al.* (1998) |
| 30 | Garbanzo bean, lentil, whole peas and split peas | Berrios *et al.* (2008) |
| 31 | Soybean-sweet potato mixture | Iwe *et al.* (1998) |
| 32 | Rice and chick pea | Bhattacharjee *et al.* (1997) |
| 33 | By product from wheat mill with yellow corn, wheat starch and isolated soy protein | Breen *et al.* (1997) |
| 34 | Wheat starch, whole wheat meal and oat flour | Smith and Singh (1996) |
| 35 | Maize grits | Llo *et al.* (1996) |
| 36 | High moisture fish and soy protein | Maryse *et al.* (1996) |
| 37 | Wheat/ rice semolina and potato grits | Singh *et al.* (1996) |
| 38 | Soyabean meal | Ling and Chou (1995) |
| 39 | Barley and rice flour, wheat flour | Berguland *et al.* (1994) |
| 40 | Soyabean and sorghum flour | Patil *et al.* (1992) |
| 41 | Wheat flour, rosted Bengal gram, green gram, ground nut, jowar, skimmed milk powder and jaggery | Tabitha *et al.* (1992) |
| 42 | Rice and soyabean residues | Wu and Chiang (1991) |
| 43 | Maize | Hazel and Johnson (1989) |
| 44 | Full fat soy flour | Hovarth *et al.* (1989) |
| 45 | Corn starch | Chinnaswamy and Hanna (1988) |
| 46 | Sorghum varieties | Fapojuwo *et al.* (1987) |

the extruder. Both amylose and amylopectin are needed to give the best expansion characteristics (Huber, 2001). Starch granules undergo gelatinization and melting by the action of heat and moisture on hydrogen binding among tightly packed polysaccharide chains in the granule structure (Jaybhaye *et al.*, 2014). Under conditions of excess water, hydrogen bindings in the less ordered amorphous regions of the granule are disrupted first and allowing water to associate with free hydroxyl-groups. Swelling is the result and further opening of the granule structure to the action occurs. Melting of the crystalline fraction results in complete disappearance of refringence, which is irreversible. Complete starch gelatinization is generally achieved at temperatures of less than 120°C, moisture of 20- 30% or even at lower moisture levels (10-20%), provided high shear and temperatures are reached during extrusion (Cheftel, 1986).

Holm et *al.* (1985) showed a close relationship between degree of gelatinization of wheat starch suspensions and rate of hydrolysis by amylase *in vitro,* as well as by blood glucose responsive rats. Both *in vitro* and *in vivo* digestibility of starch could be enhanced by extrusion and the degree to which this effect is produced is controlled by the severity of the extrusion process (Serrano, 1997).

### 3.1.1 Sources of Starches

The majority of product in the breakfast cereal, snack food and biscuit markets are formed from starch. The main sources of starch are cereal and potato crop. There may be some other crops such as cassava or sago that are also a good source of starch and large cereal crops are the most economic source of starch (Guy, 2001). Starch is contained in a large variety of plant crops, such as cereals (50-80% db starch), legumes (25-50% db), and tubers (60-95% db) (Colonna *et al.*, 1998). The three major cereals in order of world production are wheat, rice and maize and other important crops are barley, rye, oats and sorghum (Guy, 2001).

## 3.2 Water

Water is an important medium in extrusion. It is needed for starch gelatinization and ingredient dispersion. In the formation of a viscous fluid, it is conveyed and cooked. Moisture is always listed as a separated variable in addition to feed ingredients because it is often controlled separately in the extruder. Moisture can be added directly to the feed, injected into the barrel, or added in the form of steam to the pre-conditioner or barrel; it will also affect the temperature of the feed material (Yu, 2011).

## 3.3 Protein

Soybeans, oilseeds and legumes provide a good example of improved protein digestibility and bioavailability of sulphur amino acids. Thermal unfolding of the major globulins, thermal inactivation of trypsin inhibitors and other growth-retarding factors such as lectins. Extensive lysine loss can take place when legume or cereal legume blends are extruded under severe conditions of temperature (≥ 180 °C) or shear forces (>l00 rpm) at low moisture (≤15%), especially in the presence of reducing sugars (23% glucose, fructose, maltose, lactose) (Bjorck and Asp, 1983). It is not fully understood whether the damaging effects at low water contents are due to local temperature increases through intense shear forces, to specific mechanical effects, to an enhancing effect of low moisture on the maillard condensation or to a combination of these effects (Serrano, 1997).

In extrusion the protein helps to form a continuous structure from the oilseed such as soyabean, sunflower and cottonseed. Structure created by protein is similar to starch in that the proteins must be dispersed from their native bodies into a free flowing continuous mass (Guy, 2001).

## 3.4 Fibre

Fiber has the nutritive value in food products and it has been connected with a 14 healthy modern diet. Fibrous materials such as bran can be part of the dispersed phase of extruded products, included in the starchy continuous phase (Guy, 2001). Fiber is chemically unchanged by the extrusion process and influences the expansion of the product (Huber, 2001).

Modifications in particle size, solubility and chemical structure of the various fiber components could occur during extrusion-cooking. Due to this cause changes in bacterial degradation in the intestine and in physiological properties. Extrusion-cooking of white wheat flour (161-171 °C; 15% moisture) was found to cause a redistribution of insoluble to soluble dietary fiber. Thus 50-75% of total fibers were soluble in the extruded flour depending on process conditions versus 40% in the raw flour. Relative fiber solubilization was smaller in the case of extruded whole grain wheat flour (Bjorck *et al.*, 1984).

## 3.5 Lipids

Lipids have two functions in extrusion process; they can influence the quality of the product and act as a lubricant during the process. Most of the lipids will melt at 40ºC. When the moisture of the material is lower than 25%, the addition of 0.5-1% lipids will greatly reduce the energy input needed for extrusion. When oil content rises up to 2-3%, it can have undesirable effects, such as reducing the extrudate expansion (Yu, 2011).

Extrusion-inactivation of lipase and lipoxidase helps protect against oxidation during storage. Higher temperatures reduce the lipase activity and moisture level, thereby decreasing favoring free fatty acids development. The expanded porous nature of the extrudate causes the feed to be susceptible to the development of oxidation during storage, even though deterioration due to extrusion may not be immediately apparent (Serrano, 1997). The nutritional value of lipids could be affected during extrusion as a result of oxidation, hydrogenation, isomerization or polymerization. The amount of hydrogenation and cis-trans isomerization of fatty acids that takes place during extrusion is too small to be nutritionally significant (Camire *et al.,* 1990).

### 3.6 Additives

Additives are also important in the makeup of the final product. Their reactions during the extrusion process can greatly affect the flavor or color of the product. Flavoring or coloring agents are mixed into the product and confer a different appearance to the product during the process. Additives used for increasing expansion and cell wall formation or swelling are termed nucleating agents. They include sodium bicarbonate and calcium carbonate. Monoglycerides are commonly used in commercial operations (Guy, 2001) as surfactants (lubricants).

## 4. Role of Ingredients in Development and Formulation of Structure and Texture in Extruded Product

In extrusion cooking, changes in ingredients such as sugar, salt, fibre or processing parameters like screw speed and temperature can affect extrusion system variables and product characteristics such as texture, structure, expansion and sensory attributes. The most commonly used cereals in extruded are rice, wheat, oats and corn. For formulation of extruded mixture of these cereals can be used, in the form of flours, grits and whole grain flours. They can also be mixed with other ingredients such as starches, sugar, salt, malt extract or other liquid sweeteners, heat stable vitamins and minerals, flavourings, colorants and water, to vary appearance, texture, taste, aroma and other product characteristics (Riaz, 2000). Traditional snacks or breakfast cereals can be enhanced by the addition of extra fibres or whole grain flour as ingredients during extrusion, transformed into palatable cereal-based products that also promote beneficial physiological effects. Functional ingredients such as soy, and botanicals (fruit, vegetables, cereals, etc.) that present high amounts of bioactive compounds can be used in the extrusion process to develop novel products with phytochemicals and other healthful food components (Steel *et al.,* 2012).

## 5. Effect of Ingredients, Process Parameters on Quality of Extruded

### 5.1 Nutritional Properties

#### 5.1.1 Protein and Amino Acid Profile

Extrusion cooking condition significantly increased the protein digestibility. Table 2 shows the effect of processing variables on protein digestibility of extrudates prepared from various sources.

Lysine is the most limiting essential amino acid in cereal-based products, which are the majority of extruded products. Thus a focus on lysine retention during the extrusion process is of particular importance (Iwe *et al.,* 2004). Table 3 shows the effect of process variables on the lysine retention of extrudates prepared from various sources.

#### 5.1.2 Carbohydrates

***5.1.2.1 Sugar***

Sugars such as fructose, sucrose and lactose, are a great source of quick energy. They provide sweetness and are involved in numerous chemical reactions during extrusion. Control of sugars during extrusion is critical for nutritional and sensory quality of the products. It is reported that sugar losses in extrusion. It may be explained based on the conversion of sucrose into glucose and fructose (reducing sugars) and loss of these reducing sugars during Maillard reactions with proteins. The destruction of these flatulence-causing oligosaccharides might improve the nutritional quality of extruded legume products (Singh *et al.,* 2007).

***5.1.2.2 Starch***

During extrusion, starches are subjected to relatively high pressure (up to $10^3$ psi) (Lai and Kokini, 1990), heat and mechanical shear forces. Starch is a polysaccharide made up of glucose units linked together to form long chains. There are two types of starch molecules, amylose and amylopectin. In extrusion, amylose and amylopectin molecules contribute to gel formation and viscosity to the cooked paste respectively. Low die temperature and feed moisture significantly reduced the average starch molecular weight in wheat flour (Singh *et al.,* 2007).

***5.1.2.3 Dietary Fibre***

Extrusion reduces the molecular weight of pectin and hemicellulose molecules, resulting in increased water solubility of sugar beet pulp fibre. Insignificant changes in dietary fibre content in twin-screw extrudates. Increase in dietary fibre content of wheat flours with increasing product temperature (150-200 °C) was reported. Extrusion cooking increased the total dietary fibre of barley flours. The total dietary fibre increase in waxy barley was the result of an increase in soluble dietary fibre (Vasanthan *et al.,* 2002).

***5.1.2.4 Lipids***

Table 2: Effect of processing variables on protein digestibility

| S. No. | Processing parameter | Protein digestibility | Food source | References |
|---|---|---|---|---|
| 1 | Extrusion Temperature | Increased with increasing extrusion temperature | Starches<br>Protein Rich Products | Singh *et al.* (2007)<br>Maurya and Said (2014) |
| 2 | Moisture content | Decreased with increase in moisture content, | Pasta made from rice enriched with soybean by extrusion cooking | Liceti *et al.* (1995) |
| 3 | Process temperature | Increased with increasing extrusion temperature | Corn gluten–whey blends, sorghum and fish–wheat blends | Fapojuwo *et al.* (1987);<br>Bhattacharya and Hanna (1985);<br>Bhattacharya *et al.* (1988) |
| 4 | Feed ratio | Increased with increasing animal protein | Fish and wheat flour | Bhattacharya *et al.* (1988); Camire *et al.* (1990) |
| 5 | Screw speed | Insignificant effect<br>Increased with increasing screw speed | Fish and wheat flour<br>Corn gluten–whey blend | Bhattacharya *et al.* (1988)<br>Camire *et al.* (1990) |
| 6 | Length to diameter ratio | Insignificant effect | Fish and wheat flour | Bhattacharya *et al.* (1988) |

Table 3: Effects of processing variables on lysine retention

| S. No. | Processing parameter | Effect on lysine Retention | Food source | References |
|---|---|---|---|---|
| 1 | Barrel temperature | Decreased with increasing barrel temperature | High protein glutinous rice-based snack<br>Protein Rich Products | Chaiyakul *et al.* (2009)<br>Maurya and Said (2014) |
| 2 | Screw speed | Increased with increasing screw speed | Defatted soy flour and sweet potato flour mixture | Iwe *et al.* (2004) |
| 3 | Die diameter | Decreased with increasing die diameter | Defatted soy flour and sweet potato flour mixture | Iwe *et al.* (2004) |
| 4 | Feed rate | Increased with increasing feed rate | Wheat flour | Bjorck and Asp (1983) |
| 5 | Feed moisture | Decreased with increasing moisture | Cowpea and mung bean | Pham and Del Rosario (1984) |

During the extrusion of foods, native lipids might be present within the raw materials or added to the ingredients. Torque is decreased because the lipid reduces slip within the barrel and often product expansion is poor because insufficient pressure is developed during extrusion. Lipid is released from cells owing to the high temperature and physical disruption of plant cell walls (Singh *et al.*, 2007).

## 5.2 Functional Properties

Typical extrusion conditions vary depending on the type and amount of starches used. Generally, the temperature in the extruder's cooking and forming zones will be 80-150° C and 65-90° C respectively. Extrusion moisture contents range from 25 to 30%, with a residence time of 30-90 s (Huber, 2001). These conditions will change the physical and chemical properties in addition to nutritional and sensory attributes, resulted in changing the product quality. The physical properties include expansion ratio, bulk density, hardness, color, water absorption index (WAI), water solubility index (WSI) and pellet durability index (PDI) (Muthukumarappan and Karunanithy, 2012).

### 5.2.1 Expansion Ratio

The expansion ratio increases with decrease in feed moisture content and increase in screw speed and barrel temperature. Increased feed moisture leads to a sharp decrease in the expansion of extrudate (Pathania *et al.*, 2013). Changing the feed moisture content, barrel temperature and screw speed significantly affected the expansion ratio of all the extrudates. Increasing the feed moisture content and screw speed resulted in a substantial decrease in expansion ratio (Oke *et al.*, 2013). Increase in barrel temperature resulted in extrudate with higher expansion, increasing in screw speed resulted in higher expansion and increasing level of moisture resulted in lower -

Table 4: Influence of protein type and its concentration on product expansion

| Process parameters and Protein content | Type Concentration | Product type | Expansion | Reference |
|---|---|---|---|---|
| Screw speed and Temperature | - | Starch, Barley-grape pomace blends, | Increased with increases screw speed and temperature | Kumar *et al.* (2010); Altan *et al.* (2008); Upadhyay (2009); Ding *et al.* (2006) |
| Moisture content | - | Starch | Decreased with increased moisture content | Hagenimana *et al.* (2006) |
| Soy protein isolate | 1–8% | Wheat | Increased | Faubion and Hoseney (1982) |
| Wheat gluten | Up to 11% | Wheat | Decreased | Faubion and Hoseney (1982) |
| Whey protein concentrate | Up to 25% | Corn, rice, and potato | Increased | Onwulata *et al.* (1998, 2001a) |
| Whey protein concentrate | >25% | Corn, rice, and potato | Decreased | Onwulata *et al.* (1998, 2001) |

expansion (Kothakota *et al.,* 2013). Table 4 shows the influences of protein type and its concentration on product expansion.

**5.2.2 Bulk Density**

The effect of the independent variable (temperature, screw speed and moisture content) on density of extrudates was opposite of expansion ratio (Pathania *et al.,* 2013). Increase in barrel temperature resulted in lower bulk density of extrudates, increasing in screw speed resulted in lower bulk density and increasing level of moisture resulted in minimum bulk density (Kothakota *et al.,* 2013). The opposite behavior of bulk density and lateral expansion with the change in process variables have been reported by Ding *et al.,* (2006). Low screw speed (20.1-32.6 rpm) led to the increase of texturized rice bulk density value, probably due to starch gelatinization decrease (Hagenimana *et al.,* 2006). Sahagun and Harper (1980) reported similar trends using corn/ soybean feed. Bulk density was found to be most dependent on screw speed and temperature.

**5.2.3 Water Absorption Index**

The increase in water absorption index with screw speed may be attributed to high mechanical shear and higher expansion due to gelatinization. Water absorption index increased with the increase in temperature probably due to increased dextrinization at higher temperature. Increasing moisture significantly decreased WAI. Increase in screw speed and barrel temperature significantly decreased WAI (Pathania *et al.,* 2013). Increase in barrel temperature resulted in higher WAI (Kothakota *et al.,* 2013). Increased feed moisture content and screw speed significantly increased the WAI of textrurized rice whereas increase in barrel temperature was observed to cause a significant decrease in textrurized rice. Increasing barrel temperature decreased WAI, probably due to an increase in starch degradation (Hagenimana *et al.,* 2006). Altan *et al.* (2008) also reported the similar behavior due to competition of absorption of water between pomace and available starch. Water absorption index increased with the increase in temperature probably due to increased dextrinization at higher temperature (Mercier and Feillet, 1975; Pathania *et al.,* 2013).

**5.2.4 Water Solubility Index**

The WSI increases with increase in screw speed and temperature and decreased with increase in moisture (Pathania *et al.,* 2013). Increase in barrel temperature resulted in lower WSI (Kothakota *et al.,* 2013). Higher WSI of extrudate with increasing screw speed may be related to increasing specific mechanical energy with screw speed. The increase in WSI with increasing screw speed was consistent with the results reported by other researchers. Increasing temperature would increase the degree of starch gelatinization that could increase the amount of soluble starch resulting in an increase in WSI. Positive relationship of WSI and temperature was also achieved in extruded products by Ding *et al.* (2005).

**5.2.5 Hardness**

Increase in barrel temperature resulted in higher hardness, increasing in screw speed resulted in lower hardness and increasing level of moisture resulted in –

Table 5: Effect of packaging material and storage method on stability of extruded

| S. No | Type of Packaging Material | Type of Snack Food | Storage conditions | Result | Refrances |
|---|---|---|---|---|---|
| 1 | Low-density polyethylene (gauge 83 µm) and aluminium bags (gauge 36 µm) with or without nitrogen flushing and | Finger millet added with fortifying agents | Stored at room temperature | Products fortified with NaFeEDTA (sodium iron ethylenediamine tetraacetate) and packed in aluminium foil with nitrogen flushing were found optimal in terms of iron bioavailability, storability and consumer acceptability. | Gaur and Visvanathan (2015) |
| 2 | Polypropylene | Rice flour | Stored in corrugated fibre box at 30°C and relative humidity of 50%, storage analysis period of one month upto 6 month | During storage, remarkable changes were observed in structural orientation of the fibre and cellular components of extruded snack food. The microstructural, colour and textural properties of unfried, fried and seasoned extrudates changed during storage of six months and least changes in hardness and crispiness occurred in seasoned extrudates. | Anonymus (2015) |
| 3 | High density polyethylene bag (gauge size 0.03 µm) | White Yam and Bambara Groundnut blends | Stored at room temp. (28°C± 2°C) and at refrigeration temperature (9°C ± 2°C) for a period of twenty weeks. | As the storage time further increases to 8 weeks, there was a continuous increase in the total plate count particularly at the room temperature. A similar trend was observed when the extrudates were stored at 12, 16 and at 20 weeks. | Oluwole *et al.* (2013) |
| 4 | Polypropylene | Three common bean (Phaseolus vulgaris) | Storage conditions for aging at 40 °C and 60% RH for 3 months. | On storage condition of extruded, the effect of feed moisture has not significant differences, but the effect of cultivar, temperature and storage were significant in all experimental conditions. The use of stored bean grain resulted in higher values of WAI. The standard deviation range was higher in stored beans processed at higher temperatures and it was independently of the bean cultivar used. | Rocha Guzma *et al.* (2006) |
| 5 | Laminated polyester (0.5 mm), aluminum (0.0035 mm) and polypropylene (2.0 mm) | Maize based extruded snack | Incubators maintained at 25, 30 and 40°C, storage period for 90 days | Total carbonyls were found to increase in the products with increases in storage temperature. Storage of the maize snack foods at 25°C and 30°C for 30 days did not change the acceptability of the food. Higher storage temperature (40°C) reduced the sensory acceptability of the snack from 'like very much' to 'like slightly' after 30 days of storage | Lasekan *et al.* (1994) |

lower hardness (Kothakota *et al.*, 2013). Increase in moisture content, screw speed and temperature may may Hardness decreased with the increase in moisture, which may be due to reduced expansion with the increase in moisture content. It may be observed that hardness decreased with the increase in screw speed as well as decrease in hardness with increased screw speed due to lower melt density was observed by Ding *et al.* (2006). The decrease in hardness with increase in temperature may be due to higher expansion at elevated temperatures. Similar findings have been reported by Altan *et al*. (2008).

## 6. Effect of Packaging Material and Storage Method on Stability of Extruded

Snack food should be packed in flexible thermoplastic films of multi layer or monolayer construction or their laminates with paper or aluminium foil so as to provide a high resistance to the passage of oxygen, light and water vapour and to produce an effective heat seal. The air tight sealing can be done with or without nitrogen flushing to retain the contents in a fresh condition. Table 5 shows the effect of packaging materials and storage method on stability of extruded.

### 6.1 Specific Mechanical Energy (SME)

The specific mechanical energy (SME) is used as a system parameter to model extrudate properties. SME has been found to decrease with increase of moisture and temperature and increased with increase in screw speed. Specific mechanical energy (Wh/kg) was calculated from rated screw speed, motor power rating, actual screw speed, % motor torque and mass flow rate (kg/h). Moisture, screw speed and temperature had significant effects on SME. A lubricating effect is produced by high moisture resulting in less energy use and subsequently reduced SME. Increase in screw speed results in higher shear which gives higher SME (Pathania *et al*., 2013).

Specific Mechanical Energy defined as the total mechanical energy input to obtain 1 g of extrudate (J/g), could be determined by using Eq. (1) (Rosentrater *et al*., 2009).

$$SME = \frac{(\mathrm{T} \times \mathrm{w} \times 60)}{\mathrm{M_{feed}}} \qquad \dots (1)$$

Where,

SME = specific mechanical energy consumption (J/g)
T = net torque exerted on the extruder drive (Nm)
w = screw speed (rpm)
$M_{feed}$ = mass flow rate of the raw sample (g/min)

The mass flow rate of feed ($M_{feed}$) can be determined as per the procedure discussed (Oke *et al.*, 2011), $M_{feed}$ was calculated using Eq. (2)

$$\mathrm{M_{feed}} = \mathrm{M_{prod}} \frac{1 - \mathrm{MC_f}}{1 - \mathrm{MC_i}} \qquad \dots (2)$$

where,

$M_{feed}$ = mass flow rate of the raw sample (g/min)
$M_{prod}$ = mass flow rate of the extrudate (g/min)
$MC_f$ = moisture content of the collected extrudate (%wb)
$MC_i$ = moisture content of the raw sample before entering the extruder (% wb)

## 7. 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. Effects of extrusion cooking on nutritional quality are ambiguous. This technology because of its beneficial effects such as destruction of antinutritional factors, increased soluble dietary fibres, reduction of lipid oxidation and contaminating microorganisms plays an important role in the production of a wide variety of foods and ingredients. As a complex multivariate process, extrusion cooking requires careful control if product quality is to be maintained. Mild extrusion conditions (high moisture content, low residence time, low temperature) favour higher retention of amino acids, high protein and starch digestibility, increased soluble dietary fibre, decreased lipid oxidation, higher retention of vitamins and higher absorption of minerals. Severe extrusion conditions and improper formulation (e.g. presence of reducing sugars) can cause nutritional destruction given the usual residence time of 0.5-1 min in the hot-screw segments. Generally, high extrusion temperature (≥ 200 °C) and low moisture content (≤ 15%) should be avoided to maintain nutritional quality. 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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