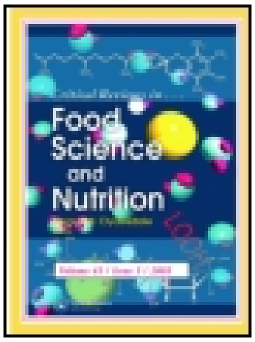

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Extrusion Processing of Raw Food Materials and by-products: A Review

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Abstract

Extrusion technology has rapidly transformed the food industry with its numerous advantages over other processing methods. It offers a platform for processing different products from various food groups by modifying minor or major ingredients and processing conditions. Although cereals occupy a large portion of the extruded foods market, several other types of raw materials have been used. Extrusion processing of various food groups, including cereals and pseudo cereals, roots and tubers, pulses and oilseeds, fruits and vegetables, and animal products, as well as structural and nutritional changes in these food matrices are reviewed. Value addition by extrusion to food processing wastes and by-products from fruits and vegetables, dairy, meat and seafood, cereals and residues from starch, syrup and alcohol production, and oilseed processing are also discussed. Extrusion presents an economical technology for incorporating food processing residues and by-products back into the food stream. In contemporary scenarios, rising demand for extruded products with functional ingredients, attributed to evolving lifestyles and preferences, have led to innovations in the form, texture, color and content of extruded products. Information presented in this review would be of importance to processors and researchers as they seek to enhance nutritional quality and delivery of extruded products.

Keywords. Nutritional changes, Value addition, By-products, Food groups, Waste utilization

1. Introduction

Food extrusion involves the process of forcing food materials to flow under a variety of operations, including kneading, melting and/or shear, through an orifice (die) which is specifically designed to shape and/or expand the material (Karwe, 2009; Riaz, 2000; Steel et al., 2012). Key advantages of extrusion cooking include the capacity to yield a diverse range of extruded products from inexpensive raw materials under minimal processing times (Akhtar et al., 2015), thus enabling uniform production through an efficient and continuous system. Food extruders may be designed to perform several unit operations concurrently, including mixing or homogenization, shearing, starch gelatinization, protein denaturation, texturization, enzyme inactivation, thermal cooking, pasteurization, dehydration, shaping and size reduction (Akhtar et al., 2015; Fellows, 2000).

Extruders may be categorized into piston, roller or screw extruders based on the conveying mechanism (Brennan and Grandison, 2012). For food processing applications, screw extruders are the most predominant, and may involve single-, twin- or multiple- screws which rotate within a fixed barrel. Regardless of the design or type, the operating principles for extruders are similar. In its most basic form, a screw extruder consists of a rotating Archimedes flight or screw, tightly fitting within a fixed barrel with a die at the discharge end (Sung et al., 2014). The raw materials, usually a set of mixed, pre-conditioned ingredients, are fed into the barrel through a hopper and conveyed by the screws along the barrel (Bordoloi and Ganguly, 2014). A design-specific die gives the product its form, as it exits from the barrel. Extruders of single screw design are equipment suitable for low-cost processing of less complex ingredients, while the more complex twin screw extruders have the capacity to handle more diverse raw material formulations at constant throughput (Clextral, 2010; Karwe, 2009; Ramachandra and Thejaswini, 2015; Steel et al., 2012).

Depending on the feed materials and desired product properties, food extruders may operate under low shear which is suitable for pasta and processed meats, medium shear which is suitable for meat analogs or high shear required for expanded snacks, texturized vegetable proteins, and ready-to-eat (RTE) breakfast cereals (Steel et al., 2012). Low-shear extruders with lower mechanical energy are employed primarily for mixing and forming, while high-shear extruders are designed to exploit high mechanical energy input for processing applications which require heat (Brennan and Grandison, 2012). Extruded products may undergo several physicochemical and nutritional changes, depending on the process and feed material (Sung et al., 2014). Such changes include lipid oxidation, protein denaturation and cross-linking, starch gelatinization and dextrinization, degradation of vitamins and denaturation of enzymes, browning and flavor formation. The properties of the resulting product are a composite of all these complex changes which are influenced by the processing conditions. The raw material properties, particularly, type of material, physical state, chemical composition including moisture, starch, proteins, fats and sugar contents, and the raw material pH are the most significant, while barrel temperature and pressure, screw configuration and rotation speed, die diameter and shear force, are important process conditions (Steel et al., 2012). Process factors including moisture content, temperature and time are often optimized to minimize adverse effects on nutritional quality (Moscicki and van Zuilichem, 2011). Since extrusion is a flexible processing method, automatic on-line process modifications could be made to achieve required product characteristics, and several different products ranging from highly viscous or wet to relatively dry materials could be manufactured using same equipment (Figure 1). Consequently, extrusion technology allows rapid and efficient transformation of various raw materials into diverse palatable food products by simply altering feed formulation and operating conditions on the same equipment

(Riaz, 2006). Various food groups, including pulses and oilseeds, meat and fish products, roots and tubers, fruits and vegetables have found useful application in extrusion processing.

Several reviews have been published on various aspects of food extrusion technology, including changes in foods (Camire et al., 1990) or vitamin stability during extrusion (Riaz et al., 2009), and effects of process parameters on quality attributes (Alam et al., 2016). However, these publications do not offer a comprehensive review of the application of extrusion processing to the various food groups, and the role of extrusion in modifications that occur as influenced by the food matrix. Large quantities of food processing wastes and by-products are generated annually, and extrusion technology plays a significant role in re-integrating these residues into edible food products. Therefore, this review presents pertinent literature on food extrusion technology in the processing of all major food classes (e.g, cereals, roots and tubers, pulses and oilseeds, fruits and vegetables, and products of animal origin), on nutritional changes and other modifications occurring during extrusion. Also, application of extrusion to value addition of food by-products is discussed to further elaborate on future prospects of the technology.

2. Extrusion processing of various food groups

Extrusion technology offers a platform for processing a variety of food products, just by changing a major or minor raw material and processing conditions. Raw materials for extruded foods tend to be mostly cereal flours, however, other ingredients from diverse food sources may be incorporated, provided they fit the required raw material characteristics for the equipment. Raw materials for extrusion processing include cereals and pseudo-cereals, fruits and vegetables, legumes, pulses, oilseeds, roots and tubers, nuts and seeds, and meats. These raw materials are often used in various combinations, and products of different shapes, textures, colors, and appearances could be produced by altering raw material mix, equipment assembly and operating parameters (Riaz, 2000). The quality of ingredients used should be high, and only permitted additives of required purity must be used (Guy, 2004). Raw material properties such as cohesiveness, hardness, and surface friction are also of importance. The most commonly used ingredients are flours and granules from starchy foods such as maize, rice, wheat and potatoes, although, other starchy raw materials such as sorghum, cassava, oats, barley, rye, and buckwheat have also been used (Guy, 1994). The underlying product structure and texture are formed by altering and manipulating the biopolymers, especially starches and proteins. In products where proteins play the major role, raw materials are chosen from oilseed proteins like soybean or from fractionated cereal proteins (Asgar et al., 2010). The materials when incorporated into a formulation tend to alter the process, thereby modifying the resulting product.

2.1 Cereals

Apart from breakfast cereals and snacks, other extruded cereal-based products include pasta, breads, soup bases and modified starches, biscuits, croutons, and confectionary (Ilo et al., 2000). Cereal grains are common staples, providing more food energy than any other food group as they represent the most important source of total food consumption in terms of calories. Cereals have relatively similar overall composition, which is often low and high in protein and carbohydrates, respectively, with the exception of oats and maize which contain comparatively higher amounts of lipids (7-9 %), compared to 1-2 % in other cereals (FAO, 1999; Riaz, 2010). This higher oil level may present problems with oxidative rancidity (Guy, 2012). Due to their high starch content, cereals are valuable ingredients in numerous extrusion applications.

Breakfast cereals are available in two types: ready-to-eat cold and hot cereals (traditional cereals). In order to reduce in-home preparation time, breakfast cereal technologies have advanced from grain milling procedures for hot cereals requiring some cooking, to more sophisticated processing methods for manufacturing RTE extruded products, that are highly convenient (Neulicht and Shular, 1995). Several products in the hot cereals category are made from oats and wheat, while rice, and corn make up a smaller percentage (Neulicht and Shular, 1995). The RTE cereals are usually cooked and modified by flaking, toasting, puffing, shredding or extruding (Varsha and Pavani, 2016). The process may require the removal of bran and germ, leaving behind the starchy endosperm. However, inclusion of bran or other sources of dietary fiber may be necessary as product requirement in the production of high fiber foods. Wheat bran, a by-product from the milling of wheat, has been used with plant proteins to produce expanded snacks and breakfast cereals of improved nutritional and fiber value (Onipe et al., 2015). The increasing demand for these different ready-to-eat cereals could be ascribed to their convenience, quick preparation time, and shelf-stability.

The RTE extruded cereal-based foods may be classified, based on product form rather than type of grain, into extruded flaked cereals, extruded puffed cereals, extruded shredded cereals, directly expanded and granola cereals (Neulicht and Shular, 1995; Whalen et al., 2000). In RTE cereal formulations, the primary functional ingredient is the grain or a grain-derived component, and within these categories, extruded products may be processed from flour, whole-grain, or grain fractions (Whalen et al., 2000). Compared to traditional flakes, extruded flaked cereals are produced by extruding kneaded ingredients through an orifice and cutting the dough into pellets of specific size (Neulicht and Shular, 1995). The processing of expanded products is comparable to the process for flaked products (Culbertson, 2008), with corn, rice, wheat meal or flour as the base raw material. Grain meal or flour is used as raw material, rather than whole grains, for the production of shredded cereals. Granola are RTE cereals made from oats mixed with added ingredients including vegetable oils, sweeteners (brown sugar, honey), flavors (cinnamon, malt extract, nutmeg, dried fruits) and protein (dried milk) (Neulicht and Shular, 1995). This blend is subsequently toasted in an even layer until it browns, and a low moisture is attained, after which it was broken into smaller pieces (Tribelhorn, 1991). The products could also be fortified with micronutrients prior to packaging.

The cooking or gelatinization of starch depends on time, temperature, availability of water, and in the case of extrusion cooking, shear (Ilo et al., 2000). These factors synergistically influence the final quality of extruded products. Although virtually all cereals can be processed using an extruder, the cereals best suited to expanded products are de-germed corn/grits and rice (Riaz, 2006). Cereals containing higher levels of lipids are not suitable for expanded products due to slippage of the dough within the extruder barrel (Ilo et al., 2000; Riaz, 2010). Such cereals would require increased moisture and elevated temperature for any significant expansion to take place. Starches which contain 5-20 % amylose would appreciably favor expansion and improve the textural appeal of breakfast cereals and snacks (Riaz, 2010). For example, the association between amylose and extrusion-expansion characteristics of corn starches studied, showed that expansion ratio of starches varied from 8 to 16.4 as amylose rose from 0 to 50 % dry basis (d.b.), and that different native starches had different optimum temperatures for expansion (Chinnaswamy and Hanna, 1988). Corn plays a very important role in the extruded cereal market as it is a primary ingredient for numerous breakfast cereals and cereal-based snacks, including collets and several pellet products (Obradovic et al., 2014).

Type of snack or breakfast cereal as well as type of extruder determines the granulation to be used. A fine granulation of corn meal gives a fine texture and softer bite, while a coarse granulation results to a crunchy texture in the product (Huber, 2001). Unlike collet extruders which require coarse granulation, twin screw extruders are more versatile, and could process both fine and coarse granulation of flour. De-germed corn expands more than whole corn, therefore, it is more often used in breakfast cereals and extruded snacks which require some degree of expansion (Riaz, 2010). Wheat flour has found useful application in various extruded products, including pasta and several baked or fried snacks, flavored crackers, and breads. Coarse semolina from hard wheat produced expansion ratio and bulk density similar to corn meal, resulting in crisp-textured products (Moore, 1994). Among grain starches, the starch granules of rice are the smallest (2-8 μm), and are easy to digest, however, their composition vary widely: normal rice varieties have amylose (15-27 %), and 100 % amylopectin for waxy rice varieties (Koehler and Wieser, 2013). Due to its excellent digestibility, rice flour is extensively used in infant food formulations, and may also serve as an important alternative to wheat for gluten-intolerant individuals (Rosell and Collar, 2007). Broken rice, which is a by-product of milling, is a cheaper alternative. (Riaz, 2010). However, rice proteins exhibit poor functional properties during processing, compared to other plant proteins (Rosell and Collar, 2007). Oats are less widely grown and may also be differentiated by their grain endosperm composition and morphologies. They are generally available as rolled oats or sold as ingredient for the manufacture of breakfast cereals. Due to their relatively high oil (7-9 %) and high lipase enzyme activity, it is best to inactivate the lipase, prior to their use in breakfast cereals and snack foods (Rasane et al., 2013). Starch granules in oats are comparatively smaller (2 – 12 μm) in size than most other starches, and amylose content may fall within 16-27 % (Riaz, 2010). Oats starch required relatively low gelatinization temperature, however, due to poor expansion, they were not ideally used in expanded products or were used at very low levels (Riaz, 2006).

Extrusion of underutilized grains and pseudo cereals is of particular interest to the cereal processing firms. Some cereals including sorghum (*Sorghum bicolor L.*), millets (pearl millet, finger millet and others), rye (*Secale cereal L.*) and ancient wheat species (einkorn, emmer, spelt wheat) were listed and classified as under-utilized (Sinkovic, 2016). Pseudo cereals, which are seeds of non-grass species, are nutritionally similar to conventional cereals, and may be consumed or utilized in the same manner. Common pseudo cereal species are buckwheat (*Fagopyrum spp*.), amaranth (*Amaranthus L*) and quinoa (*Chenopodium quinoa*) (Sinkovic, 2016). Total starch of amaranth, quinoa and buckwheat were reported as 61.4 %, 64.2 % and 58.9 % d.b., respectively (Alvarez-Jubete et al., 2009). These underutilized cereals and pseudo cereals have been well explored in extruded products (Table 1).

2.2 Roots and tubers

In most developing countries of Africa, Latin America and Asia, roots and tubers are major staples and a cheap source of carbohydrates for dietary energy (Ugwu, 2009). Thus, they have great potential in the development of extruded products, especially considering their high starch content. After cereals, they are the next most important source of carbohydrates globally. Major root and tuber crops common to the tropics include cassava (*Manihot esculenta Crantz*), yam (*Dioscorea spp.*), sweet potato (*Ipomoea batatas L.*), potato (*Solanum spp*.), and cocoyams (*Colocasia spp.* and *Xanthosoma sagittifolium*) (Chandrasekara and Kumar, 2016). Among these, potato and cassava are the most commonly used in extruded snacks, as flour, granules, starch or flakes (Ilo et al., 2000). The granules are produced from diced tubers, tempered to tenderize the cell walls, cooked and dried in a well-defined process (Riaz, 2006). The differences in raw materials and processing factors could alter the performance of the granules. Dough from potato flour were stiffer and stickier than those prepared from the granules (Guy, 2012). Potato flour served as a major ingredient in directly expanded snacks and fabricated chips (Riaz, 2006). Potato starch may contain amylose (20-25 %), and a low lipid (0.1 to 0.2 %) content (Guy, 2012; Riaz, 2006), and could be incorporated into extruded snacks to provide additional expansion and improved functional properties (Guy, 2012). Potato starch developed high viscous flow during cooking and exhibited excellent swelling and binding capacity. Tapioca starch ideally contains about

17 % amylose, and is most often used in third generation snack formulations (Riaz, 2006). Tapioca starch also developed very high viscosity, excellent binding properties and required only moderate temperatures during extrusion cooking (Riaz, 2006).

Extrusion of flours from root and tuber crops has enabled the production of a range of snacks and pre-gelatinized flours, thereby providing an economic means of diversifying the utilization of such crops (Akinoso and Abiodun, 2016). Native starches from these crops have been modified by means of extrusion, leading to improved functionality. Owing to their improved viscosity, higher gel strength, and suppressed retrogradation tendency, modified starches have a wider range of applications compared to their native forms (Santana et al., 2014).

Studies on the effects of processing factors including barrel temperature, moisture content and screw speed on physical characteristics of cassava starch showed that some of the starch quality attributes (color, specific volume, expansion index, water absorption index, initial viscosity, peak and final viscosities) were influenced by barrel temperature, while others (specific volume, color, final viscosity and retrogradation) were influenced by feed moisture content (Leonel et al., 2009). Less starch breakdown, desirable in pre-cooked starches, was attained at intermediate temperature, high moisture, and low screw speed. Barrel temperature had the most profound influence on paste properties, color and expansion. In a similar study, the effects of cassava bran (10-50 %), barrel temperature (150–210 ^{o}C), feed moisture (16–20 %) and screw speed (120–180 rpm) on products from cassava starch, using a single screw extruder, were evaluated (Hashimoto and Grossmann, 2003). Levels of cassava bran, extruder barrel temperature and screw speed all played significant roles in influencing the water absorption and water solubility indices of the products. A study aimed at investigating the expansion ratios of extruded starch from varieties of water yam reported values ranging from 1.05 to 1.93, which were influenced by all three variables studied (feed moisture, barrel temperature, and screw speed), although screw speed and feed moisture exerted greater influence (Oke et al., 2013). High water solubility index was reported for yam flour extruded using a single screw extruder at high barrel temperature and high feed moisture, however, the greatest expansion was attained at low moisture and high temperature (Serbio and Chang, 2000). Additionally, the properties of double-extruded potato starch, obtained by grinding and re-extruding potato starch, were observed to differ from those of the single-extruded starch, and were influenced by processing temperatures (Tomaszewska-Ciosk et al., 2012). Higher temperatures and re-extrusion resulted in increased solubility and decreased water absorption capacity. For extrusion processing of cocoyam, increased density, water absorption index and hardness, decreased expansion, and water solubility index were reported at high feed moisture content, while high barrel temperature increased the expansion ratio and water solubility index (Peluola-Adeyemi and Idowu, 2014). Similarly, in extruded snacks developed from cocoyam flour using a single screw extruder, lower expansion and higher hardness was reported when feed moisture was increased, and higher barrel temperature led to increased expansion and water solubility index (Peluola-Adeyemi et al., 2014). In another study on extrusion of cocoyam flour using a single screw extruder, higher barrel temperatures also produced increased expansion and water solubility index, but reduced product density, water absorption index and hardness of extruded products, and increased feed moisture led to lower expansion (Daramola et al., 2010). Expansion ratio of extruded products from arrowroot starch varied from 3.22 to 6.09, and the product showed higher oil absorption index, water absorption index, and water solubility index, than native starch, however, products processed at high feed moisture and low barrel temperature exhibited increased hardness and toughness (Jyothi et al., 2009). Meanwhile, feed moisture was considered as one of the most important factors in the extrusion of taro flour (Nurtama and Lin, 2009), using a collet extruder.

2.3 Pulses and oilseeds

Pulses are annual leguminous crops which yield one to twelve seeds of varying shapes, sizes and colors in a pod, and are solely harvested for the dry grain (Berrios, 2016). They are important protein source, especially for populations in developing countries. Until recent times, pulses and their flours were underutilized in the formulation of conventional extruded snacks (Patil et al., 2016). This category does not include green beans and green peas, classified as vegetable crops, and soybeans and peanuts, considered as oilseeds. The important pulses are dry bean (*Phaseolus spp.*), dry peas (*Pisum spp.*), pigeon pea (*Cajanus cajan*), dry broad beans (*Vicia faba*), chickpea/Garbazo (*Cicer arietinum*), dry cowpea (*Vigna unguiculata*), lentils (*Lens culinaris*), and bambara groundnut (*Vigna subterranean*) (Berrios, 2016). The dominant proteins found in legumes are albumins and globulins (Patil et al., 2016). Pulses like lentils, dry beans, and peas are classified by USDA Food Pyramid-Dietary Guidelines as high-protein and vitamin-rich vegetables (Berrios, 2016).

Legumes contain compounds such as lectins, saponins, cyanogenic compounds, trypsin and chymotrypsin inhibitors, which exert anti-nutritional effects upon ingestion (Berrios, 2016). However, due to their heat sensitivity, most of these factors are reduced or destroyed during extrusion cooking (Soetan and Oyewole, 2009). Simple extruded products such as RTE snacks and pasta have been formulated from blends of legume flours and other components, especially cereal flours and starches (Hulse, 2012). Incorporation of legume flours may serve to enhance flavor and improve physical attributes and nutritional quality. Furthermore, high protein fractions such as legume protein concentrates and isolates are used in the processing texturized vegetable proteins and meat analogs (Hulse, 2012). Meat analogs, very similar to meats in mouthfeel and appearance, have been developed using extrusion cooking (Kearns et al., 2013). Texturized proteins may be formulated from a range of raw material specifications. Despite the wide range of legumes available, soybean protein is considered the best choice for processing texturized products. Defatted soy flour traditionally used in texturized products usually has a minimum protein content of 50 %, and protein dispersibility index (PDI) of 60 to 70, however, general raw material specifications for extrusion of texturized proteins include 20-80 PDI, 0.5-6.5 % fat, up to 7 % fiber, and up to 8 mesh particle size (Kearns et al., 2013).

A number of plant protein sources have been used as raw materials for texturized products. Moisture content of meat analogs prepared from soy protein isolate and wheat starch was reported as a more important determinant than cooking temperature in influencing the product texture, however, higher temperatures at a constant moisture content produced softer analogs (Lin et al., 2000). In addition, feed moisture of soy protein isolate and peanut flour was reported as the most dominant parameter influencing product texture in texturized meat analog (Palmer et al., 2004). Properties of texturized protein products from lima beans and African oil bean seeds were mainly affected by barrel temperature and screw speed, indicating optimized process conditions of barrel temperature (92.45 ^{o}C), screw speed (101.48 rpm), feed moisture (59.63 %), and 1 % African oil bean seed protein concentrate (Arueya et al., 2017). Increased feed moisture produced increased density, water absorption index, oil absorption index, and swelling power but decreased lateral expansion in texturized meat analog from mucuna bean flour, while changes in screw speed had the least effect on product responses, with the optimized product obtained at barrel temperature (120.12 ^{o}C), feed moisture (47 %), and 119.19 rpm screw speed (Omohimi et al., 2014). Higher barrel temperatures led to reduced essential amino acid contents, while higher feed moisture had a positive effect on essential amino acid retention in products from bambara groundnut flour and sorghum malt (Jiddere and Filli, 2015).

Apart from texturized products, various extruded snacks and RTE foods have been developed from legumes and cereals/root crops. Varieties of legume sources have been used to enhance the nutritional quality of extruded products. The protein content of extruded products from wheat supplemented with lentil, green pea, yellow pea and chickpea, increased by 1 %–1.5 %, and extrusion processing improved protein digestibility by 37 % - 62 % (Patil et al., 2016). A wide range of snacks made with soy proteins have become increasingly popular among health-conscious consumers (Riaz, 2006). Maize-based extruded snacks have also been developed by supplementing maize with full-fat soybean (Rweyemamu et al., 2015), and partially-defatted soybean (Obatolu et al., 2006). Supplementation of pasta with different legumes, milk and egg proteins indicated that among all the protein sources used at variable levels, the best quality pasta was obtained for 15 % mung bean flour, 10 % whey protein concentrate and 6 % egg albumen (Savita et al., 2013).

Vegetable oils are a significant resource with a wide range of food applications, and the method of extraction from oilseeds is key in determining oil quality. Oilseeds include legumes such as soybean and peanuts primarily grown for oil extraction, and non-leguminous oil crops such as linseed, cottonseed, sunflower, safflower, sesame, rapeseed, mustard seed, melon seed, hempseed, among others (Yadava et al., 2011). Extruders are increasingly finding more use in oilseed industries, with new designs increasing their range of applications. The development of improved oil mill processing methods holds more promise for increasing the utilization of these oilseeds. The conventional industrial extraction process typically entails mechanical pressing prior to solvent extraction, however, this process is discontinuous (Kartika et al., 2007). Methods for continuous oil extraction using extrusion technology, as well as optimization of the operating conditions, have received considerable research interest. Quality attributes, such as color, flavor, protein solubility, functional and nutritional properties, of the resulting protein concentrates and isolates after oil extraction are of importance, and extrusion-expelling of oilseeds provides a means for obtaining good quality oil and meal (Berrios, 2016). Among the oilseeds, soybean has relatively higher economic importance over other oilseeds, which may be attributed to their low cost, ease of extraction by solvents, and nutritional quality of the soybean proteins.

Several studies have evaluated the use of extrusion technology for vegetable oil extraction and optimization of oil extraction processes (Evon et al., 2013; Evon et al., 2007; Martin, 2016; Olajide et al., 2014; Uitterhaegen et al., 2015). Although efficiency of solvent extraction alone could be as high as 98 %, extrusion processing offers the advantages of continuous processing, flexibility, efficient control over process variables and high product quality. Extraction of oil from sunflower seeds, using a twin-screw extruder, showed 80 % extraction efficiency and yielded a good quality high protein meal by-product, which was further improved by high pressing temperature and low moisture content (Dufaure et al., 1999). Studies on flaking and extrusion of dehulled soybeans as a means of enhancing the efficiency of oil extraction during enzyme-mediated processing of soybeans showed that the use of cellulose did not improve the process, however, flaking and extruding enhanced protease hydrolysis, thereby improving oil extraction, up to 88 % (Lamsal et al., 2006). An investigation of the effects of screw configuration and operating parameters, pressing temperature, screw rotation speed and seed input flow rate, of a co-rotating twin screw extruder on oil extraction of sunflower seeds showed that the highest oil yield (85 %) was obtained for the screw speed (75 rpm), seed input flow rate (19 kg/h), and 120 ^{o}C pressing temperature (Kartika et al., 2007). The residual oil content in the cake meal was lower than 13 %, and the operating parameters had minimal effect on acid and iodine values of the oil.

Over 90 % oil extraction efficiency was reported when extrusion was used as a pre-treatment prior to mechanical pressing of soybeans (Bargale et al., 1999). Oil extraction yield from jatropha seeds by mechanical pressing, using a co-rotating twin screw extruder was increased with decreasing temperature and screw speed, and the highest yield of 70.6 % was realized at 153 rpm, 5.16 kg/h inlet flow rate and 80 ^{o}C pressing temperature (Evon et al., 2013). Also, a co-rotating twin-screw extruder was used for thermo-mechanical pressing and solvent extraction using fatty acid methyl esters, of sunflower oil, and it was shown that screw rotation speed, feed rate and solvent-to-solid ratio affected oil yield (Kartika et al., 2010). However, decrease in screw rotation speed and feed rate along with increased solvent-to-solid ratio led to an increase in oil yield. In a similar investigation on the extraction of oil from coriander through mechanical pressing in a twin-screw extruder, screw configuration was reported to play a significant role in the efficiency of extraction and press cake containing 15 % residual oil was obtained at 80 ^{o}C pressing temperature, and filling coefficient of 47.1 g/h rpm (Uitterhaegen et al., 2015).

In single screw press, conveyance of the material is dependent on frictional force generated during the rotation of the screw (Isobe et al., 1992). Thus, the presence of solid fractions like seed hulls improved the performance of the press, although generation of excessive frictional heat could impair oil quality. Twin screw oil press has better crushing, mixing and transport capacity, and are therefore more efficient for oil extraction. Oils expressed using twin screw oil press are generally of better quality than those from single screw press, owing to the presence of less foreign material. A number of authors have reported higher grade oil and press cake quality from twin screw extrusion, compared to single-screw extrusion (Evon et al., 2013; Isobe et al., 1992; Uitterhaegen et al., 2015, 2017). Use of by-products obtained from oilseed extraction are reviewed in more detail below.

2.4 Fruits and vegetables

Fruit and vegetable fractions have been incorporated into raw material formulations for extrusion-cooked products. Most extrusion applications which utilize fruits and vegetables use them in the form of pomace, which are a source of dietary fiber and other functional compounds like flavonoids, anthocyanins and carotenoids (Djilas et al., 2009). Breakfast cereals and RTE snacks colored with natural fruit present an appealing alternative for consumers interested in making healthier choices. Incorporation of fruits and vegetables into extruded products presents a convenient approach towards increasing consumption of this food group and enhancing nutritional quality of the product (Karkle et al., 2009). High sugar and moisture in most fruits limit their use in extrusion, however, spray-dried powders and concentrates could be easily incorporated into product formulations. For instance, dehydrated powders from concord grape, blueberry, red raspberry and cranberry fruits were incorporated into breakfast cereals from de-germed white cornmeal (Camire et al., 2007). Antioxidant activity was highest in the products containing cranberry fruit powder, compared to those containing the other fruit powders. In another study, fruit and vegetable-based directly-expanded snacks containing 25 or 50 % of dehydrated powders of kulfa leaves, pumpkin, curry leaves, lotus stems, or Indian gooseberry using whole cornmeal in a twin screw extruder were developed (Karkle et al., 2009). Snacks which had up to 50 % dehydrated powder had lower radial expansion compared to those which contained 25 %, with the exception of gooseberry. Extruded products containing either gooseberry, pumpkin or curry had lower breaking force compared to the 100 % cornmeal that was used as a control. The extruded snacks containing both 25 % and 50 % dehydrated powder were deemed acceptable by a sensory panel, for all five dehydrated powders (Karkle et al., 2009). The effects of screw speed (150–250 rpm), extrusion temperature (140–180 °C), and feed moisture (14–19 %, w.b.) on antioxidant activity, phenolic content and sensory properties of vegetable-enriched corn-based extruded snacks, using blends of broccoli flour (4-10 %) and olive paste (4-8 %) in broccoli/corn and olive paste/corn formulations were studied (Bisharat et al., 2015). In broccoli/corn products, increase in extrusion temperature and broccoli flour level led to increased antioxidant activity and phenolic content. In olive paste/corn products, antioxidant activity increased with higher olive paste levels. Crispness and cohesiveness decreased with feed moisture. Although extrusion temperature improved porosity and hydration, the products' diameter and crunchiness were decreased. Also, sensory properties decreased with increase in feed moisture. A more desirable product was obtained at 14 % w.b. feed moisture, 140 °C extrusion temperature and 150–250 rpm screw speed for broccoli products, and 14 % feed moisture, 4 and 8 % olive paste, 180 °C extrusion temperature and 150 and 250 rpm screw speed, for olive paste products (Bisharat et al., 2015).

Extrusion of barley flour and pomace from tomato and grape using a co-rotating twin-screw extruder showed that increasing pomace level influenced water absorption index of the products, and led to reductions in starch digestibility (Altan et al., 2009). Also, rice/maize-based products were formulated using the fruits, guava and banana, and the vegetables, tomato and pumpkin pulps, in order to improve nutritional value and flavor. Although, addition of 10 % fruit or vegetable pulp provided additional advantage in terms of nutrition and structure to the products, maximum expansion was reported for both rice and maize products which contained banana pulp (Jain et al., 2013). Higher apple pomace levels in extruded products from corn flour and hydrodynamic cavitated sorghum flour, in combination with low die temperature and screw speed, led to increased total phenolic content and antioxidant activity (Lohani and Muthukumarappan, 2016). Improved products with higher phenolic content, and enhanced antioxidant activity, textural and functional properties were obtained at higher apple pomace levels. In addition, material formulations of rice flour and cactus pear fruit pulp, in the ratios 6:1, 8:1 and 10:1 rice flour: cactus pear puree, were extruded using a twin-screw extruder at 15 kg/h feed rate, 13 % (w/w) feed moisture, 400 rpm screw speed and 40:1 L/D ratio (Sarkar et al., 2011). Increase in cactus pear fruit level increased breaking strength and apparent density of products, however, porosity and radial expansion ratio decreased with increase in fruit solid level.

2.5 Animal products

Animal products including fish flour/powder, minced fish and fish pastes, egg white powder, meat, milk powder, and cheese, which are excellent sources of proteins and other nutrients, have also found useful application in extrusion processing of novel food products (Dileep et al., 2010; Dubey, 2011; Muralidharan, 1999). A variety of extruded products which utilize these food materials have been successfully developed (Adhikari et al., 2009; Qi and Onwulata, 2011; Yadav et al., 2013). The rationale behind the incorporation of these ingredients into extruded products include improved nutritional value, new product development and market creation, flavor generation and ingredient diversification. Incorporation of under-utilized seafood has garnered recent research interest, and incorporating these high protein fractions into extruded products creates value for low-cost and underutilized seafood, thereby enhancing their utilization (Surasani, 2016). These extruded products typically have a shelf life of about 4-6 months with proper packaging. Fish pastes and minced fish are more economical compared to fish powders. Fish- and meat-based products were developed using extrusion cooking, and the major factors during the process which affected product quality were high barrel temperature, feed moisture, protein and starch content, and screw speed (Surasani, 2016). In chicken meat noodles from whole wheat flour and meat at inclusion levels of 0, 30, 40 and 50 %, increased meat levels led to reduced crude fiber, yield, water solubility index, volume increase and cooking loss, however, fat, protein, ash and water absorption index significantly increased with higher meat inclusion levels (Verma et al., 2014), and the most desirable noodle product was that which contained 30 % meat. Also, extruded snacks were formulated from 50:50 rice flour: meat, 50:50 corn flour: meat and 60:40 wheat flour: meat blends, and although the product which contained 100 % meat had higher pH, bulk density, moisture, protein and fat than all the blends, it had lower hydration ability, water solubility and water absorption index (Anandh, 2013).

Pasta was formulated using refined wheat flour, semolina, green gram, black gram, cheese flavor and fish (*Katla Katla*) mince, and the most preferred product was that which contained 32.5 refined wheat flour: 32.5 semolina : 10 black gram dhal : 5 cheese flavor : 20 fish mince (Devi et al., 2013). In a similar study, pasta enriched with tilapia (*Oreochromis niloticus*) fish flour had higher amounts of protein, total essential amino acids, lipid, ash, and total polyunsaturated fatty acids, and incorporation of fish flour decreased lightness and water activity, while pH values, redness, yellowness, and lipid oxidation were increased as level of substitution increased (Monteiro et al., 2016), and enrichment with tilapia flour had negligible effects on the chemical stability of pasta stored at 25 ^{o}C for 21 days.

Nutrient-rich RTE snacks developed from croaker fish flour (*Johnius dussumieri*) and blends of rice flour, corn flour and soybean flour, using a twin-screw extruder gave the most desirable product, in terms of quality and acceptability, when formulated from 18 % fish flour, 45 % rice flour, 30 % corn flour, and 5 % soybean flour, while the product containing less fish flour (12 %) had better expansion (Mulye and Zofair, 2015). Fish meal from parts of tilapia (*Oreochromis niloticus*), salmon (*Salmo salar*), tuna (*Thunnus spp*.) and sardine (*Sardinella brasiliensis*) were used to formulate extruded snacks, and products containing fish meal naturally had higher protein (Goes et al., 2015). In a study on the effects of extrusion parameters and *Labeo rohita* fish flour (10, 15, 20, 25 and 30 %) on properties of extruded products, an inverse relationship between expansion ratio and both moisture content and fish flour was reported (Singh et al., 2014).

In extruded snacks developed from ribbonfish mince and rice flour using a twin-screw extruder under varying barrel temperatures, the most acceptable product was formulated from 10 % fish mince at 90 ^{o}C barrel temperature, and products containing fish mince had higher lysine, glutamic acid and leucine contents (Dileep et al., 2010). Barrel temperature had a significant effect on expansion ratio in products containing 10 % fish mince, and breaking strength of the products improved with the inclusion of 20 % fish mince. In another study, the physical properties and oxidative stability of extruded snacks fortified with fish oil at 0.5–2.5 % were evaluated (Pankyamma et al., 2014). Porosity, expansion ratio and crispness were most affected by feed moisture, and then fish oil level. Fish oil inclusion level up to 0.8 % was oxidatively stable.

Puffed corn-shrimp snacks from yellow corn grits and whole kiddi shrimp (*Parapenaeopsis stylifera*) powder have been developed, and increased inclusion levels of shrimp powder yielded products with lower expansion (Shaviklo et al., 2015). Shrimp powder was therefore considered valuable in formulating value-added snacks with long shelf life. Similarly, a study on the effect of extrusion on water absorption index, expansion index, water solubility index and acceptability of a snack from polished rice grains, rice grits and whole shrimp (*Macrobrachium amazonicum*) flour showed that an optimal product with good expansion, water absorption and water solubility could be obtained at 130 g/kg initial moisture and 80 g/kg shrimp and using a temperature of 85 °C in the third extruder zone (Lourenço et al., 2016). An extruded snack from shrimp powder and shrimp protein hydrolysate was developed using a co-rotating twin screw extruder, and an optimum product formulation included rice flour (47.75 %), corn flour (38.64 %), shrimp protein hydrolysate (5.95 %) and shrimp protein powder (7.67 %). Shrimp hydrolysate levels above 5 % resulted in products with improved crispness (Jeyakumari et al., 2016).

Fish crackers were developed from tapioca starch, fish paste and egg white powder using a single screw extruder and four egg white powder inclusion levels: egg white powder at 1.5 and 3.0 % reportedly had no significant effect on diametric and longitudinal expansion, but inclusion at 4.5 % led to reduced expansion. Increasing egg white powder inclusion levels led to increases in bulk density and protein content in the products (Julianty et al., 1994). In a similar but earlier study, puffed egg products were developed from dried whole egg solids and dried egg white. Dried egg powders were rehydrated to varying moisture contents, whipped into batter and extruded onto pyrex glass plates, and extrudates were then oven heated (Froning et al., 1981). Volume index for the resulting products from egg white solids were highest for batters which were rehydrated to 50 % moisture and whipped for 16 min. and highest for whole egg solids when rehydrated to a batter moisture of 40 % and whipped for 16 min. Optimum puffing was obtained at specific gravity of 0.80 to 0.85 for egg white batter, and 0.90 for whole egg batter. Whole egg solids gave puffed products which had the highest volume. In expanded whole egg products, hardness and acceptability were improved with higher amounts of modified corn starch, however, in puffed egg white products, hardness decreased and acceptability increased with higher amounts of corn starch (Froning et al., 1981). Addition of a starch source to egg batters for puffing was necessary to optimize puffing characteristics under high pressure and temperature conditions (Froning, 2012). Products with super functional properties could be processed from fractionated egg yolk and egg white components (Froning, 2012). Egg fractions, in liquid or dehydrated forms, have also been incorporated into pasta products to impart deeper yellow color and improve flavor, nutritional quality and mouthfeel (Serna-Saldivar, 2016). Liquid eggs containing 20-25 % solids are typically used, as well as spray dried egg products which are more shelf stable, have less microbial risk and are easier to use (Serna-Saldivar, 2016).

In RTE extruded snacks from blends of 35-50 % corn flour, 35-50 % rice flour and 5-30 % spray dried egg albumin powder or spray dried cheddar cheese powder, protein content improved by 20 to 50 %, however, the control product made from 50 % corn flour and 50 % rice flour had the lowest expansion ratio (Kocherla et al., 2012). A study on the effect of moisture content (440 and 480 g kg^{-1}), extrusion temperature (80 and 90 °C), and emulsifying salt (10 and 15 g kg^{-1}) for the production of extrusion-processed cheese showed that moisture content was the most important influencing factor on product quality. Extruded cheese with lower moisture were chewier and firmer in texture, and the lower-moisture cheeses processed at 80 °C were more acceptable (Adhikari et al., 2009). Similarly, in the development of a texturized product from whey protein isolate, the effect of extrusion moisture content on protein quality, protein solubility, and molecular structure was demonstrated (Qi and Onwulata, 2011).

3. Structural and nutritional changes during extrusion cooking

Extrusion cooking produces variable effects in different food systems, due to the varying levels of starch, proteins, moisture and other components which influence the structure and texture of the resulting products (Fellows, 2012). Exposure to the combined effects of high pressure, high temperature and shear leads to several reactions and modifications in nutritional composition of the food materials with resultant changes in functional properties (Brennan and Grandison, 2012). The changes which occur during the process may be simple or complex, and encompass gelatinization, solubilization and dextrinization or complex formation of starches, protein denaturation, polymerization or crosslinking and texturization, partial or complete deactivation of enzymes, browning reactions, denaturation of vitamins and inactivation of anti-nutritional factors (Riaz, 2010; Steel et al., 2012). The amount of applied shear is also significant: high shear disrupts protein and starch molecules, affecting their functionality, such as solubility, viscosity, and water-holding capacity (Karwe, 2009). Most chemical reactions take place in the high-pressure zone of the extruder barrel, therefore heat-sensitive components like flavors and vitamins may be introduced immediately before the die in order to minimize exposure to heat and shear (Steel et al., 2012).

A specific feature of extrusion cooking is the manipulation of biopolymers in food materials at low moisture contents, and the formation of plasticized dough or fluid systems (Guy, 2003). Due to the high temperatures reached within the dough, typically 110 to 200 ^{o}C, water present is superheated but remains in a liquid state (Ajita and Jha, 2017). This facilitates changes in the forms and structures of the natural biopolymers. Recent advances have made it possible to control the thermo-mechanical changes during the extrusion process in order to achieve the required product properties. Since extrusion cooking is a high temperature short time process, it may favor the retention of some sensitive nutrients (Singh et al., 2007).

Starch gelatinization, which occurs due to the high temperature and shear, does not alter total starch content but may cause some degradation and influence the digestibility of the product (Bao and Bergman, 2004). Starch digestibility is largely dependent on the degree of gelatinization. Gelatinization, which involves the cleavage of intermolecular hydrogen bonds, leads to an increase in water absorption and breakage of starch granules, which in turn leads to increased viscosity (Moscicki and van Zuilichem, 2011). On exiting the extruder die, starchy materials rapidly expand due to vaporization, and assume a porous structure. Protein membranes close over the pores forming cell-like spaces, and the starch stiffens on cooling as a result of dehydration, resulting in a fixed structure (Moscicki et al., 2013). This is predictable for carbohydrate complexes embedded in a protein matrix and completely enclosed by membranes of hydrated proteins. Major sources of starch in extruded products are cereals and root or tuber crops (Riaz, 2006). Depending on the source and variety, starch granules possess differing characteristics, and the two starch components, amylose and amylopectin, exhibit different physical and chemical properties (Alcázar-Alay and Meireles, 2015). The effects of amylose-amylopectin ratio on extrusion products has been extensively studied (Chanvrier et al., 2007; Chinnaswamy and Hanna, 1988; Horstmann et al. 2017;

Tacer-Caba et al., 2014; van Soest and Essers, 2006). Amylopectin produces harder extrudates with less expansion, while amylose contributes lightness and elasticity to products, albeit with a sticky surface (Chinnaswamy and Hanna, 1988). For products with good texture and hardness, 5 to 20 % amylopectin content is recommended in feed materials (Moscicki et al., 2013). Waxy starches require high gelatinization temperature and contain less than 15 % amylose, while other starches may have amylose content greater than 30 % (Alcázar-Alay and Meireles, 2015). Lipids associated with amylose fractions can appreciably reduce starch swelling capacity. Gelatinization temperature is specific for starch granules from different sources and some typical ranges include 62–80 ^{o}C (maize), 52–85 ^{o}C (wheat), 58–65 ^{o}C (potato), and 52–65 ^{o}C for tapioca (Moscicki et al., 2013). Starch gelatinization is characterized by loss of birefringence and crystalline order, which alters viscosity and water solubility (Alcázar-Alay and Meireles, 2015). Functional properties of starches depend on these changes, which include water uptake and swelling by the starch granules, development of a viscoelastic paste as heating progresses, re-association or retrogradation of dispersed starch chains on cooling and gel formation (Wang et al., 2015). Starch functionality plays a major role in determining quality attributes of the final product, including moisture, viscosity, texture or consistency, mouth-feel and shelf-life. Expansion of a product after its exit from the die is influenced by gelatinized starch, cellulose complex and cellular proteins, and the final product structure is irreversibly altered. The effects of starch gelatinization on physical properties of wheat-based and corn-based extruded products were studied (Case et al., 1992). Half-products from corn meal, corn starch, wheat flour and wheat starch were produced using a twin-screw extruder, during which starch was gelatinized from 20 to 100 % (Case et al., 1992). Products were cooked at 196 ^{o}C in vegetable oil. Bulk density decreased while puffed product volume increased with increase in gelatinization. All the products attained minimum bulk density at about 75 % gelatinization, with the exception of corn meal, at 55 %

gelatinization. The degree of starch gelatinization and subsequent retrogradation influence the susceptibility of processed starch to enzymatic digestion; the more the disruption of the native starch structure, the greater its susceptibility to digestive enzymes (Wang et al., 2015).

Proteins undergo several changes during extrusion, with denaturation being the most important (Steel et al., 2012). Thermo-mechanical energy applied during extrusion cooking cause protein macromolecules to lose their native structure as they form a viscoelastic mass (Riaz, 2004). Denaturation results in decreased protein solubility and improved digestibility (Steel et al., 2012), and enzymes lose their biological activity following exposure to high temperature and shear (Ramachandra and Thejaswini, 2015). The inactivation of lipoxygenase-1, -2, and -3 enzymes during extrusion cooking at different temperatures, ranging from 77 to 121 °C was studied, and the order of inactivation was lipoxygenase-2 > lipoxygenase-1 > lipoxygenase-3 (Zhu et al., 1996). The protein digestibility index (PDI) of approximately 22 was obtained for the extruded products at 100 % inactivation of all three lipoxygenases. The PDI often serves as an indicator of the degree of heat treatment. As soybean feed moisture rose from 9.2 % to 16.3 %, PDI fell from 68.4 to 24.2. The inactivation of enzymes by extrusion cooking lowers the risk of lipid oxidation and other enzyme-mediated adverse reactions (Zhu et al., 1996). Texturization of proteins results in products that imitate the structure and texture of meats (Joshi and Kumar, 2015). During this process, disulfide bonds are broken and may re-form, and smaller units may be formed from the dissociation of high molecular weight proteins (Steel et al., 2012). Re-alignment of protein molecules during extrusion processing leads to cross-linking and restructuring of the protein molecules, resulting in a chewy texturized product (Riaz, 2004). Numerous studies have been carried out on the texturization of vegetable proteins using extrusion cooking (Arueya et al., 2017; Jiddere and Filli, 2015; Kearns et al., 2013; Lin et al., 2000; Omohimi et al., 2014; Palmer et al., 2004; Seker, 2005). Also, extrusion was established as the most effective processing method for destruction of the antinutritional factors; phytic acid (99.30 %), trypsin inhibitors (99.54 %) and tannins (98.83 %) in lentils, without altering protein content (Rathod and Annapure, 2016). Starch and protein digestibility were also improved by 96 % and 89 % respectively (Rathod and Annapure, 2016).

In assessing the effects of extrusion on proteins, the temperature, type of material, physical and chemical properties of the components within the food all play significant roles (Moscicki et al., 2013). Extrusion processing may influence reductions in albumins, globulins, prolamins and glutelins in the final product (Moscicki et al., 2013). Apart from Maillard reactions which involve amino acids, other reactions that occur during extrusion and influence final product color are caramelization, dextrinization, and pigment degradation (Steel et al., 2012). Reducing sugars produced during the extrusion process may react with the free amine groups of lysine and other amino acids (Steel et al., 2012). Low moisture content and high temperature process conditions favor the reaction between amino acids and reducing sugars, leading to the development of colored compounds. Maillard reactions between protein and sugars decrease the protein quality, depending on the types of raw material, composition and processing conditions (Steel et al., 2012). In a study which assessed the effects of extrusion conditions on the total amount of amino acid enantiomers in dry full fat soy, the concentration of several L-amino acids were reportedly reduced following extrusion; L-glutamic acid by 10 %, L-serine by 17 %, L-phenylalanine by 5 %, L-aspartic acid by 6.6 % and L-lysine by 21 %, at 220 ^{o}C, and some of these losses were attributed to racemization (Csapó et al., 2008). Another study on essential amino acids retention during extrusion processing of egg and milk proteins (10 and 30 %), and the reducing sugars galactose and fructose at 0, 2, and 8 % levels, using pre-gelatinized flour from wheat showed that lysine reportedly had the lowest retention, while retention values for the other amino acids ranged from 80 % to 100 % in most products (Singh et al., 2007). At higher feed moisture and lower temperatures, lysine had better retention.

Lipids serve as plasticizers or as lubricants by reducing friction during extrusion cooking, and greatly influence texture, stickiness and other product quality attributes (Ilo et al., 2000; Steel et al., 2012). At temperatures exceeding 40 ^{o}C, they assume a liquid state, being dispersed with other materials as minute oil droplets (Steel et al., 2012). The dispersed droplets modify the melt viscosity and flow behavior of the material mix through the extruder, and this is influenced by the degree of shear within the extruder (Ilo et al., 2000). Lipids form amylose-lipid complexes during the process of extrusion cooking, and this modifies the physicochemical properties of the products, including expansion ratio, bulk density and water solubility index (Bhatnagar and Hanna, 1994). Formation of such complexes depends on the nature of starch and lipids present in the formulation. Lipid levels above 5 % may significantly reduce expansion, especially due to its effects on starch gelatinization, and levels below 3 % may not affect expansion considerably (Steel et al., 2012). High lipid levels reduce extruder performance by reducing shear within the extruder barrel. For some snack products, lowering moisture content may compensate for expansion in formulations with high lipid content.

Based on their water solubility, dietary fibers are categorized as insoluble or soluble, and both fractions are associated with various health benefits. Insoluble fiber fractions may be redistributed to soluble fibers as a result of the modifications in their physicochemical and structural properties which take place during extrusion cooking (Martínez-Bustos et al., 2011; Moscicki et al., 2013). This has been attributed to cleavage of non-covalent and covalent bonds between fibers and other molecules, with the resultant smaller molecules being more soluble (Steel et al., 2012). Degree of fiber degradation could depend on shear stress intensity (Moscicki et al., 2013). Several researchers have reported decreased expansion in extruded products on increasing the level of dietary fiber, probably due to inhibition of complete starch gelatinization (Frohlich et al., 2000; Mendonca et al., 2000; Yanniotis et al., 2007). Also, the water binding capacity of fibers may inhibit moisture vaporization, and thus expansion of products as they exit from the die. Although there may be no changes in total fiber content in relation to feed material, numerous reports have been made on increased soluble fiber content in extruded products (Gualberto et al., 1997; Rashid et al., 2015; Robin et al., 2012).

Mineral absorption may be improved by extrusion due to the destruction of inhibitory factors like condensed tannins and phytates (Steel et al., 2012). Loss of heat sensitive vitamins is expected during thermal treatments at 100 ^{o}C and above, especially for water-soluble vitamins such as vitamin C (Moscicki et al., 2013). However, due to the high temperature short time nature of extrusion cooking and rapid cooling after extrusion, such losses are usually minimal when compared to other traditional thermal treatments. Several studies have been carried out especially on retention of B-vitamins in cereals, particularly thiamine, riboflavin and niacin (Athar et al., 2006; Riaz et al., 2009). Retention of such vitamins are often influenced by temperature, moisture content and screw speed. Vitamins A and E are highly stable during extrusion cooking. In order to achieve products with good nutritional quality, careful control of extrusion parameters is requisite (Moscicki et al., 2013). A common practice among manufacturers is post-extrusion enrichment of extruded products by spraying with micronutrients.

4. Value addition to food wastes and by-products

4.1 Fruits and vegetables

Food processing wastes encompass all food residues left behind from various processing operations (Shilev et al., 2006). Per capita production for human consumption of edible food parts is about 460 kg/year in sub-Saharan Africa and South/Southeast Asia, while per capita food loss is approximately 120-170 kg/year (FAO, 2011). Substantial amounts of food wastes are generated from processing industries globally. Globally, approximately one-third of food intended for human consumption is wasted, from initial agricultural production, through processing and down to consumption (FAO, 2011). There is heightened interest in the recovery of these food wastes, especially with the industrialization and technological advances in food processing techniques that has led to explosion in waste generation (Altan and Maskan, 2016). With the appropriate means, these wastes could beccome useful by-products or residues that may be transformed into end products whose cost exceeds the cost of reprocessing (Shilev et al., 2006). Strategies for efficient reutilization of these agricultural industry residues and by-products have been the focus of several publications (FAO, 2014; Helkar et al., 2016; Jayathilakan et al., 2012). Such residues could become a supplementary resource to manufacturers if methods for cost-effective recycling or reprocessing are available. With the numerous advantages of extrusion cooking in handling diverse food materials at low cost, several of these industrial by-products and residues have found useful application in extruded products. A diverse range of extruded foods have been developed using by-products from food industries, and these materials naturally influence the textural, functional, sensorial, physical and nutritional characteristics of the products (Altan and Maskan, 2016).

Different processing applications and raw materials generate various amounts and types of by-products and wastes. Processing residues include those generated from processed fruits and vegetables, dairy and meat products, grain mill and bakery products, sugar and confectionary products, fat and oil processing, beverages and other sundry food preparation residues (Kasapidou et al., 2015). Wastes generated from fruits and vegetables alone may account for an estimated 30 % of the processed material (Gowe, 2015; Kasapidou et al., 2015). These by-products are valuable sources of antioxidants, essential fatty acids, dietary fiber, minerals, vitamins, and phytochemicals including polyphenols, carotenoids, phytosterols, and hesperidin (Ezejiofor et al., 2014; Kasapidou et al., 2015; Varzakas et al., 2016). Numerous health-promoting benefits have been attributed to these functional components (Altan and Maskan, 2016). Most of these by-products have been traditionally used as feed ingredients in animal nutrition, however, there is growing interest in their utilization for human nutrition. The fraction of residue left behind after juice extraction is approximately 15 % for grapes and 50 % for citrus (Rohm et al., 2015). High dietary fiber has been reported in most fruit and vegetable pomace, and depending on the source, they may be characterized by different levels of cellulose, hemicellulose lignin and other fractions (Nawirska and Uklanska, 2008). Recycling methods that add value to such residues increase the overall profit from food processing and reduce the adverse environmental effects that may arise from disposal.

Some fruit and vegetable residues and by-products which have been used to develop extruded foods include tomato peel and seed (Devi et al., 2016), pineapple waste pulp (Kothakota et al., 2013), carrot pomace (Alam and Kumar, 2014; Kumar et al., 2010), cauliflower trimmings (Stojceska et al., 2008), milled orange peel, grape seeds and tomato pomace (Yagci and Göğüş, 2009), tomato and grape pomace (Altan et al., 2009), avocado seeds (Olaeta et al., 2007), cranberry pomace (White et al., 2010) and dehydrated naranjita fruit bagasse (Ruiz-Armenta et al., 2018) (Table 2).

4.2 Dairy, meat and seafood

Some poultry, meat and fish processing residues and by-products, which when randomly disposed may constitute environmental hazards, can be transformed into useful value-added products (Jayathilakan et al., 2012). This is especially important considering the increased demand for food industries to develop strategies aimed at recovering processing by-products and residues. The classification of edible and inedible animal-based by-products vary in different countries, and some regulatory agencies consider all residues left behind, aside from dressed meat, to be by-product or offal (Jayathilakan et al., 2012). Characterization of these by-products depend on society, religion, and traditions, however, they most often include trimmings, fatty materials, feet, bones, skins, among others (Helkar et al., 2016). Edible portions depend on usage and may include the internal organs, such as liver, heart, and kidney. Other by-products include spleen, brains, intestines, and tripe. These materials are very susceptible to microbial contamination, and careful handling is essential in order to reduce the risk of transmitting pathogenic microorganisms (Barbut, 2015). Their handling often entails treatments such as trimming, washing, packaging and cooling. Due to bovine spongiform encephalopathy outbreak, animal by-products handling is very strictly regulated.

These by-products are nutritionally rich, and contain high levels of lipids, carbohydrates, proteins and other bioactive components (Helkar et al., 2016). Liver and kidneys contain about five to ten times more riboflavin than lean meat, and are great sources of vitamins B12, B6, and folacin (Jayathilakan et al., 2012; Pearson and Gillet, 2012). Major limiting factors to the use of these materials for human consumption are the associated health concerns and low prices, causing most processors to instead channel their research efforts and marketing towards non-food uses. Total by-products from pigs, cattle and lambs represents approximately 52, 66 and 68 % of their live weight, respectively (Jayathilakan et al., 2012). An estimated half of these materials are considered unfit for consumption because of their distinctive properties. Acceptance of these materials in products by consumers depends on nutrient content, cost and usage. Intestines have found very useful application as sausage casings. Fish protein hydrolysates from fish residues and by-products have good potential as functional components in food formulations (Chalamaiah et al., 2012; Hordur and Rasco, 2000). The recovery of fish proteins from by-products by various extraction methods results in products with good protein quality which could be incorporated into various processing lines (Jayathilakan et al., 2012).

Another segment of the animal-based market is the dairy sector, which includes milk and milk products. The major by-product from milk processing is whey, a translucent liquid remnant from cheese production (Hoffman and Falvo, 2004). Various separation techniques may be employed to concentrate and purify the proteins. Whey proteins account for about 20 % of milk, while casein accounts for 80 % (Hoffman and Falvo, 2004). Whey constituents include immunoglobulin, α-lactalbumin, β-lactoglobulin, lactoferrin, bovine serum albumin and lactoperoxidase as some constituents present in whey (Helkar et al., 2016). Also, milk by-products have been used in various confectionary, bakery, and health supplements, especially in dry form, where they serves as nutritional and functional ingredients (Helkar et al., 2016; Królczyk et al., 2016; Rebouillat and Ortega-Requena, 2015). While most animal-based by-products are employed in the formulation of animal feed, several have been incorporated into extruded products for human consumption including residue fish meal (Goes et al., 2015), whey protein (Walsh and Wood, 2010), whey protein isolate (Qi and Onwulata, 2011), whey protein concentrate (Onwulata, 2009; Yadav et al., 2013), crab by-products (Murphy et al., 2003; Obatolu et al., 2005), and egg shell powder (Su, 2007).

4.3 Cereal by-products and residues from starch, syrup and alcohol production

Grain mill industries are those industries which primarily engage in milling flour or meal from grains. Aside these, other industries utilize grains as a major raw material stream. These include sugar (glucose and high fructose corn syrups) and starch industries, rice mills, breweries, and distilleries. By-products from grains include those from rice polishing, dry milling and wet milling of grains for animal feedstuff, human foodstuff and industrial products. Dry milling is employed for products like meal and flour, while production of starch, syrups, and oil entail wet milling. A large percentage of by-products of the primary processing of cereals are mainly used as animal feedstuffs. Although most brewing and distillation processes use starchy cereals, roots crops especially sweet potatoes and cassava have been used to produce alcoholic beverages as well as starch and sweeteners like glucose and high fructose syrups (Johnson et al., 2010; Kaur and Sandhu, 2016).

The by-product terms like hulls, bran, germ, are often applied for multiple grains like rice, wheat, sorghum, however, some terms may be exclusively used to describe a by-product of a specific grain. In order to meet consumer preferences, cereal grains for food are milled to separate the germ and bran, thereby removing important nutrients like vitamins and minerals (Elmekawy et al., 2013). Rice milling, which involves separation of bran and husk from the edible portion, yields about 70 % rice endosperm, 20 % rice husk, 8 % bran and 2 % germ (Esa et al., 2013). Due to their high contents of vitamins, minerals, fiber and phenolic compounds, some by-products of grain milling have received a lot of research interest, especially as functional ingredients.

Co-products from the milling of wheat to flour include wheat husk, germ, bran, and middlings (Chattopadhyay, 2012). Wheat gluten is obtained as a by-product from the manufacture of wheat starch. Dry gluten typically contains approximately 75 % protein, 8 % moisture, and some quantities of lipids, fiber and starch (Day et al., 2006). Extrusion technology has been used to texturize wheat gluten and simulate the fibrous structure of meat (Day et al., 2006). Milling of rice paddy to produce polished grains yield broken rice in addition to rice hull and bran. Some cereal brans like those from rice are high in lipids making them very susceptible to rancidity. An ideal process may yield approximately 68-72 % milled rice, 8-12 % rice bran and 20 % husk, depending on rice variety used (Esa et al., 2013). The most common feed brans are corn, rice, and wheat bran. Germ refers to the embryo of the grain which is high in lipids and proteins, the commonest of which are wheat and corn germ meals. Rice germ is rich in vitamins E, B_1, B_2, B_6 and dietary fiber (Esa et al., 2013). Dietary fiber in rice mill by-products comprises mainly of cellulose, lignin, hemicellulose, hydrocolloids and pectins.

Sorghum or corn gluten meal, a by-product from the wet milling of sorghum or corn, contains primarily proteins left behind after the removal of the germ and starch (Elmekawy et al., 2013). By-products from biofuel industries and distilleries include dried distillers' grain with solubles (DDGS) and spent brewer's grains (Wadhwa and Bakshi, 2016). Cereal spent grains are often dried to a low moisture content and sold as feed. In addition to grain milling, barley may be used in the malting and brewing industries and distilleries, and by-products from these include malted barley, distiller's solubles, brewer's yeast and spent hops. A number of these by-products, like distillers' grains and spent brewers' grains, are classified as protein sources due to their relatively high protein content. Distillers' grains, a by-product of the distillation process, results from the primary fermentation of a mix of corn, rice and other grains into alcohol by yeast (Zentek et al., 2014). Brewers' grains ideally refer to extracted residues of barley malt produced as a by-product of brewing. Distillers' dried grains with solubles (DDGS) are the dried distillers' grains to which the soluble residues have been added. Some distillers' grain with solubles may contain up to 27–35 % protein, and spent brewer's grains up to 27–33 %, dry matter basis, although they are both limiting in lysine (Wadhwa and Bakshi, 2016). Pelletized wheat-based DDGS had dry matter and crude protein in the ranges of 91.27–92.60 % and 37.37–40.33 %, respectively (Tumuluru et al., 2010). Extruded products were developed from wheat flour and corn starch with the inclusion of 10 % brewer's spent grain (BSG), and higher total dietary fiber in the wheat-BSG and corn starch-BSG products was reported (Stojceska et al., 2009). Furthermore, extruded fiber-rich, barley-based snacks were developed using brewer's spent grains from malted barley (Kirjoranta et al., 2016). Cereal-based extruded snacks were also formulated using increasing levels of BSG, and increasing phenolic content and anti-oxidant capacity were reported in extrudates (Reis and Abu-Ghannam, 2014). Extruded snacks were also richer in fiber and had low glycemic index. Pasta was developed from yam starch and brewers spent grain, BSG (5–15 %) and the optimum conditions for extrusion, based on functional properties and proximate composition, were 121.47 rpm screw speed, 110 ^{o}C barrel temperature and 9.58 % BSG (Phillip et al., 2013), with the BSG serving as a good source of dietary fiber in the products. Increased protein content, bulk density, and phytic acid, and reduced sectional expansion index were reported with the addition of BSG in RTE expanded products from wheat flour and corn starch at 10-30 % (Stojceska et al., 2008). Increased levels of BSG led to a reduction in specific mechanical energy input, and addition of BSG caused an increase in apparent density of expanded snacks from rice and brewer spent grains (Nascimento et al., 2017). Additionally, in extruded snacks that have been produced from brewer's spent cassava (BSC), a by-product from the production of beer using high quality cassava flour (Ha et al., 2014), the level of BSC used influenced bulk density of the products, which was reduced with increasing BSC. The optimum product based on lateral expansion, water solubility index, water absorption index and bulk density was obtained at 121.25 ^{o}C barrel temperature, 30 Hz screw speed, 1.88 % water content, and 4 % BSC flour. Noodles and extruded snacks were developed from wheat flour and semolina supplemented with defatted corn germ, corn bran and corn gluten meal (0, 5, 10, 15 and 20 %). Cooking time for noodles increased as blending ratio for all the by-products increased, water absorption ratio was highest in bran noodles, followed by gluten noodles and germ noodles, and expansion ratio in extruded snacks was highest in bran snacks than gluten snacks (Sharma et al., 2012).

In a study on the effect of corn bran substitution on rice noodles, noodles which contained corn bran were softer in texture and had lower expansion ratio (Baek et al., 2014). The rice-corn bran mixture exhibited lower pasting properties as corn bran levels increased. Wheat flour was extruded with increasing levels of wheat bran fibers (2.8, 12.6 and 24.4 %), using different barrel temperatures, water contents, and screw speeds (Robin et al., 2011). The varying concentrations of bran in the formulations may have induced differences in starch transformation, thereby modifying the expansion properties of the products.

Compared to untreated rice starch, extruded rice starch had lower viscosity, which further decreased with the addition of stabilized rice bran, in the production of extruded products from a blend of rice starch with 10 % w/w stabilized rice bran using a co-rotating twin-screw extruder (Wang et al., 2017). The crystalline structure of rice starch and retrogradation rate changed with the addition of stabilized rice bran and extrusion (Wang et al., 2017). The nutritional, functional and biophysical properties of rice bran were compared before and after stabilization using a twin-screw extruder. Stabilized rice bran had lower protein, which was attributed to the denaturation of proteins during the process, while the color of rice bran was improved, compared to unstabilized rice bran (Rafe et al., 2017). Folic acid, niacin, pantothenic acid and riboflavin contents were reduced while dietary fiber, water-holding and foaming capacity were improved by the extrusion process (Rafe et al., 2017). Antioxidant activity and total phenolic content of bran-enriched snacks (10, 20 and 30 %) decreased during ambient storage for six months, however, water activity and free fatty acids increased in the products (Dar et al., 2016).

Increase in broken rice inclusion levels led to increased expansion, water solubility and water absorption index, in the development of extruded products from lupin and broken rice, a by-product of rice milling (Oliveira et al., 2015). Extrusion conditions that produced better color and improved expansion in products were 85 ^{o}C temperature and 12 g/ 100 g moisture, in the development of extruded snacks from broken rice grains, rice bran and dried black soybean okara (81:9:10), and ash content in rice bran was 45 times higher than that of the broken rice (Coutinho et al., 2013).

4.4 By-products from oilseed processing

The major by-product of oilseed extraction is pressed cake, which may be useful depending on the oilseed and oil extraction method applied. Processing methods, especially those involving heat, may eliminate or reduce antinutritional factors to an extent. However, this may denature some proteins, reduce the availability of certain amino acids and adversely affect protein digestibility. Pressed cake derived from water-extraction are typically low in nutrients, and other extraction methods may yield by-products better suited for human consumption. Screw-press or hydraulic press meals are higher in oil than residues from solvent extraction, and these may subsequently be solvent-extracted to obtain more oil. Decortication prior to oil extraction reduces the fiber content but improves protein levels in the residual meal. Some more common oilseed meals include soybean meal, peanut meal, canola meal, cottonseed meal, and sunflower meal (Bernard, 2011). Soybean is the most preferred source of good quality protein residue from oil processing, with crude protein content ranging from 44 to 50 % and good amino acid composition (FAO, 2004). Residues from oil extraction may be processed into flour or meal, and the extent to which residues or by-products can be usefully applied in food products depends on its quality which in turn is influenced by toxic factors and the processing required to reduce these factors. Thermal and physico-chemical treatments during processing of vegetable proteins affect the functional properties and nutritional quality of the products (Moure et al., 2006). Some oilseed by-products and residues which have been used in extruded products include defatted sunflower meal (Bhise et al., 2015), glandless cottonseed meal (Jáquez et al., 2014; Reyes-Jáquez et al., 2012), partially defatted soybean flour (Olusegun et al., 2016), defatted flaxseed meal (Bhise et al., 2013), partially defatted peanut flour (Suknark et al., 1997), soybean meal (Aguilar-Palazuelos et al., 2006), soybean meal and vital wheat gluten (Chaiyakul et al., 2008), and defatted groundnut cake flour (Purohit and Rajyalakshmi, 2011) (Table 3).

5. Conclusion and future prospects

Extrusion processing is a useful tool for handling diverse raw materials and provides a useful means by which unconventional, under-utilized nutrient sources and food processing residues can be incorporated into food systems. Under-utilized cereals, pseudo cereals and food materials which have demonstrated low economic or processing value have been successfully integrated into consumer markets. Extrusion remains a highly popular technique for modifying the properties of food commodities and fabricating products with special attributes, and the food matrix and extruder operating conditions play important roles in final product quality. Also, large quantities of by-products and wastes are generated from food processing operations, some of which have been incorporated as useful components into extruded products.

Contemporary food extruders have advanced beyond tools for handling predominantly cereal- or starch-based materials. With the increasing innovations and advances in food extrusion technology, areas relating to value addition and bioprocessing are being explored and rapidly expanding to accommodate new ideas and consumer demand for healthier products. Extrusion cooking offers a great potential for converting or re-structuring high protein sources into edible forms. Today, a number of products from alternative protein sources, which taste, feel and smell better, are accepted as meat analogs, and there are increasing demands and opportunities for these products. The possibilities for developing novel products by extrusion and creating even newer markets for these products in future is seemingly limitless, and consumers have a continually expanding range of products to choose from. Extrusion technology is also well-suited to specialty applications for food ingredients which require some form of protection or stability, and this could involve dispersion of the active ingredient in a polymer-based matrix. With the rapid evolution in extrusion technology, a range of active ingredients and polymers have been explored to allow the formulation of improved delivery systems. Application of extrusion for the smart delivery of nutrients and food bioactives is a recent practice, which holds great promise for the food sector. Presently, food extruders are regarded as high temperature, short time (HTST) bioreactors capable of modifying a diverse range of food materials and transforming them into intermediate and finished products with desired properties.

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Table 1. Under-utilized and pseudo cereals in extruded products

Reference	Product Type	Underutilized/ Pseudo Cereal	Effects
Byaruhanga et al. (2014)	Sorghum and soy-based extruded snacks	Sorghum (*Sorghum bicolor*)	Four sorghum varieties (*Seso1*, *Epuripur*, *Seso3* and *Eyera*) evaluated performed well during extrusion, as assessed by the physico-chemical properties of the extrudates
Delimont et al. (2017)	Extruded, sorghum-cowpea and sorghum-soy fortified blended foods (FBF)	Sorghum (*Sorghum bicolor*)	The study indicated that sorghum could serve as a useful alternative for corn in extruded FBFs
Gulati et al. (2016)	Extruded snack	Proso millet (*Panicum miliaceum*)	High expansion and antioxidant activity were obtained by extruding proso millet under low moisture and high screw speed
Patil et al. (2016)	Composite bread	Finger millet (*Eleusine coracan L.*)	Composite breads produced using extruded finger millet flour had increased loaf volume and height, as well as a softer texture

Zelazinski et al. (2016)	Extruded snack	Spelt (*Triticum spelta*)	Despite its weaker baking properties, extruded spelt products had high water holding capacity and quality similar to conventional corn extrudates
Altan et al. (2008)	Extruded snack	Barley (*Hordeum vulgare*)	Desired textural characteristics and color were obtained when extruded at 156 °C and 166 rpm
Brennan et al. (2012)	Extruded breakfast cereal	Amaranth (*Amaranthus spp*), Millet *(Pennisetum spp)* and Buckwheat (*Fagopyrum esculentum*)	The study illustrated the potentials of these non-traditional cereal flours in extruded breakfast cereals
Robin et al. (2015)	Extruded whole grain products	Millet *(Pennisetum spp)*, Teff (*Eragrostis tef*), Sorghum (*Sorghum bicolor*), Quinoa (*Chenopodium quinoa*), and Amaranth (*Amaranthus spp*)	Expansion properties varied differently among the grain, with the lowest exhibited by amaranth flour
Dogan and Karwe (2003)	Extruded snack	Quinoa (*Chenopodium quinoa*)	The study demonstrated the potentials of quinoa as an ingredient in extruded snacks
Gearhart and Rosentrater (2014)	Extruded gluten-free snacks	Quinoa (*Chenopodium quinoa*) and Amaranth (*Amaranthus spp*)	Extrudates exhibited good quality attributes, without the use of any binding agents.

Table 2. Fruit and vegetable by-products in extruded foods

Reference	Product	By-product/ Residue	Effect
Devi et al. (2016)	Puffed snack from corn flour, rice flour and tomato pomace	Tomato peel and seed, at 0-30 % and 0-5 % inclusion respectively	Significant increases in crude fiber and protein contents with the addition of tomato pomace were reported. Incorporation of tomato pomace reduced expansion values. An optimal product was obtained using 40 % corn flour, 30 % rice flour, 25 % tomato peel and 5 % tomato seed
Kothakota et al. (2013)	Extruded snack from broken rice flour, red gram powder and pineapple waste pulp	Pineapple waste pulp (12.5 %)	Overall acceptability of the products ranged from 5.2-7.5 %
Kumar et al. (2010)	Extruded products from carrot pomace, rice flour and pulse powder	Carrot pomace (equal levels of carrot pomace and pulse powder CPPP, at 10-30 % inclusion)	Optimum processing conditions were 16.5 % CCPP in rice flour, 19.23 % moisture content, 310 rpm screw speed and die temperature of 110 °C
Stojceska et al. (2008)	RTE wheat-based expanded snack	Cauliflower trimmings (5 %, 10 %, 15 % and 20 %)	Expansion index showed negative correlation to level of cauliflower
Yagci and Göģüş (2009)	Expanded snack from rice grits, durum flour, partially defatted hazelnut and fruit wastes	Fruit wastes from milled orange peel (80 % d.b.), grape seeds (10 % d.b.) and tomato pomace (10 % d.b.), at 3-7 % inclusion levels	There was positive correlation between waste content and radial expansion ratio
Alam and Kumar (2014)	RTE snack from rice flour, red lentil flour and carrot pomace	Carrot pomace (10 %)	Optimum process parameters for high quality extrudates were 14 % feed moisture, 394 rpm screw speed, 120 °C die temperature and formulation of 80:10:10; rice flour: pulse flour: carrot pomace flour
Altan et al. (2009)	Barley-based extruded food	Tomato pomace and grape pomace (0	Anti-oxidant activity increased with increase in tomato pomace level. Both barley-tomato and barley-grape pomace extrudates

		%, 2 %, 6 %, 10 % and 12.7 %)	were lower in β-glucans than barley extrudates
Olaeta et al. (2007)	Corn-based extruded product	Avocado seed (40 % and 100 %)	Water absorption rate was higher in products containing 40 % avocado seed, while rate of water solubility was higher in products from 100 % avocado seed
White et al. (2010)	Corn starch extruded products	Cranberry pomace (30 %, 40 % and 50 %)	Highest anthocyanin retention was observed at 150 °C and 30 % pomace. Flavonols increased by 30-34 % following extrusion.
Ruiz-Armenta et al. (2017)	Third generation snack from whole-grain yellow-corn and naranjita fruit	Dehydrated naranjita bagasse, DNB (1.12 to 11.88 %)	Expansion index decreased with increasing DNB. Optimal processing conditions were 125 °C extrusion temperature, 23 % moisture content and 8.03 % DNB

Table 3. Oilseed by-products in extruded foods

Reference	Product	By-product/ Residue	Effect
Bhise et al. (2015)	Textured defatted sunflower meal	Defatted sunflower meal	Texturized product had improved functional properties
Jáquez et al. (2014)	Corn-based extruded snacks	glandless cottonseed meal in corn flour (0:98, 5:93, 10:88, 25:73 and 98:0 %)	A more irregular and fluorescent structure was obtained in products as cottonseed meal content increased
Olusegun et al. (2016)	Cassava-based extruded products	Partially defatted soybean flour (10, 20, 30 %)	An optimum product was obtained using 16 g water/100 g feed moisture, 20 g soybean/100 g flour and 170 °C barrel temperature
Bhise et al. (2013)	Texturized defatted flaxseed meal	Defatted flaxseed meal	An optimized product contained 2.61 % moisture, 2.70 % fat, 38.24 % protein and 12.24 % fiber.
Reyes-Jáquez et al. (2012)	Corn-based extruded snacks	Glandless cottonseed meal	Optimal conditions were 120 ^{o}C barrel temperature, 179.9 rpm screw speed, 10 % cottonseed meal and 16.8 % moisture content
Suknark et al. (1997)	Directly puffed products from starch and partially defatted peanut flour	Partially defatted peanut flour, PDPF	Optimum conditions which provided high expansion, low bulk density, and low shear strength were 20–30 % PDPF at 18–19 % moisture content for tapioca starch and 5–30 % PDPF at 18–19 % moisture content for corn starch.
Chaiyakul et al. (2008)	Extruded snacks from rice flour, soybean meal and wheat gluten	Soybean meal	Hardness and crispness were reportedly improved by increasing protein content

Aguilar-Palazuelos et al. (2006)	Extruded pellets from potato starch, quality protein and soybean meal	Soybean meal (15 %)	Maximum expansion of the pellets was reported at 123-140 ^{o}C barrel temperature and 24.5-30 % feed moisture.
Purohit and Rajyalakshmi (2011)	Rice-based extruded snacks and wheat-based noodles	Defatted groundnut cake flour, DGCF	As the level of DGCF increased, darker colors were observed for both noodles and extruded snacks, which was attributed to Maillard reaction due to the higher protein content.

Figure 1.

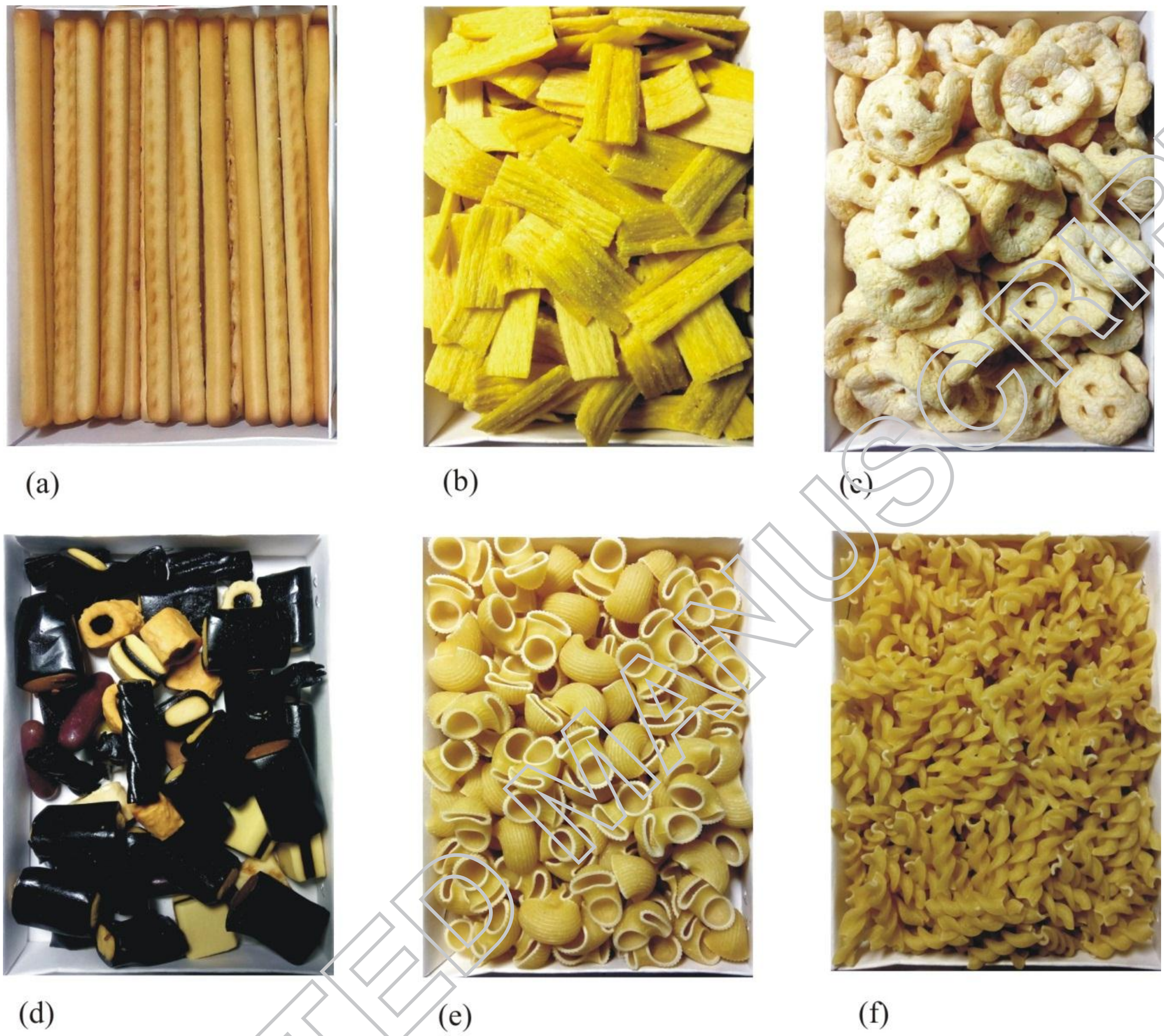

Figure 1. Some extruded products from different raw materials
(a) Milk stick biscuits (b) Extruded wheat snacks (c) Wheat flower chips
(d) Liquorice (e) Pasta (Escargot) (f) Pasta (Torsades)