

Extrusion Technology and its Application in Food Processing - An Overview

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Abstract

Extrusion cooking technology is a multi-step, multi-functional and thermal/mechanical processing method involving high temperature and pressure that is used to prepare a variety of processed foods. HTST processes are preferred because of the retention of nutrients in the product. In addition to the usual benefits of these processes, extrusion offers the possibility of modifying the functional properties of food ingredients and/or of texturizing them. Like other processes for heat treatment of food, extrusion cooking may have both beneficial and undesirable effects on nutritional value. Beneficial effects include gelatinization of starch, destruction of anti-nutritional factors, increased soluble dietary fibre, reduction of lipid oxidation and contaminating microorganisms and retains natural colours and flavours of foods. Despite these advantages, occurrence of Millard reaction that leads to reduce the nutritional value of the protein and loss of heat-labile vitamins are the disadvantages of this process. Careful control of process parameters is essential to obtain a nutritionally balanced extruded product. Mild extrusion conditions (high moisture content, low residence time, low temperature) improve the nutritional quality, while high extrusion temperatures (200 °C), low moisture contents (<15%) and/or improper formulation (e.g. presence of high-reactive sugars) can impair nutritional quality adversely. To obtain a nutritionally balanced extruded product, careful control of process parameters is essential.

Keywords: Extrusion, food processing, Technology, history, cold extrusion

La Technologie d'Extrusion et Son Application dans la Transformation des Aliments - Un Aperçu

Résumé

La technologie de cuisson par extrusion est une méthode de traitement thermique/mécanique en plusieurs étapes, multifonctionnelle et impliquant une température et une pression élevées qui est utilisée pour préparer une variété d'aliments transformés. Les procédés HTST sont préférés en raison de la rétention des nutriments dans le produit. Outre les avantages habituels de ces procédés, l'extrusion offre la possibilité de modifier les propriétés fonctionnelles des ingrédients alimentaires et/ou de les texturer. Comme d'autres procédés de traitement thermique des aliments, la cuisson-extrusion peut avoir des effets à la fois bénéfiques et indésirables sur la valeur nutritionnelle. Les effets bénéfiques comprennent la gélatinisation de l'amidon, la destruction des

facteurs anti-nutritionnels, l'augmentation des fibres alimentaires solubles, la réduction de l'oxydation des lipides et des micro-organismes contaminants et la conservation des couleurs et des saveurs naturelles des aliments. Malgré ces avantages, l'apparition de la réaction de Millard qui conduit à réduire la valeur nutritionnelle de la protéine et la perte de vitamines thermolabiles sont les inconvénients de ce procédé. Un contrôle minutieux des paramètres du processus est essentiel pour obtenir un produit extrudé équilibré sur le plan nutritionnel. Des conditions d'extrusion douces (haute teneur en humidité, faible temps de séjour, basse température) améliorent la qualité nutritionnelle, tandis que des températures d'extrusion élevées (200 °C), une faible teneur en humidité (<15 %) et/ou une formulation inappropriée (par exemple la présence de sucres hautement réactifs) peut altérer négativement la qualité nutritionnelle. Pour obtenir un produit extrudé équilibré sur le plan nutritionnel, un contrôle minutieux des paramètres du procédé est essentiel.

Mots-clés : Extrusion, agroalimentaire, Technologie, histoire, extrusion à froid

تقنية البثق وتطبيقاتها في معالجة الأغذية - نظرة عامة

الملخص

تقنية الطهي بالبثق هي طريقة معالجة حرارية / ميكانيكية متعددة الخطوات ومتعددة الوظائف تتضمن درجة حرارة عالية وضغطاً يستخدم لتحضير مجموعة متنوعة من الأطعمة المصنعة. تُفضل عمليات HTST بسبب الاحتفاظ بالمغذيات في المنتج. بالإضافة إلى الفوائد المعتادة لهذه العمليات، يوفر البثق إمكانية تعديل الخصائص الوظيفية لمكونات الطعام و / أو تركيبها. مثل العمليات الأخرى للمعالجة الحرارية للأغذية، قد يكون للطهي بالبثق آثار مفيدة وغير مرغوب فيها على القيمة الغذائية. وتشمل الآثار المفيدة تحويل النشا إلى جيلاتين، وتدمير العوامل المضادة للتغذية، وزيادة الألياف الغذائية القابلة للذوبان، وتقليل أكسدة الدهون، وتلويث الكائنات الحية الدقيقة، والاحتفاظ بالألوان والنكهات الطبيعية للأطعمة. على الرغم من هذه المزايا، فإن حدوث تفاعل ميلارد الذي يؤدي إلى تقليل القيمة الغذائية للبروتين وفقدان الفيتامينات القابلة للحرارة هي عيوب هذه العملية. يعد التحكم الدقيق في معلمات العملية أمراً ضرورياً للحصول على منتج مبثوق متوازن من الناحية التغذوية. ظروف البثق المعتدلة (محتوى رطوبة مرتفع، وقت مكوث منخفض، درجة حرارة منخفضة) تعمل على تحسين الجودة الغذائية، في حين أن درجات حرارة البثق العالية (200 درجة مئوية)، ومحتويات رطوبة منخفضة (أقل من 15٪) و / أو تركيبة غير صحيحة (على سبيل المثال، وجود سكريات عالية التفاعل) يمكن أن يضر بالجودة الغذائية. للحصول على منتج مبثوق متوازن من الناحية التغذوية، فإن التحكم الدقيق في معلمات العملية أمر ضروري.

الكلمات المفتاحية: البثق، تجهيز الأغذية، التكنولوجيا، التاريخ، البثق البارد

Introduction

Extrusion cooking is a high-temperature short-time (HTST, thermo-mechanical) process which heat transfer, mass transfer, pressure changes and shear are combined to produce effects such as, Cooking, Melting, Texturizing, Conveying,

Puffing, Mixing, Kneading, Forming, reduction in microbial contamination and inactivates enzymes (Khushbu *et al.*, 2020 and Ranjit *et al.*, 2014). It also 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 (Offiah *et al.*, 2018; Khushbu *et al.*, 2020 and Riaz, 2000). 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 and Fellows *et al.*, 2000). Extruders may be categorized into piston, roller or screw extruders based on its conveying mechanism (Brennan and Grandison, 2012). In food processing applications, screw extruders are the most used, and may involve single, twin or multiple screws which rotate within barrel. Regardless of the design or type, the operating principles are the same. In 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 mixture of pre-conditioned ingredients, are introduced into the barrel through a hopper and conveyed by the help of 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 (Riaz, 2000 and Karwe, 2009). 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 (). 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. 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 (Offiah *et al.*, 2018 and Ramachandra and Thejaswini, 2015). Various food groups, including pulses and oilseeds, meat and fish products, roots and tubers,

fruits and vegetables have found useful application in extrusion processing. Lots of reviews had been published on many aspects of food extrusion technology, including changes in foods (Riaz, 2006) or vitamin stability during extrusion (Ramachandra and Thejaswini, 2015), and effects of process parameters on quality attributes (Camire *et al.*, 1990). 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 reintegrating these residues into edible food products (Offiah *et al.*, 2018).

Brief history of Extrusion Technology

Historically, one can trace the use of a screw as a conveying device to the Greek philosopher Archimedes, who used a single screw in a cylindrical open channel to pump water uphill. Today's extruder consists of one or more screws encased in a metal barrel, attached to a drive motor. A hopper at one end is used to feed raw materials, while a die on the other gives shape to the product (Adekola, 2016). Extruders were developed in the 1870s to manufacture sausage. Packaged dry pasta and breakfast cereals have been produced via extrusion since the 1930s, the method was applied to pet food production since the 1950s (first extruded dog food in 1957 - Purina Dog Chow and first extruded cat food - Purina Friskies in 1962). It has also been incorporated in kitchen appliances, such as meat grinders, herb grinders, coffee grinders, and some types of pasta makers. Application of the single-screw extruder evolved during the 1930s, when it was used to mix semolina flour and water to make pasta products. It was also used in the process of making ready-to-eat (RTE) cereals to shape hot, precooked dough. In both of these applications, the level of shear rate was low. During the late 1930s and 1940s, directly expanded corn curls

were made using extruders, which were characterized by extremely high shear rates. The first patent on an application of twin-screw extrusion technology was filed in the mid-1950s. Since then, the application of extrusion technology has widened and grown dramatically (Karwe, 2009).

Principles of Extrusion

The principles of operation in extrusion are similar in all types: raw materials are fed into the extruder barrel and the screw(s) then convey the food along it. Further down the barrel, smaller flights restrict the volume and increase the resistance to movement of the food. As a result, it fills the barrel and the spaces between the screw flights and becomes compressed. As it moves further along the barrel, the screw kneads the material into a semi-solid, plasticized mass. If the food is heated above 100°C the process is known as *extrusion cooking* (or *hot extrusion*). Here, frictional heat and any additional heating that is used cause the temperature to rise rapidly. The food is then passed to the section of the barrel having the smallest flights, where pressure and shearing is further increased. Finally, it is forced through one or more restricted openings (dies) at the discharge end of the barrel as the food emerges under pressure from the die, it expands to the final shape and cools rapidly as moisture is flashed off as steam. A variety of shapes, including rods, spheres, doughnuts, tubes, strips, squirls or shells can be formed. Typical products include a wide variety of low density, expanded snack foods and ready-to-eat (RTE) puffed cereals. Cold extrusion, in which the temperature of the food remains at ambient is used to mix and shape foods such as pasta and meat products. Low pressure extrusion, at temperatures below 100°C, is used to produce, for example, liquorice, fish pastes, surimi and pet foods (Riaz, 2000).

Cold Extrusion

Cold extrusion is a processing technique typically used in the single-screw extruder in which the

temperature of the food products remains at ambient and is used to produce products such as pasta and various meat products (Riaz, 2000). These cold extruded products (e.g. pasta and macaroni) have been recalled from the market due to the presence of microorganisms. Because these products are made with raw ingredients such as flour and semolina that may be contaminated with pathogens and the product is not heated during the commercial processing which may lead to presence of some microorganism in the product. Viable microorganism remains unaffected by the cold extrusion processing technique. The interest in research related to the safety of extruded products led to the study of the effect of temperature and screw speed on the survival of *Staphylococcus aureus* and *Salmonella* Typhimurium during the production of spaghetti. Tushar, (2017) determined that *S. Typhimurium* population survived the extrusion process at temperatures from 35 to 55°C and 12 rpm. Faster screw speeds (12-30 rpm) led to the greater reduction of *S. Typhimurium* at 35°C due to the mechanical destruction (Alam *et al.*, 2016). Tushar, (2017) also determined that a 1-log reduction of *S. aureus* was obtained at 35-55°C and 20-50 rpm. To ensure the food safety of pasta products, food components used for products with intermediate moisture content need to be pasteurized before the mixing process to the lower water activity (aw) (Alam *et al.*, 2016).

Hot or Thermal Extrusion

When the food is heated typically above 75°C, the process is known as hot extrusion, also known as extrusion cooking or thermal extrusion. This high temperature relatively short-time process has proved to be effective in reducing the load of microbial contamination. Studies of extrusion on microbial inactivation are usually of limited scope often targeting one product matrix and characterizing a limited set of processing parameters (Alam *et al.*, 2016). In 1989, a study was done using a twin-screw extruder on

reduction of *Streptococcus thermophilus* in whey protein isolate with low moisture content (4-5 % w/w), operating temperature of 80-204°C, and a constant screw speed of 50 rpm (Alam *et al.*, 2016). Results indicated a reduction of 4.2 log of *Streptococcus thermophilus* at 143°C. This study demonstrated the efficacy of hot extrusion in assuring the safety of food and feed products. Tushar, (2017) reported the inactivation of *Bacillus globigii* during the extrusion of corn/soybean mixture (70/30%, w/w) at a moisture of 18% running at different screw speeds (80-160 rpm). Results indicated a reduction of 1-7 log when the product was extruded at high temperatures (110-130°C), while the increased screw speed resulted in lesser lethality. In another study, thermal inactivation and injury of *Clostridium sporogenes* spores were studied in a mixture of mechanically deboned turkey and white corn flour. Thermal inactivation was observed at 93.3°C with a 2-log reduction and at 115.6°C with a 4-5 log reduction (Alam *et al.*, 2016). Bianchini *et al.* (2012) used a response surface methodology to study the effect of moisture and temperature on the inactivation of *Enterococcus faecium* NRRL B-2354 in a carbohydrate-protein mix. The greatest reduction of 5-log occurred at the temperature of 81.1°C and at the highest moisture content of 28.1% evaluated in their study. Tushar, (2017), determined that thermal extrusion completely eradicated *Salmonella* when the processing temperatures were above 93.3°C. Anderson *et al.* (2017) studied the destruction of *Salmonella* Agona during the extrusion of oat flour with indigenous fat content of 8% when extruded at different temperatures (65-100°C) and water activity (0.72-0.96). Pathogen reduction was observed and ranged from 1-7 log CFU/g with the greatest reduction obtained at higher temperature and high-water activity levels. Processing conditions above 82°C and 0.89 aw achieved on average greater than a 5-log reduction of *Salmonella*. Based on the available research, it

seems that the bacterial destruction is greatest at higher temperatures with the mixture to be extruded having higher moisture levels. Little or no destruction was observed at low moisture and low temperature.

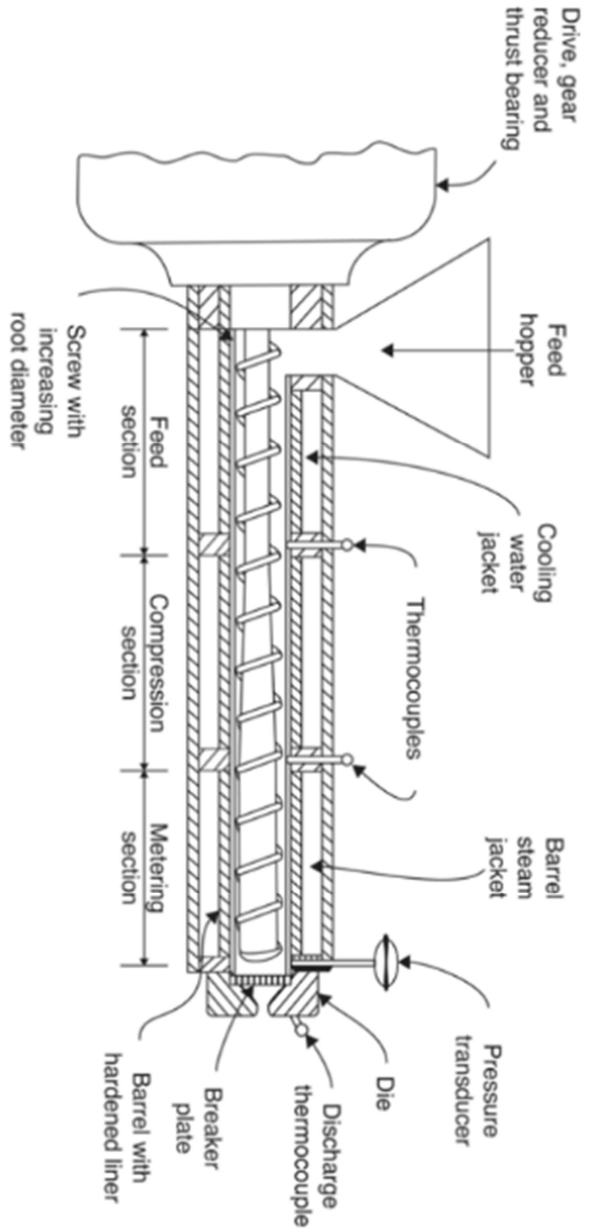


Fig 1: A typical single screw extruder

Table 1: Some Investigation and findings on used of Extrusion in food Processing

INVESTIGATOR	Year	Findings
MC ANELLY	1964	First to describe a process for the production of spongy elastic particles from soy flour.
Atkinson	1970	Disclosure of a continuous cooking extrusion process
EL-Dash	1981	First to process breakfast cereal products
Noguchi	1998	Extrusion cooking of high moisture protein foods
Fast	2000	RTE cereals
Satalai	2011	Degradation of aflatoxins by extrusion
Ryan	2011	Oat based breakfast cereal snack

Source : Rao and Thejaswini, (2015)

Extrusion processing of foods

Extrusion technology provides a platform on which processing various food products could be done by simply changing a major or minor raw material and processing conditions. Raw materials for extrusion tend to be majorly from cereal. Nevertheless, 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 etc. They 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 are of high standard, and only permitted additives of required purity must be used (Tushar, 2017). 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 (Offiah *et al.*, 2018).

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 (Guy, 2004). The materials when incorporated into a formulation tend to alter the process, thereby modifying the resulting product.

Extrusion processing of plant foods.

Cereals

Apart from breakfast cereals and snacks, other extruded cereal-based products include pasta, breads, soup bases and modified starches, biscuits, croutons, and confectionary (Asgar *et al.*, 2010). Cereal grains are common staples, providing more food energy than any other food group as they represent the most vital 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 (Offiah *et al.*, 2018 and Ilo *et al.*, 2000). This higher oil level may present problems with oxidative rancidity (Riaz, 2010). 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, which are highly convenient (Offiah *et al.*, 2018). Several products in the hot cereals' category are made from oats and wheat, while rice and corn make up a smaller percentage ((Offiah *et al.*, 2018). The RTE cereals are usually cooked and modified by flaking, toasting, puffing, shredding or extruding (Guy, 2012). 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 (Varsha and

Pavani, 2016)). 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 (Offiah *et al.*, 2018 and Onipe *et al.*, 2015). 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 (Onipe *et al.*, 2015). 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 (Offiah *et al.*, 2018). The processing of expanded products is comparable to the process for flaked products (Whalen *et al.*, 2000), 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) (Offiah *et al.*, 2018). This blend is subsequently toasted in an even layer until it browns, and low moisture is attained, after which it was broken into smaller pieces (Offiah *et al.*, 2018). 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 (Asgar *et al.*, 2010). 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 degermed corn/grits and rice (Ramachandra and Thejaswini, 2015). Cereals containing higher levels of lipids are not suitable

for expanded products due to slippage of the dough within the extruder barrel (Asgar *et al.*, 2010 and Ilo *et al.*, 2000). 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 (Ilo *et al.*, 2000). 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 those different native starches had different optimum temperatures for expansion (Offiah *et al.*, 2018). 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 (Offiah *et al.*, 2018). 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. Degermed corn expands more than whole corn; therefore, it is more often used in breakfast cereals and extruded snacks which require some degree of expansion (Ilo *et al.*, 2000). 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 (Offiah *et al.*, 2018).

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 (Culbertson,

2008). 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 (Koehler and Wieser, 2013). Broken rice, which is a by-product of milling, is a cheaper alternative. (Ilo *et al.*, 2000). However, rice proteins exhibit poor functional properties during processing, compared to other plant proteins (Koehler and Wieser, 2013). 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 (Rosell and Collar, 2007). Starch granules in oats are comparatively smaller (2 – 12 μm) in size than most other starches, and amylose content may fall within 16-27 % (Ilo *et al.*, 2000). Oat's 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 (Ramachandra and Thejaswini, 2015). 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 (Rasane *et al.*, 2013). 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*) (Rasane *et al.*, 2013). Total starch of amaranth, quinoa and buckwheat were reported as 61.4 %, 64.2 % and 58.9 % d.b., respectively (Sinkovic, 2016). These

underutilized cereals and pseudo cereals have been well explored in extruded products.

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 (Alvarez-Jubete *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 (Djilas *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 degermed white cornmeal (Karkle *et al.*, 2009). 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 (Djilas *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 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 (Djilas *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 (Camire *et al.*, 2007). 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 (Camire *et al.*, 2007).

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 (Bisharat *et al.*, 2015). 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 (Altan *et al.*, 2009). 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 (Jain *et al.*, 2013). 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 (Lohani *et al.*, 2016). 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.

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 (Sarkaret *et al.*, 2011). 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 crop 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*) (Ugwu, 2009). Among these, potato and cassava are the most commonly used in extruded snacks, as flour, granules, starch or flakes (Asgar *et al.*, 2010). The granules are produced from diced tubers, tempered to tenderize the cell walls, cooked and dried in a well-defined process (Ramachandra and Thejaswini, 2015). The differences in raw materials and processing factors could alter the performance of the granules. Dough from potato flour was stiffer and stickier than those prepared from the granules (Riaz, 2010). Potato flour served as a major ingredient in directly expanded

snacks and fabricated chips (Ramachandra and Thejaswini, 2015). Potato starch may contain amylose (20-25 %), and a low lipid (0.1 to 0.2 %) content (Ramachandra and Thejaswini, 2015 and Riaz, 2010), and could be incorporated into extruded snacks to provide additional expansion and improved functional properties (Riaz, 2010). 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 (Ramachandra and Thejaswini, 2015). Tapioca starch also developed very high viscosity, excellent binding properties and required only moderate temperatures during extrusion cooking (Ramachandra and Thejaswini, 2015). 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 (Chandrasekara and Kumar, 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 (Akinoso and Abiodun, 2016). 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 (Santana *et al.*, 2014). 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 °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 (Leonel *et al.*, 2009). 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 (Oke *et al.*, 2013).

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 (Serbio and Chang, 2000). 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 (Tomaszewska-Ciosk *et al.*, 2012). 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 and Idowu, 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 (Peluola-Adeyemi *et al.*, 2014). 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 (Daramola *et al.*, 2010). Meanwhile, feed moisture was considered as one of the most important factors in the extrusion of taro flour (Jyothi *et al.*, 2009), using a collet extruder.

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 (Nurtama and Lin, 2009). 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 (Berrios, 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/Garbazzo (*Cicer arietinum*), dry cowpea (*Vigna unguiculata*), lentils (*Lens culinaris*), and bambara groundnut (*Vigna subterranean*) (Nurtama and Lin, 2009). The dominant proteins found in legumes are albumins and globulins (Berrios, 2016). Pulses like lentils, dry beans, and peas are classified by USDA Food Pyramid-Dietary Guidelines as high-protein and vitamin-rich vegetables

(Nurtama and Lin, 2009). Legumes contain compounds such as lectins, saponins, cyanogenic compounds, trypsin and chymotrypsin inhibitors, which exert anti-nutritional effects upon ingestion (Nurtama and Lin, 2009).

However, due to their heat sensitivity, most of these factors are reduced or destroyed during extrusion cooking (Patil *et al.*, 2016). 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 (Soetan and Oyewole, 2009). 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 (Soetan and Oyewole, 2009). Meat analogs, very similar to meats in mouthfeel and appearance, have been developed using extrusion cooking (Hulse, 2012). 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 (Hulse, 2012). 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 constant moisture content produced softer analogs (Muelbauer and Kaiser,). 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 (Kearns *et al.*, 2013). 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 °C), screw speed (101.48 rpm), feed moisture (59.63 %), and 1 % African oil bean seed protein concentrate (Lin *et al.*, 2000).

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 °C), feed moisture (47 %), and 119.19 rpm screw speed (Palmer *et al.*, 2004). 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 (Arueya *et al.*, 2007). 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 % (Berrios, 2016). A wide range of snacks made with soy proteins have become increasingly popular among health-conscious consumers (Ramachandra and Thejaswini, 2015). Maize-based extruded snacks have also been developed by supplementing maize with full-fat soybean (Omohimi *et al.*, 2014), and partially-defatted soybean (Jiddere and Filli, 2015). 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 (Rweyemamu *et al.*, 2015). 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 (Obatolu *et al.*, 2006). 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 (Savita *et al.*, 2013). 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 (Nurtama and Lin, 2009). 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 (Offiah *et al.*, 2018). 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 (Offiah *et al.*, 2018). 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 % (Yadava *et al.*, 2011). 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 °C pressing temperature (Djilas *et al.*, 2009). 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 pretreatment prior to mechanical pressing of soybeans (Offiah *et al.*, 2018).

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 °C pressing temperature (Kartika *et al.*, 2010). 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 (Savita *et al.*, 2013). 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 °C pressing temperature, and filling coefficient of 47.1 g/h rpm (Lamsal *et al.*, 2006). In single screw press, conveyance of the material is dependent on frictional force generated during the rotation of the screw (Offiah *et al.*, 2018).

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 is therefore more efficient for oil extraction. Oils expressed using twin screw oil press is 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 (Offiah *et al.*, 2018 and Kartika *et al.*, 2010).

Extrusion processing of animal foods

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 (Offiah *et al.*, 2018; Evon *et al.*, 2013; Uitterhaegen *et al.*, 2015). A variety of extruded products which utilize these food materials have been successfully developed (Dubey, 2011; Dileep *et al.*, 2010; Adhikari *et al.*, 2009). 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 (Onwulata, 2009).

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 (Onwulata, 2009). 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 (Yadav *et al.*, 2013), 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 (Surasani, 2016). 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 grams dhal: 5 cheese flavors: 20 fish mince (Verma *et al.*, 2014). 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 (Anandh, 2013), and enrichment with tilapia flour

had negligible effects on the chemical stability of pasta stored at 25 °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 (Devi *et al.*, 2016). 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 were 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 °C barrel temperature, and products containing fish mince had higher lysine, glutamic acid and leucine contents (Evon *et al.*, 2011). 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 (Monteiro *et al.*, 2016). 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 oxidative 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 (Mulye and Zofair, 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 (Pankyamma *et al.*, 2014). 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 (Shaviklo *et al.*, 2015). 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 (Offiah *et al.*, 2018). 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 (Offiah *et al.*, 2018). 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 (Offiah *et al.*, 2018).

Addition of a starch source to egg batters for puffing was necessary to optimize puffing characteristics under high pressure and temperature conditions. Products with super functional properties could be processed from fractionated egg yolk and egg white components (Offiah *et al.*, 2018). 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 (Lourenço *et al.*, 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 (Lourenço *et al.*, 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 (Culbertson, 2008). 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 cheeses with lower moisture were chewier and firmer in texture, and the lower-moisture cheeses processed at 80 °C were more acceptable (Dileep *et al.*, 2010). 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 (Jeyakumari *et al.*, 2016). Some merits and demerits of Extrusion processing on food are presented below;

Merits of Extrusion processing

- a) It is a continuous process
- b) It involves series of unit operation simultaneously
- c) Allows efficient control over process variables
- d) It produces no effluents
- e) Versatility: - many products can be made by changing the composition
- f) Production of new foods — Extruders can modify starches, proteins, and other food materials to produce a wide variety of new food products.
- g) increase digestibility
- h) increase palatability
- i) destruction of anti-nutritional constituents
- j) toxic substances and
- k) microorganisms

Demerits of extrusion processing

- a) High capital cost
- b) Non availability of spare parts
- c) Repair and maintenance
- d) Increased packaging cost
- e) Start-up time is high

Effect of Extrusion on Physical, Chemical and Nutritional Properties of Food Components

Carbohydrate and Fibre

During extrusion process, starch undergoes various structural changes including gelatinization, melting, and fragmentation and the extent of the transformation depends upon pressure, temperature, moisture content, and shearing force. Control of sugars during extrusion is critical for nutritional and sensory quality of the products. It is reported that sugar losses in extrusion and 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 (Serna-Saldivar, 2016). The destruction of these flatulence-causing oligosaccharides might improve the nutritional quality of extruded legume products (Koehler and Wieser, 2013). Fruit and vegetables contain large amounts of dietary fibre (DF), which benefits the physiological activities of humans by decreasing cholesterol levels, reducing hyperlipidemia and hypertension, and maintaining gastrointestinal health (Qi and Onwulata, 2011). Moreover, DF in vegetables and fruits has a higher insoluble/soluble dietary fibre (IDF/SDF) ratio. In particular, SDF is more effective than IDF in maintaining systemic health. An extrusion technology was successfully applied to orange pomace to increase its SDF fraction under optimal conditions. The increase in SDF content in the extrusion was mainly contributed by redistribution of IDF to SDF, which was likely due to modification of the cell-wall structure during extrusion, where degradation of IDF generally occurs (Navale *et al.*, 2015).

Protein and Amino acids

The change in the screw-speed during extrusion leads to the variation in shear forces which play an important role in changing the nutritional value of proteinaceous materials. Researchers found behavior of molecular aggregation and chemical cross-linking of soybean protein at both low and high moisture content during extrusion. The results showed that, hydrophobic interactions, hydrogen bonds, disulfide bonds, and their interactions collectively hold the structure of protein extrudate regardless of the location and moisture level in the extruder and the contribution of non-covalent bonds during process also exceeds covalent bonds to bring about the change (Singh *et al.*, 2007). Denaturation of proteins at high temperature during extrusion cooking inactivates anti-nutritional factors (such as antitrypsin factor, lectins, etc.) and improves digestibility. The extrusion of soy protein reduces the undesirable

volatile compounds and the bitter taste (Kendall *et al.*, 2010). Very high drying temperatures have shown to decrease in protein digestibility and lysine bioavailability (Koehler and Wieser, 2013).

Apart from lysine, a few other amino acids have been affected by a decrease in moisture content during extrusion. Cysteine decreases below 14.5% moisture content during the extrusion (181–187 °C mass temperature, 12–25% feed moisture, 35 to 79-Nm torque) of maize grits [92]. Biological evaluation also revealed a decrease in the availability of aspartic acid, tyrosine and arginine with decreasing moisture content. With increasing energy input to the extruder, a significant reduction in the availability of several amino acids was found. The loss of available arginine (21%), histidine (15%), aspartic acid (14%) and serine (13%) was significant at 135–160 °C mass temperature and 150 or 200-r.p.m. screw speed (Skarma *et al.*, 2020). Extrusion cooking of a cereal blend resulted in a considerable loss of arginine, and to a lesser extent also of histidine (170 °C mass temperature, 10% feed moisture and 40- r.p.m. screw speed). Lysine and methionine availability was not affected below 149 °C during extrusion cooking of soybeans (127–154 °C mass temperature, 14% feed moisture and 20-s residence time). At the highest temperature, lysine showed the greatest loss (31%), although a 13% decrease in methionine was noted (Chen *et al.*, 2011). Free amino acids are much more sensitive to damage during extrusion cooking than those in proteins. Phenylalanine, tyrosine, serine, isoleucine and lysine decreased considerably during potato flake extrusion at 70–160 °C barrel temperature, 48% feed moisture, 100 r.p.m. screw speed. At 160 °C, the total loss of amino acids was 89%. Potato flakes extruded at 100 and 130 °C contained higher levels of free amino acids than the product processed at 70 °C. This is probably the result of some hydrolysis of

protein at elevated temperatures (Chen *et al.*, 2011).

Fats and Lipids

The class of chemical compounds known as lipids is a heterogeneous group of nonpolar materials, including glycerides, phospholipids, sterols and waxes. Although many types of lipids occur in foods, the triglycerides are the most common. A triglyceride consists of three fatty acid molecules esterified to one glycerol molecule. Although lipids serve as a concentrated form of energy, excess dietary lipid consumption is associated with chronic illnesses, such as heart disease, cancer and obesity (Maurya and Said, 2014). During the extrusion of foods, native lipids might be present within the raw materials or added to the ingredients. Cereals, such as wheat and corn are typically low (2%) in oils, although oats may contain up to 10% oil. The oil is concentrated in the bran and germ portions of the seed kernel, and is removed during milling to improve storage stability. Oilseeds, such as soybeans and cottonseed may contain up to 50% by total seed weight as oil. Oilseed flours used in extrusion may be full fat or partially or wholly defatted. Extrusion of high-fat materials is generally not advisable, especially in the case of expanded products, as lipid levels over 5–6% impair extruder performance (Iwe, 2003). 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. At the same time, small lipid levels (<5%) facilitate steady extrusion and improve the texture.

A decrease in extractable fat after extrusion cooking has been found with an average of 40% of the original recovered in extruded maize, by using different solvents (Shivendra *et al.*, 2007). Some lipid might be lost at the die as free oil, but this situation only occurs with high-fat materials, such as whole soy. Another explanation for the

lower lipid level is the formation of complexes with amylose or protein (Iwe, 2003). When extrudates are digested with acid or amylase and then extracted with solvent, lipid recovery is higher. Although only 50% of the extractable lipids in extruded whole wheat were recovered, acid hydrolysis indicated that total fat was not significantly changed owing to extrusion (Chen *et al.*, 2011). High levels of free fatty acids in foods create a number of problems. Increased levels of free fatty acid produce off flavours and affect the storage quality of foods. Free fatty acids are produced in foods from hydrolysis of triglycerides, mainly because of lipase enzymes and high temperatures. The extrusion process can prevent free fatty acid release by denaturing hydrolytic enzymes (Chen *et al.*, 2011). Lipid oxidation has negative impact on sensory and nutritional qualities of foods and feeds. It probably does not take place during extrusion owing to the very short residence time. However, rancidity is a concern for extruded products during storage. Screw wear is a concern as metals can act as pro-oxidants. Iron content and peroxide values were higher in extruded rice and dhal compared with similar products processed by drying methods. The larger surface area created by the air cells throughout highly expanded extrudates, favours oxidation. On the other hand, extrusion denatures enzymes that can promote oxidation, and lipids held within starch are less susceptible to oxidation. Compounds produced by Maillard reactions can also act as antioxidants. Oatmeal cookies with added potato peels had lower peroxide values than control samples, and higher antioxidant activity was observed for extruded peels compared with unextruded peels. In summary, feed with low fat level is favourable for extrusion cooking. The extrusion process minimizes lipid oxidation, thus increasing the nutritional and sensory quality of foods and feeds (Chen *et al.*, 2011).

Mineral and Vitamins

Although mineral elements represent a minor portion of the composition of foods, they play major roles in food chemistry and nutrition. Minerals are solid, crystalline, chemical elements that cannot be decomposed or synthesized by ordinary chemical reactions. Minerals are classified as macro- and micro minerals. Macro minerals include calcium, phosphorous, sodium, potassium and chloride. Of these, calcium and phosphorus are needed in large amounts, while the rest are needed in smaller amounts. Micro minerals include magnesium, manganese, zinc, iron, copper, molybdenum, selenium, iodine, cobalt and chromium, which are needed in minute amounts. The distribution of minerals is widespread in foods. Phosphorus, in the form of phosphates, is commonly added during food processing; however, iron and calcium are the mineral elements typically added to foods for improving nutritional value (Chen *et al.*, 2011). Metals, particularly iron (Fe), copper (Cu), magnesium (Mg), and calcium (Ca), act as catalysts for enzymes. Iron is essential for the prevention of anaemia, and calcium is necessary for bone health. Depending upon the product and the population for which it is intended, other minerals may be added at fortification or enrichment levels. Extrusion cooking generally affects macromolecules. Smaller molecules may be impacted upon by either the extrusion process itself or by changes in larger molecules, which in turn affect other compounds present in the food. Despite the importance of minerals for health, relatively few studies have examined mineral stability during extrusion because they are stable in other food processes (Chen *et al.*, 2011). Minerals are heat stable and unlikely to become lost in the steam distillate at the die. Extrusion can improve the absorption of minerals by reducing other factors that inhibit absorption. Phytate may form insoluble complexes with minerals and eventually affect mineral absorption adversely. Extrusion hydrolyses phytate to release phosphate molecules. Extrusion of peas and

kidney beans resulted in phytate hydrolysis, which explains the higher availability of minerals after processing (high temperature extrusion) (Shivendra *et al.*, 2007). A 13–35% reduction in phytate content was observed after extrusion of a wheat bran–starch–gluten mix (Chen *et al.*, 2011). Extrusion reduces phytate levels in wheat flour, but not in legumes, at low extrusion temperature. Boiled legumes and ones extruded under high-shear conditions had less dialysable iron than samples extruded under low-shear conditions; although phytic acid was lower under all processing conditions, total phytate was not affected. Thus, processing conditions play an important role in the reduction of phytate in legumes. The presence of natural polyphenols might be an inhibitory factor in mineral absorption, although tannin content is substantially low. Tannins might form insoluble complexes with divalent ions in the gastrointestinal tract, lowering their bioavailability (Chen *et al.*, 2011). The increase in mineral absorption, observed after extrusion, could be partly attributed to the destruction of polyphenols during heat treatment. Changes in the polyphenol content after thermal treatment might result in the binding of phenolics with another organic material present (Shivendra *et al.*, 2007). Mineral absorption could be altered by fibre components. Cellulose, lignin and some hemicelluloses affect the mobility of the gastrointestinal tract and interfere with the absorption of minerals. Extrusion processing (high temperature) might have reorganized dietary fibre components, changing their chelating properties. Moreover, it must be taken into consideration that complex agents, present in foodstuffs, such as phytate may interact with fibre, modifying the mineral availability. Extrusion does not significantly affect mineral composition of pea and kidney bean seeds, except for iron. Iron content of the flours is increased after processing and it is most likely to the result of the wear of metallic pieces, mainly screws, of

the extruder (Shivendra *et al.*, 2007). The incorporation of wheat bran in broken rice flour in extrusion (300-r.p.m. screw speed, 27-kg h⁻¹ feed rate, 5/32 inches die size, 93–97 °C outlet temperature) increases the content of calcium, phosphorus, iron and copper, which might be attributed to the addition of these minerals through water used during extrusion and also from the extruder barrel (Singh *et al.*, 2000). Fortification of foods with minerals prior to extrusion poses other problems. Iron forms complexes with phenolic compounds that are dark in colour and detract from the appearance of foods. Ferrous sulphate heptahydrate was found to be a suitable source of iron in a simulated rice product, because it did not discolour. Added calcium hydroxide (0.15–0.35%) decreased expansion and increased lightness in the colour of cornmeal extrudates. In conclusion, extrusion cooking enhances apparent absorption of most minerals studied in either pea- or kidney bean-based diets. This increased absorption can be explained by the positive effect of extrusion in the reduction of anti-nutritional factors (phytates, condensed tannins). Chemical alteration, induced by heat in other compounds of legume flours, such as fibre, can also be responsible for the higher mineral absorption observed in processed seeds. Extrusion cooking increases the amount of iron available for absorption, almost in all cases. However, the effects of extrusion on iodine and other essential elements have not been studied in detail. Further research in this area is necessary, particularly if extruded foods are produced as vehicles for mineral fortification (Chen *et al.*, 2011).

The daily vitamin intakes might be small compared with other nutrients, but the small quantities consumed are crucial to good health because of the role of vitamins as coenzymes in metabolism. The increase in the consumption of extruded infant foods and similar products, which may form the basis of an individual's diet, has focused concern on the effects of extrusion on the

recovery of vitamins and minerals that are added prior to extrusion. As vitamins differ greatly in chemical structure and composition, their stability during extrusion is also variable. The extent of degradation depends on various parameters during food processing and storage, e.g. moisture, temperature, light, oxygen, time and pH. This subject is addressed in reviews on nutritional changes during extrusion (Chen *et al.*, 2011) and in a review of vitamin retention by Killeit (1994). Minimizing temperature and shear within the extruder protects most vitamins. Among the lipid-soluble vitamins, vitamins D and K are fairly stable. Vitamins A and E and their related compounds – carotenoids and tocopherols, respectively, are not stable in the presence of oxygen and heat. Thermal degradation appears to be the major factor contributing to β -carotene losses during extrusion. Higher barrel temperatures (200 °C compared with 125 °C) reduce all trans- β -carotene in wheat flour by over 50% (Chen *et al.*, 2011). Pham and Del Rosario (1986) and Guzman-Tello and Cheftel (1987) began to assess the effects of high temperature, short-time extrusion cooking on vitamin stability using mathematical models. Thiamine has been investigated most frequently, followed by riboflavin, ascorbic acid and vitamin A.

Very few studies dealt with other B-complex vitamins or vitamin E. Ascorbic acid (vitamin C) is also sensitive to heat and oxidation. This vitamin decreased in wheat flour when extruded at a higher barrel temperature at fairly low (10%) moisture (Chen *et al.*, 2011). Blueberry concentrate appeared to protect 1% added vitamin C in an extruded breakfast cereal compared with a product containing just corn, sucrose and ascorbic acid (Chen *et al.*, 2011). When ascorbic acid was added to cassava starch to increase starch conversion, retention of over 50% occurred at levels of 0.4–1.0% addition (Camire, 2001). In summary, the retention of vitamins in extrusion cooking decreases with

increasing temperature, screw speed and specific energy input. It also decreases with decreasing moisture, feed rate and die diameter. Depending on the vitamin concerned, considerable degradation can occur, especially in products with high sensory appeal. The following options for the nutritional enrichment of extruded products with vitamins are possible.

1. The usage of specific vitamin compounds or forms of application with improve stability;
2. Addition of extra amount to compensate for losses during extrusion and storage;
3. Post extrusion application, e.g. by dusting, enrobing, spraying, coating or filling together with other ingredients;

Anti-Nutritional Factors

Effect of Extrusion on Anti-Nutritional Factors and Functional Compounds Legumes contain several anti-nutritional factors, such as trypsin inhibitors, lectins, tannins, and phytates (Camire *et al.*, 1990). Variations in the operative conditions of extrusion cooking influence the content of these compounds (Table 2). An increase in temperature and feed moisture lowers the content of inositol hexaphosphate, trypsin inhibitors and lectins, but has an adverse effect on phenolic compounds and tocopherols. On the other hand, an increase in temperature raises the content of total galactosides. Levels of 15–19 trypsin inhibitor units (TIU) mg^{-1} have been reported in chickpeas, 6–15 TIU mg^{-1} in peas, 5–10 TIU mg^{-1} in faba beans and 3–8 TIU mg^{-1} in lentils (Camire, 2000a). The content of trypsin inhibitors markedly decreases after extrusion, due to heat and intense mechanical stress. A reduction accounting for 90% has been observed after the extrusion of lentils (Camire, 2000). A 95% decrease has been reported by extruding beans at temperatures comprised between 120 and 150 °C, with a total inactivation at 180 °C (Camire, 2000a). Significant destruction of trypsin inhibitors can be achieved by extrusion at elevated temperatures or by increasing residence time when extrusion is done at lower

temperatures (Alonso *et al.*, 2000b). Lectins bind sugar branches of the epithelial surface proteins of the digestive tract, resulting in a disruption of the barrier function, which hampers the absorption of nutrients in the gut. Some lectins are toxic, causing vomit and diarrhea. Legume lectins, however, also have anti-viral, anti-fungal, and anti-cancer activity. The content of lectins strongly decreases with extrusion cooking.

A 90% decrease was reported after extrusion of lentils. Reductions between 50 and 97% were observed in extruded products containing pea flour. Tannins have the ability to complex and precipitate proteins in aqueous solutions. The condensed tannins of some legumes, such as faba beans, reduce the digestibility of proteins. Faba beans, indeed, have the highest tannin content (0.5–24 g kg⁻¹) among legumes, followed by beans (0.3–12.6 g kg⁻¹), cowpeas (1.4–10.2 g kg⁻¹), peas (0.6–10.5 g kg⁻¹) and chickpeas (0.6–2.7 g kg⁻¹). The content of tannins of navy beans, chickpeas, cowpeas and lentils can be reduced by extrusion with decreases ranging from 31 to 76% compared to raw legumes (Antonella *et al.*, 2020). Inositol hexaphosphate (IP6), or phytate, is the most abundant inositol phosphate in legume extrudates (Sriburi and Hill, 2000). IP6 and inositol pentaphosphate (IP5) negatively influence mineral bioavailability, forming complexes with iron, zinc, and calcium. On the other hand, since phytic acid chelates pro-oxidant minerals such as iron, it has an antioxidant effect (Berrios, 2006). In addition, the less phosphorylated forms IP4, IP3, IP2, and IP have a positive role in type 2 diabetes and promote the intestinal absorption of minerals. Extrusion cooking causes a reduction in total phytates, which is essentially due to a decrease in IP6, whereas some of the less phosphorylated forms, particularly IP4 and IP5, show an increase (Alonso *et al.*, 2000b). The decrease in total phytates was mostly imputable to the heat treatment, although an effect of feed moisture was also observed. Extrusion of beans at 150 °C,

with a moisture content of 20%, reduced the total phytate content by about 20–30%. Another study, carried out on navy and red beans, reported a reduction by 44% working at 160 °C and 22% moisture. The content of total phytates significantly decreased during the extrusion of lentils, with greater reductions at 160 than 140 °C. A decrease in total phytates was also observed during the extrusion of faba beans. Phenolic compounds are abundant both in the usual raw materials for extrusion cooking, i.e., cereals, and in legumes. The extrusion conditions influence the overall impact on phenolics: the adoption of low moisture (<14%) and low temperature (<140 °C) can help to retain those. However, the effect of extrusion cooking on the various classes of phenolic compounds is controversial: some studies report an increase in anthocyanins and total phenolics, whereas other studies report a decrease in anthocyanins, an insignificant variation in flavonols, and a decrease in total phenolics. Anthocyanins, in particular, are present in black beans and in black chickpeas. The decrease in total phenolics was observed in pea/rice extrudates and in starch/navy bean extrudates. In extrudates containing pea, rice and carob flour, instead, an increase in total phenolics was observed, highlighting that if phenolics in the starting flour are mostly bound to dietary fiber of the cell walls, as in carob, than the extrusion process, which tends to partially disrupt fiber, can release phenolics (Alonso *et al.*, 2000b). In addition, the extrusion cooking prevents the oxidation of phenolic compounds by inactivating the oxidative enzymes responsible for their degradation. On the other hand, a detrimental effect of extrusion cooking may be due to the high temperature reached, which affects the phenolic compounds. Therefore, opposite effects take place, whose result mostly depends on the specific characteristics of the raw material. A marked decrease in total tocopherols content after extrusion was reported. High extrusion temperature negatively affects tocopherol, in

particular, whereas high moisture lowers the content of-tocopherol. Regarding the antioxidant activity of legume-added extruded foods, it has to be highlighted that it is not only due to the presence of antioxidant bioactive compounds contributed by the extruded raw materials, as modified by the extrusion process, but also to antioxidant compounds, such as Maillard reaction products, which may arise from the thermal modifications related to the extrusion cooking process. Therefore, generally the antioxidant activity increases during the extrusion cooking process. In particular, comparing the values of antioxidant activity with those of raw materials, the extrusion process increased the antioxidant activity of green and yellow peas, and chickpea, at an extent varying in the ranges of 27–114, 12–67, and 25–40%, respectively. Other compounds influenced by extrusion cooking are the galactosides, such as rabinose, stachyose, and verbascose (Alonso *et al.*, 200b). These compounds cause flatulence due to the lack of galactosidase in the human intestinal mucosa, but at the same time they have a prebiotic effect because are easily fermented by the colonic flora, resulting in the production of short chain fatty acids that stimulate bifido-bacterial growth. It has been observed that extrusion cooking causes a significant increase, up to 85%, in the content of total galactosides, compared to the not extruded raw material. The extent of this increase is higher as the extrusion temperature raises. The content of total galactosides was higher in lentil

extrudates obtained at 160 than 140 °C. These oligosaccharides, indeed, are relatively heat-stable. Therefore, mechanical-structural modifications in the cell walls (such as partial ruptures with increase in porosity) coupled with the increase in surface area, taking place during the extrusion cooking, may probably increase their availability in the extrudates. An increase in the total content of galactosides was also reported by Arribas *et al.*, (2019) during the extrusion of lentil-based formulations. The single galactosides, however, may show a different behavior, also according to the legume type. The instant controlled pressure drops, a technique that combines steam pressure and heat, similar to extrusion cooking, caused an increase in stachyose in lentil, opposed to a decrease in chickpea; further, a decrease in rabinose was observed both in lentil and chickpea, and an increase in verbascose (which was absent in chickpea) in lentil. From the technical point of view, extruding cereal–legume formulations could be therefore a good strategy to produce shelf-stable ready-to-eat nutritious food products. This is of particular importance in geographic areas where is needed to relief malnutrition. However, the cost of purchasing and operating the extruders may be not affordable in developing countries. A solution to this situation may be the application of simple, autogenic single-screw extruders, which are still available on the markets (Alonso *et al.*, 200b).

Table 2. Effect (positive/negative) of the increase in the main processing parameters of extrusion cooking on the content of functional and anti-nutritional compounds of legume-based extruded products.

Parameter	Phenolics	Tocopherols	Antioxidant Activity	α -Galactosides	Anti-Nutritional Compounds			
					Trypsin Inhibitors	Phytate (IP6)	Tannins	Lectins
Temperature	-	-	+	+	-	-	NS	-
Feed moisture	-	-	NS	NS	-	-	-	-
Screw speed	NS	NS	NS	NS	-	-	-	NS

NS = not studied; IP6 = inositol hexaphosphate.

Source: Antonella *et al.*, 2020

Conclusion

Extrusion Technology is an important tool for handling versatile raw materials and provides a means by which unconventional, lesser-known and under-utilized food sources are processed. Under-utilized cereals, pseudo cereals and food materials which have demonstrated low economic or processing value have been successfully integrated into consumer markets. It is an important technique for modifying the properties of foods and fabricating products with peculiar attributes. Also, large quantities of by-products and wastes are generated from food industrial operations could be incorporated as useful components into extruded products. Future research may be focused 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. High-moisture extrusion and use of less reactive sugars may create a new line of research objectives.

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