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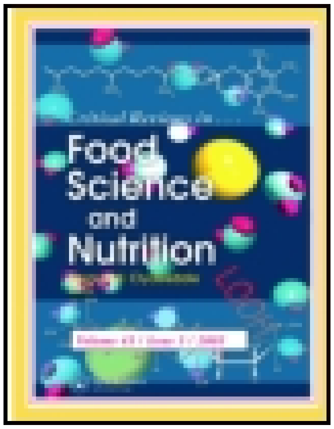

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Extrusion and Extruded Products: Changes in Quality Attributes as Affected by Extrusion Process Parameters: A Review

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Extrusion and extruded products: Changes in quality attributes as affected by extrusion process parameters: A review

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Abstract: Extrusion of foods is an emerging technology for the food industries to process and market a large number of products of varying size, shape, texture and taste. Extrusion cooking technology has led to production of wide variety of products like pasta, breakfast cereals, bread crumbs, biscuits, crackers, croutons, baby foods, snack foods, confectionery items, chewing gum, texturized vegetable protein (TVP), modified starch, pet foods, dried soups, dry beverage mixes etc. The functional properties of extruded foods plays an important role for their acceptability which include water absorption, water solubility, oil absorption indexes, expansion index, bulk density and viscosity of the dough. The aim of this review is to give the detailed outlines about the potential of extrusion technology in development of different types of products and the role of extrusion operating conditions and their effect on product development resulting in quality changes i.e physical, chemical and nutritional, experienced during the extrusion process.

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INTRODUCTION

Extrusion cooking, a process of forcing a material to flow under a variety of conditions through a shaped hole (die) at a predetermined rate to achieve various products. Extrusion cooking of foods has been practiced over fifty years. The food extruder which was initially limited to mixing and forming macaroni and ready to eat cereal pellets is now considered a high temperature-short time bioreactor that transforms raw ingredients into modified intermediate and finished products. During extrusion thermal and shear energies are applied to raw food materials causing structural, chemical and nutritional transformations such as starch gelatinization and degradation, protein denaturalization, lipid oxidation, degradation of vitamins, antinutritions and phytochemicals, formation of flavors, increase of mineral bioavailability and dietary fiber solubility (Camire, Caminre and Krumhar 1990; Camire, 2003; Singh et al., 2007; Riaz et al., 2009).

Extrusion technology has led to production of a wide variety of cereal based foods, protein supplements and sausage products. Presently several products are developed by extrusion i.e. pasta, breakfast cereals, bread crumbs, biscuits, crackers, croutons, baby foods, snack foods, confectionery items, chewing gum, texturized vegetable protein, modified starch, pet foods, dried soups and dry beverage mixes (Chang and Ng, 2009). Extrusion cooking is becoming popular over other common processing methods due to its automated control, high capacity, continuous operation, high productivity, versatility, adaptability, energy efficiency, low cost. Moreover, it also enables design and development of new food products, high product quality, unique product shapes and characteristics, energy savings and no effluent generation (Faraj et al., 2004). Extrusion cooking also helps in modifying the structure, improving the solubility, swelling power, water hydration viscosity and water holding capacity. It also increases the soluble fiber content of fibrous materials such as plant cell-wall rich materials, brans and hulls of various cereals and legumes (Gaosong and Vasanthan, 2000; Gourgue et al., 1994; Hwang et al., 1998; Ralet et al., 1993; Ralet et al., 1990; Rouilly et al., 2006).

Food extruders provide thermo-mechanical shear necessary to cause physicochemical changes of raw materials with an intense mixing for dispersion and homogenization of ingredients including conveying, mixing, shearing, heating or cooling, shaping, venting volatiles and moisture, flavor generation, encapsulation, and sterilization (Linko et al., 1981; Wiedman and Strobel, 1987). Extrusion is a thermal processing that involves the application of high heat, high pressure, and shear forces to an uncooked mass, such as cereal foods (Kim et al., 2006). Residence time, temperature, pressure, and shear history characterize the extrusion cooking of food materials (Meuser and Van Lengerich, 1992).

The suitability of extruded foods for a particular application depends on their functional properties like water absorption, water solubility and oil absorption indexes, expansion index, bulk density and viscosity of the dough (Ali et al., 1996; Hernandez-Diaz et al., 2007).

High moisture extrusion is an emerging and promising technology for transforming vegetable protein into palatable meat-like products (Cheftel et al., 1992; Liu and Hsieh, 2008; Yao et al., 2004). Additionally, extrusion cooking has been used to partially or totally inactivate several anti nutritional compounds that limit the widespread use of beans as a primary staple food (Alonso et al., 2000; Shimelis and Rakshit, 2007). Extrusion has also been reported to be the most effective method for improving protein and starch digestibility of kidney beans extrudates (Alonso et al., 2000; Berrios, 2006).

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A number of researchers have used fruits and vegetable by-products such as apple, pear, orange, peach, blackcurrant, cherry, artichoke, asparagus, onion, carrot pomace as sources of dietary fibre supplements in refined food. Dietary fibre concentrates from vegetables showed a high total dietary fibre content and better insoluble/soluble dietary fibre ratios than cereal brans**.**

Limited information is available on extrusion processing of vegetable by-products. Some authors have used extrusion technology to solubilise the pectic substances from sugar beet pulp by-products. The effects of extrusion cooking on the physicochemical characteristics and microstructure of cell walls on onion waste were evaluated. It was found that extrusion cooking increase the solubility of pectic polymers and hemicelluloses accompanied by an increase in swelling of the cell-wall material. Later, the properties of fibre components in orange pulps using extrusion technology have been modified. Rice flour has been incorporated with cauliflower by-products as a new source of dietary fibre, antioxidants and proteins in cereal based ready-to-eat expanded snacks. There is an ample scope for inclusion of vegetable and fruits waste (by products) in the snack food as a source of mineral, vitamin and dietary fibre.

Many of the early reviews primarily focused on the methodology of evaluation of texture, reaction kinetics of extruded products and on the potential use of dietary fiber in extruded cereals (Robin et al., 2012; Anton and Luciano, 2007; Zhao et al., 2011). Moreover, the changes in mycotoxins during extrusion process of cereal based extruded products has also been reported (Castells et al., 2005). This review comprehensively covers the detailed outlines about the potential of extrusion technology in development of different types of products, effect of extruders and process parameters on the product. It also covers the modeling and scaling of extrusion process as well as importance of ingredients in extruded products. Special emphasis

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has been given on value addition and by- product waste utilization in extruded products and the quality characteristics of the developed products along with the quality changes during the extrusion process. Thus, extrusion cooking has a potential for becoming the most important food processing technology in future which can potentially be exploited.

APPLICATIONS OF EXTRUDERS AND EXTRUSION PROCESS VARIABLES IN PRODUCT DEVELOPMENT

There are three major types of extruders being used in the food industry; piston extruders, roller-type extruders and screw extruders. Screw extruders are most common extruders used these days and can be categorized as single and twin screw extruders.

Single screw extruder

Single-screw extrusion cooking is an attractive method for making pasta products due to its low capital cost and is a feasible process to produce non-fried instant noodles and rice noodles (Yeh and Hwang, 1995; Yeh and Tien, 1995).

In the single-screw extrusion cooking process, the extruder can be divided into three regions: conveying, swelling, and melting/degradation in terms of the transition of rice starch. Both the conveying and swelling regions are located in the cooling zone, where the flow pattern behaved as a plug flow reactor. The melting of starch granules and degradation of starch molecules occur simultaneously in the third region. The flow pattern is changed from plug flow reactor to continuous stirred tank reactor, thus more mixing and longer residence time occurred in the heating zone. Davidson et al. (1984) and Diosady et al. (1985) postulated that only fully-cooked wheat starch (amylopectin) is susceptible to shear degradation during single-screw extrusion. Whereas, Rodis et al. (1993) suggested that both shear and thermal fields in a single-screw

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extruder affect the fragmentation of corn starch at temperatures higher than 100°C and moisture levels lower than 30%. Van Zuilichem et al. (1990) suggested that the length-to-diameter ratio of the barrel should be greater than 30 in order to attain reasonably higher dextrose equivalent values. Researches also indicate that significantly higher dextrose equivalent values can be obtained with a longer barrel, such as a 1222 mm (Hakulin et al., 1983).

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Esseghir and Sernas (1994) have measured the temperature distribution in the screw channels of a single-screw extruder using a cam-driven thermocouple synchronized with the rotating screw shaft. In another experiment, Goedeken (1991) investigated single screw extrusion cooking of corn starch with selected proteins in which dairy proteins showed good results, such as acceptable expansion, but they also indicated a mixed effect on solubility, expansion and shear strength depending on the technique used to isolate the protein.

Short-term reactive extrusion of 1:1 w:w ratios of corn gluten meal and distillers' dried grains with citric acid were reported by Sessa and Wing (1999). The results yielded reaction products that possessed similar degrees of carboxylation as a lengthy, 24 h oven-baking procedure at 120°C. Iwe et al. (2001) extruded the blends of defatted soy flour and sweet potato flour. The extrudate from combination of wheat flour and wheat–black soybean blend was produced by Shihani et al. (2006). Orange pulp was extruded by Cespedes et al. (2010), the apparent density and apparent viscosity values of the extruded orange pulp increased during extrusion. Extruded orange pulp showed a higher glucose retardation index (16.04–25.92%). While, in another experiment by Menegassi et al. (2011) extruded amaranth flour obtained from laboratory single screw extruder; length to diameter ratio 15.5:1, 3.6 mm die diameter, feed rate at 150 g/min and temperature calibrated in first and second zones, 30^{0}C and 80^{0}C, respectively had a good potential as an ingredient for food exposed to heat treatment at a high temperature and mechanical shear, for use in instant meal products. Some authors like Huber (1990) and Carvalho and Mitchell (2000) postulated that high sucrose concentrations increase the viscosity of the dough which could be a limiting factor in single screw extrusion processing

Twin screw extruder

It is a common practice in the art of extrusion cooking with twin-screw extruders, to employ a section of spirally flighted screw elements behind the die head zone to provide a steady pumping action and to generate high die pressure. However, Roberts and Guy (1987) found that the equilibrium operating state in such a configuration is prone to catastrophe (i.e. sudden change) and metastability.

Wang et al. (2012) developed pea starch noodles using twin-screw extruder and observed that increasing dough moisture content increased the b value (yellowness), expansion ratio, percentage of gelatinized starch, resistant starch content, cooking time, firmness and surface stickiness, but reduced cooking loss.

Bakalis and Karwe, 1999 investigated two velocity components, namely the transverse (Ux), and the axial (Uy) and measured these velocities in the nip region of a 14 mm pitch screw element at screw speeds of 90, 60 and 30 rpm. The velocity distributions were very different from those reported in the translation region, indicating the distinct character of the nip region. While *Ux* did not vary significantly with respect to the angular position, the axial velocity component, Uy, varied significantly. The screw speed did not affect the shape of the velocity distributions; it only affected the velocity values.

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In another study, Pilli et al. (2005) investigated the effects of some operating conditions on oil loss and physical properties of products obtained by doughs containing almond flour extruded in a co-rotating twin-screw extruder. The lowest loss of oil was obtained at low percentages of dough moisture and high values of screw speeds and the best results were obtained by extruding at 36% dough moisture and 200 rpm screw speed. The operating conditions suitable to obtain both a low oil loss and a good product structure were low percentages of dough moisture and high values of screw speed and extrusion temperature. The effects of eggshell powder on the extrusion behaviour and extrudate properties of rice in a co-rotating twin-screw extruder was investigated by Chung (2007). Microstructure of eggshell powder added extrudates showed a fine and friable texture with thinner cell walls and more cell numbers. With increase in levels of eggshell powder could increase L* values but decrease b* values of extrudates.

Stojceska et al. (2009) used co-rotating twin-screw extruder for wheat flour and corn starch with the addition of 10% brewer’s spent grain and red cabbage. Choudhury and Gautam (2003) studied the effects of hydrolysed fish muscle on intermediate process variables during twin-screw extrusion of rice flour. Hydrolysis of arrow tooth muscle beyond 5 min had very little effect on energy input, residence time, mixing index and die temperature. Fish solids level played a dominant role in lowering specific mechanical energy input, raising the mean residence time, and reducing mixing.

Extrusion parameters and process variables

Research has led to a growing awareness of the importance of variables (screw speed, feed rate and die geometry) which control the mechanical history and residence time of material in the extruder (Owusu-Ansah et al., 1983). Several extrusion processing conditions are accounted for

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the quality of finished products. The control of feed rate, screw speed, barrel temperature and barrel pressure, together with the above mentioned critical parameters, will determine the crispness, hardness and various other characteristics that will influence the success of the product (Harper, 1981). During extrusion high temperature and large shearing forces cause deterioration of quaternary and tertiary structure of biopolymers and favor interactions between food components increased moisture influenced the rheological behavior of the food material in the extruder by reducing shear load (Harper, 1988). Low moisture extrusion increases extrudate expansion (Davidson et al., 1984; Miller, 1985). Structural characterization of extrudates derived from cereal starches have indicated that these materials have undergone macromolecular degradation (Colonna and Mercier, 1983), reflected as changes in melt rheology (Vergnes and Villemaire, 1987) and product functional properties such as water solubility (Fitton, 1986), water absorption and dispersion viscosity (Doublier et al., 1986).

The effects of extrusion parameters on some properties of dietary fiber from lemon (*Citrus aurantifolia* Swingle) residues were studied by Méndez-Garcia et al. (2011). They found that extrusion process increased the soluble fiber from 38.60% in unprocessed lemon residues to 40.00 to 50.01% in extruded samples. The highest content of soluble fiber was 50.00% when operating conditions were high in temperature (100°C), low in moisture content and screw speed. The results of this study indicated that extrusion is a process that has the capability to transform insoluble fiber to soluble fiber in lemon residues. For the development of honey based extruded product Juvvi et al. (2012) optimised process variables using the blends of rice flour, wheat flour and honey and reported the optimized range of process variables as temperature (119 to 122°C),

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screw speed (301 to 321 rpm) and feed composition (9.68 to 10.35%) as optimum variables to produce acceptable honey based extrudates.

In a food extrusion cooking process, the product expansion, i.e. extrudate expansion, is a fundamentally important property describing the product quality and directly related to degree of cook. Many theories and models have been proposed to describe the extrudate expansion (Alvarez-Martinez et al., 1988; Bruin and Jongen, 2003; Tayeb et al., 1992; Moraru and Kokini, 2003). Some researchers use empirical regressions through process operation parameters and raw material compositions to explain the extrudate expansion (Cai and Diosady, 1993a; Ding et al., 2006; Altan et al., 2008a). Perez et al., 2008 studied the extrusion cooking of a maize/soybean mixture and factors affecting expanded product characteristics and flour dispersion viscosity. Cooking extrusion of maize/soybean mixture resulted in expanded products with good physical characteristics, the best extrusion conditions being those corresponding to intermediate temperature (170° C) and moisture around 16%. In another study, addition of 5–20% soy protein concentrate resulted in lower specific mechanic energy and expansion of NCS, and higher mechanical strength of extrudates. It is also known that expansion properties of high amylase corn starch were different from that of NCS (Chimnaswamy and Hanna, 1988; Launay and Lisch, 1983).

The extrusion barrel temperature is one of the other important parameters which determine the quality of extruded product. Mahungu et al. (1999) observed that the profile of isoflavones during corn/soy blend is greatly influenced by the extrusion barrel temperature followed by moisture content with small changes in isoflavone content. Sacchetti et al. (2004) studied the effects of extrusion temperature and feed composition on the functional, physical and sensory

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properties of chestnut and rice flour-based snack-like products. Chestnut flour was found to be suitable for the extrusion-cooking process adopted if properly mixed with rice flour. Chestnut flour (30%) along with rice flour was processed at 120° C producing a snack-like product with limited density and browning. Extrudate's storage stability was not affected by either extrusion temperature nor cereal flour type in an experiment conducted by Smithey et al. (1995). Higher temperature increased the activation energy for starch conversion by the shear in a single-screw extruder and a capillary rheometer (Wang et al., 1992; Zheng and Wang 1994). Zhao et al. (2011) studied reaction kinetics in Food Extrusion and found that while being heated and sheared simultaneously, food raw materials experienced a non-isothermal process and their residence time in the extruder was distributed. Starch gelatinization with excess water follows pseudo first order Arrhenius kinetics (Okechukwu and Rao, 1996; Turhan and Gunasekaran, 2002). The activation energy for starch gelatinization during extrusion was 3.325 kJ/mol from Ibanoglu and Ainsworth (1997) and 0.046 kJ/mol from Cai and Diosady (1993b). Both estimates were much lower than the activation energy for thermal conversion.

Feed composition is a dominant parameter that influences the intermediate process variables. Extrusion conditions, characteristics of the starch granule and presence of other components such as protein, fibers and sugars directly affect the degree of transformation (Chanvrier et al., 2007). Matz (1993) reported the importance of particle size of material during extrusion cooking of puffed snacks; however, they reported no details. Huber and Rokey (1990) reported that a soft texture product resulted from a fine granulation and a coarse meal led to a crunchier product. Studies showed that incorporation of fish proteins to starch-rich ingredients such as rice flour significantly decreased mechanical energy input, and resulted in products with reduced expansion and increased hardness (Gogoi et al., 1996a; Gogoi et al., 1996b; Gautam et al., 1997; Choudhury et al., 1998).

Robin et al. (2011a) explained the effect of increasing the bran to a higher concentration on the mechanical properties of extruded starchy foams and reported that they depended on the cell wall thickness and bran particle dimensions. At higher relative density, the strength of the foams was further increased due to the even finer structures obtained. At lower relative density, even though finer structures were also obtained, the stress at rupture of the foams was decreased. Lazou and Krokida (2010) reported that the number of air cells in extruded corn decreased with increasing lentil level. In an experiment by Sowbhagya et al. (2005) stability of water-soluble turmeric colourant in an extruded food product made from corn and defatted soybean flours during storage was investigated. After 10 weeks of storage, the retention of curcumin is about 77%, and the effective shelf life of the product is 6 weeks at ambient condition with 83% retention of curcumin.

The structural property changes of corn starch material during extrusion as a function of feed moisture content was studies by Thymi et al. (2005). It was found that higher feed moisture decreased the radial expansion ratio of extrudates, resulting in a higher apparent density and lower porosity values. Marzec and Lewicki (2006) varied water activities for flat extruded wheat and rye bread by using saturated salt solutions. Above the critical water activities water plasticizes the breads, and decrease of compression force with increasing water activity was recorded. Onwulata and Konstance (2006) studied that the blend of whey protein concentrate and corn meal showed that controlling moisture content had the beneficial effect on quality attributes such as expansion ratio, porosity and breaking strength. Navneet et al. (2010) observed

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significantly higher influence of moisture content on lateral expansion; temperature on water absorption index; screw speed and temperature on hardness and screw speed on sensory score. In another study, higher moisture content increased the activation energies for the thermal conversion of starch (Wang et al., 1989) and the thiamin destruction during extrusion (Ilo and Berghofer, 1998), but decreased the activation energies for the polymerization and degradation of gluten and glutenin during shear treatments (Strecker et al., 1995). Effect of extrusion conditions on the physicochemical properties and sensory characteristics of rice-based expanded snacks which were dependent on process variables was studied by Ding et al. (2005). Feed rate, feed moisture and barrel temperature had significant effect on various extrudate properties, with feed moisture having the greatest influence on the properties of the extrudate.

Akdogan (1996) used stepwise regression analysis to determine the contribution of each extruder operating parameter (temperature, moisture, feed flow rate, screw speed) on the variance of die pressure drop, torque, and specific mechanical energy. Gujral et al. (2001) explained extrusion behavior of grits from flint and sweet corn. Among feed moisture, extrusion temperature and screw speed, feed moisture showed the most pronounced effect on die pressure, expansion and WSI (Water Solubility Index). Die pressure of the extruder was significantly greater for sweet corn than flint corn grits. The particle size distribution revealed that flint corn grits had more fine and opaque particles and resulted in extrudates with lower WSI and expansion than those from sweet corn grits which had fewer fine particles.

Akdogan and Rumsey (1996) studied the dynamic responses of a lab-size co-rotating twin screw extruder at a constant temperature (80^{0}C) and moisture (60%), applied to a rice starch system. Increased specific mechanical energy was desired for expanding products, but SME was

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reduced as a result of incorporating whey protein concentrate and sweet whey solids. Quality indices for expansion and breaking strength decreased significantly, indicating poor textural effects. By reducing the moisture and adding reverse screw elements, SME was increased, which increased product expansion and breaking strength (Onwulata et al., 2001). Karla et al. (2010) observed that the extrusion significantly decreased anti nutrients and water solubility, water absorption index and in vitro protein and starch digestibility were improved by the extrusion process. Several researchers viz. Rao and Artz (1989); Guzman et al. (1992); Mustakas et al. (1964); Sayre et al. (1985) reported that even mild extrusion conditions can increase the stability of rice bran stored for 6 weeks.

MODELING AND SCALING OF EXTRUSION PROCESS

Modeling and scaling of extrusion process paves the way for predicting extruder behavior (such as pressure, temperature, fill factor, residence time distribution and shaft power) under various operating conditions (such as feed rate, screw speed, feed temperature/moisture and barrel temperature). A one-dimensional computer model of extrusion cooking was developed by Chin-hsien li (1999). This model could simulate and predict extruder behaviour. This model was user friendly, and could be used as a tool for designing, optimizing and control of extruder operating conditions.

Cheng and Friis (2010) modelled extrudate expansion in a twin-screw food extrusion cooking process through dimensional analysis methodology. A new phenomenological model was proposed to correlate extrudate expansion and extruder operation parameters in a twin-screw food extrusion cooking process. Buckingham's pi dimensional analysis method was applied to

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establish the model. Three dimensionless groups, i.e. pump efficiency, water content and temperature, were formed to model the extrusion process from dimensional analysis. The model was evaluated with experimental data for extrusion of whole wheat flour and fish feed.

In another study, Kumar et al. (2008) determined modeling residence time distribution in a twin-screw extruder as a series of ideal steady-state flow reactors. In cases of scaling-up and transferring processes to different extruder geometries, most of the time, residence time distribution was useful for comparison since it was measured easily and was a result of mass flow patterns (Jager et al., 1991). Residence time distribution in extrusion could be modeled assuming plug flow in series with a finite number of continuously stirred tank reactors with dead volume fractions. The best-fit model was found to be a plug flow in series with a finite number of constantly stirred tank reactors having dead volume fractions. Gogoi and Yam (1994) developed an empirical exponential equation to relate mean residence time with screw speed in a twin-screw extruder. Increasing screw speed shifted the RTD to the left with respect to the time axis and shortened the mean residence time (Altomare and Ghossi, 1986).

INGREDIENTS USED AND MANUFACTURE OF DIFFERENT FORMS OF EXTRUDED PRODUCTS

Extruded foods are composed mainly of cereals, starches, and/or vegetable proteins. The major role of these ingredients is to give structure, texture, mouth feel, bulk, and many other characteristics desired for specific finished products (Launay and Lisch, 1983; Jamora et al., 2002; Tahnoven et al., 1998). The success or failure of a new extruded snack food product is directly related to the sensory attributes, where texture plays a major role. Consumer acceptance of extruded foods is mainly due to the convenience, value, attractive appearance and texture

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found to be particular for these foods, especially when it concerns snack products (Anton and Luciano, 2007; Harper, 1981). Apart from their sweet or salty taste, for the majority of consumers attributes like crunchiness or crispiness are most important (Corradini and Peleg, 2006).

Rice flour has become an attractive ingredient in the extrusion industry due to its unique attributes such as bland taste, attractive white colour, hypoallergenicity and ease of digestion (Kadan et al., 2003). Whereas, wheat flour has been widely used in the extrusion industry and the effects of process variables on wheat extrudate properties have been studied (Ali et al., 1996; Anderson et al., 1969a; Harper, 1979; Ilo et al., 1996; Mercier & Feillet, 1975). Wheat flour, rice flour, maize grits, barley flour and their combinations along with byproducts of different industries like carrot and grape pomace, have been widely used in the extrusion industry and the effects of process variables on the physical and functional properties of extrudates have been studied (Yagci and Gogus, 2008; Altan et al., 2008a; Ding et al., 2006; Ali et al., 1996; Carvalho and Mitchell, 2001).

Among other materials, incorporation of legume flours has been shown to cause a positive impact on levels of proteins and dietary fibre of corn starch-based extruded snacks (Berrios, 2006). On the other hand, addition of high-fibre, high-protein alternate ingredients to starch has been demonstrated to significantly affect the texture, expansion and overall acceptability of extruded snacks (Liu et al., 2000; Veronica et al., 2006). For the production of nutritious acceptable snacks, rates of starch fortification seem to vary according to the nature of each material. Legumes, for example, have been reported to cause good expansion and are regarded as highly feasible for the development of high-nutritional, low-calorie snacks (Berrios, 2006). High

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in fibre, protein, and low in fat, bean consumption has been inversely associated with reduced risk of coronary diseases and some types of cancer (Azevedo et al., 2003; Winham and Hutchins, 2007).

Singh and Smith (1997) compared wheat starch, whole wheat meal and oat flour in the extrusion cooking process. Wheat starch and meal behaved broadly similarly but differed from oats in pressure, expansion, WSI and WAI in their response to moisture content and temperature. Addition of WGO to wheat starch increased the expansion, whereas it had little effect on the wheat meal. WGO increased the upper bound WSI and decreased the lower bound WAI for starch or meal.

Lazou and Krokida (2010) determined the functional properties of corn and corn–lentil extrudates. Extrusion temperature increased the values for all functional properties (WAI, WSI and OAI), while feed rate had a decreasing effect. Feed moisture content increased the WAI, but had an opposite effect on the WSI and OAI. Comparatively, extrudates from corn flour had higher values of functional properties than those from corn–lentil flour.

Hagenimana et al. (2006) evaluated rice flour modification by extrusion cooking. Microviscoamylograph analyses showed that increasing the severity of extrusion conditions resulted in low CPV, HPV, and low final viscosity of the extrudate. Peak viscosity indicated a high positive correlation with hot paste viscosity and cold paste viscosity. SDS was inversely related to the amount of RDS and this relationship depended on the processing treatments.

De Muelenaere and Buzzared (1969) extruded degermed corn grits and whole corn meal and found that degermed corn grit had much greater expansion than whole corn. Zhang and Hoseney (1998) reported extrusion behavior of corn meal with poor and good expansion properties. They

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reported large particle size alone caused poor expansion, however, the differences in particle between good and poor corn meals was relatively small and not completely responsible for differences in expansion.

Products for human consumption

Ready-to-eat cereals

Extrusion cooking of ready-to-eat cereals (RTE) provides several advantages over conventional processing methods. Extrusion cooking allows for faster processing times, lower processing costs, less square footage of the plant required for processing equipment, and greater flexibility leading to more types of end-products. Lorenz and Jansen (1980) studied the extrusion of maize/soy blends using a low cost extrusion cooker. Instant cereal-legume products are manufactured by extrusion cooking a mixture of a cereal product, a legume product and a fat; the finished products have a relatively high moisture content. Ready-to-eat extruded products containing high levels of vegetable protein was formulated with semi defatted Brazil nut cake and cassava flour mixtures (Souza et al., 2008). The mixtures with higher Brazil nut levels present higher levels of protein, fat and ash, while the mixtures with less Brazil nut present higher levels of carbohydrate. Gupta et al. (2008) developed a ready-to-eat extruded food with blends of Indian barley and rice using a single-screw laboratory extruder having barley flour (10–30%). Sensory scores indicated that barley flour content at 20%, feed moisture content at 30%, and die temperature at 175°C resulted in an acceptable product. Ready-to-eat infant flour was prepared from rice based blends prepared with a very-low cost extruder. The increase in starch content increased the loss of lipid, the expansion ratio, the degree of gelatinization of starch, and the water absorption index. In another experiment, Onwulata (20100 created

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nutritious high-protein puffed crunchy snacks of corn meal with texturized whey protein isolate. While, Zhuang et al. (2010) produced a new palatable rice extrudate with mesona blumes gum and had good antioxidation ability, water solubility and bulk density.

Snack Foods

Consumer acceptance of extruded foods is mainly due to the convenience, value, attractive appearance and texture found to be particular for these foods, especially when it concerns to snack products (Harper, 1981). Snack food extrusion includes subjecting selected grains to a variety of complex physical processes to yield snacks with varied shapes and textures (White, 1994).

In extruding snack foods, grain and other ingredients are mixed and cooked under pressure, shear at high temperature in a tube, which is also called barrel. The resulting mass is forced through a die, cut into individual pieces and assumes the various shapes that consumers have come to expect in the snack food aisles of markets (Harper, 1981). Novel ingredients, cutting-edge extrusion technology and innovative processing methods are combined to yield new snack products with ever widening appeal to health-conscious consumers that are seeking different textures and mouth feeling with convenience (Pamies et al., 2000). In addition, several extrusion processing conditions are accounted for the quality of finished products. The control of feed rate, screw speed, barrel temperature and barrel pressure, together with the above mentioned critical parameters, will determine the crispness, hardness and various other characteristics that will influence the success of the product (Harper, 1981).

The success or failure of a new extruded snack food product is directly related to sensory attributes, where texture plays a major role. In such foods, where expansion is desired and puffed

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products are expected, texture is of major importance, with crispness being one of the most important attribute (Pamies et al., 2000). Several researchers agree that crispness should result from the structural properties of a food (Bouvier et al., 1997; Mohamed et al., 1982; Stanley and Tung, 1976). According to Heidenreich et al. (2004) crispness is perceived through a combination of tactile, kinesthetic, visual and auditory sensations and represents the key texture attributes of dry snack products.

Martinez et al. (1996) developed and characterised a snack food utilising normal maize and quality protein maize as its main ingredient in single screw and showed low density and high expansion degree. Extruded flours from Fresh and Hardened Chickpea was prepared and had higher values of total colour difference, water absorption index and dispersabiliy and lower Hunter L value, particle size index and water solubility index than conventional flours (Carrillo et al., 2000). Sweet whey solids (SWS) or whey protein concentrate (WPC) were added at concentrations of 250 and 500 g/kg to corn meal, rice or potato flour to make snack products (Onwulata et al., 2001a). High-temperature short time (HTST) air puffing was used for production of potato–soy ready-to-eat snack food as it ideally produced highly porous and light texture viz. puffing temperature (185–255^{0}C) and puffing time (20–60 s) for potato–soy blend with varying soy flour content from 5% to 25% (Nath and Chattopadhyay, 2008). In another study by Miranda et al., 2011 extruded snacks were prepared from flour blends made with taro and nixtamalized (TFeNMF) or nonnixtamalized maize (TFeMF) using a single-screw extruder with taro flour proportion in formulations (0-100 g/100 g) and extrusion temperatures (140-180^{0}C) and flour mixtures made from taro and nixtamalized maize flour produced puffed extruded snacks with good consumer acceptance.

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Texturized vegetable protein

Texturization of vegetable protein is the restructuring of protein molecules (usually soy protein) into a layered, cross linked mass which is resistant to disruption upon further heating and/or processing. Texturized vegetable protein (TVP) is divided into two classification; extrusion cooked meat extenders and extrusion cooked meat analogs. In a particular study, Hayashi et al. (1992) reported that extruder barrel temperature was the most important parameter for the texturization of the dehulled whole soybean. Melt temperature is a critical factor in protein cross-linking reactions. According to study by Areas (1992) Increasing temperature from 140 to 180^0 C results in a proportional decrease in disulfide linkages formed in extruded soy protein isolates. Temperatures lower than 90^0 C hinder the expansion and layer formation (Cheftel et al., 1992).

Perilla et al. (1997) extruded chicken diets from full-fat soybeans at 122 and 126^0C contributed to maximum growth in broiler chickens, whereas diets extruded at 118 and 120^0C resulted in significantly lower body weights. Cheftel et al. (1992) produced cheese analogs from caseinate and butter oil, and fat analogs from whey protein isolates through wet extrusion. For cheese analogs, extruder operating temperatures are lower than for other high moisture extrusion applications (60° C) and moisture levels vary from 60 to 75%. To minimize the water binding property of dairy proteins, nonfat dried milk, whey protein concentrate, and whey protein isolate were modified/ texturized using a twin-screw extruder which can be used to boost the protein content in puffed snacks made from corn meal (Onwulata et al., 2010). Qi and Onwulata (2011) investigated the effect of extrusion texturization at various temperatures (50, 75, and 100°C) and varying moisture levels of the feed (20, 30, 40, and 50%) on changes in the composition,

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molecular structure, and protein quality of food products containing whey protein isolate and showed that the protein quality of the extruded whey protein isolate remained relatively unchanged as a function of moisture level. A reduction in β-lactoglobulin content was observed at 50°C with increasing moisture content whereas the amount of α-lactalbumin remained unchanged at all moisture contents used at a set temperature.

Pasta products

Pastas are generally wheat-based products that are formed from dough, where no leavening is necessary. They are generally made of flour and water, although eggs are sometimes added. Durum semolina is the best material for making flour for pasta. Durum wheat is a hard wheat and gives pasta its yellow color and is generally different from common wheat. The pasta-like pea product processed by Wang et al. (1999) also exhibited a dense, compact structure, with relatively few swollen starch granules. Their products appeared to be completely coated with a gelatinized starch and protein matrix. Physicochemical properties and water status of fresh pasta (both extruded and laminated) produced with recently designed mixers that induce a uniform hydration of the solids and allow the formation of a dough in 1-2 s were evaluated (Carini et al., 2010). A study to determine the effects of semolina, hydration level during extrusion and flaxseed flour concentration on the physical and cooking characteristics of freshly extruded pasta was carried out by Manthey et al. (2008). Wojtowicz and Moscicki (2011) produced enriched precooked pasta-like products with wheat bran addition. In another study, precooked pasta-like products were processed on a single screw extrusion-cooker. The firmness of hydrated products was decreasing with increasing bran addition (20 and 25% of bran in the recipe), whilst processing at low rpm caused poor quality of pasta-like products with great adhesiveness and

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stickiness. The microstructure showed unmodified bran fractions at low screw speed, in turn higher rpm disrupted wheat bran cell walls. Barnes et al. (1997) manufactured an acidified pasta product by mixing a farinaceous material, an edible acid and water to obtain acidified dough; forming the acidified dough into a shape; contacting the surface- gelatinized product with water to obtain a wet, acidified pasta product and steaming the wet product and packaging the steamed product.

Chillo et al. (2010) studied the influence of repeated extrusions on some properties of non-conventional spaghetti. The dough gelatinization degree of the quinoa and oat significantly increased with the re-extrusion, whereas no influence of re-extrusion was found for the amaranth dough. Moreover, the re-extrusion number improved sensorial color and homogeneity for oat and quinoa dry spaghetti and had no effects on the sensorial characteristics of all cooked spaghetti.

Meat products and Co-extruded products

In addition to extruded chicken products, mechanically deboned turkey snacks (Hsieh et al., 1991) and fish meat sol (Kitabatake et al., 1985) have been texturized by extrusion. Meat extenders have been extruded from cottonseed proteins, peanut proteins, sesame proteins, sunflower proteins, pea proteins, and bean proteins (Riaz, 2004; Strahm, 2006). Mechanically deboned chicken was extruded with non meat binders to improve the water binding capacity and textural properties indigenous to processed meat products by Alvarez et al. (1990). Ground beef chuck was extruded with yellow corn flour, white corn flour and white corn flour with soy fibre acting as the nonmeat binders (Smithey et al., 1995). The influence of process variables on the resistance to stretching, colour and final water content (after immersion in water) of extrudates

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from a mix of fish surimi and soy protein concentrate texturized by extrusion cooking was studied by Thiebaud et al. (1996).

Extrusion process further involves fortification of various products with meat components in order to increase their nutrient content. Pinto et al. (1997) produced extruded bovine lung in a laboratory extruder (L/D 20:1) at several processing temperatures and moisture contents which can be used as a good iron source. Cian et al. (2010) fortified extruded maize products with hydrolysates from bovine hemoglobin concentrate using a brabender single-screw extruder and could increase potential iron availability. Extruded corn-fish snacks, containing freeze-dried saithe protein were produced and described no odor and flavor change during storage (Shaviklo et al., 2011).

In co-extruded products, the outer layer is processed with a cooker extruder with a die that forms a hollow center. The center is then filled with a viscous filling which will not flow freely at ambient temperatures. Krasaekoopt et al. (2003) suggested to encapsulate the probiotics for in the fermented and other dairy products can be achieved through co-extrusion devices or dropping into a bath of coating material which react at the droplet surface, producing entrapped, rather than encapsulated core material, although encapsulation This method can be difficult for large-scale production because of slow formation of beads compared with the emulsion technique. Co-extruded soybean poultry by-product meal with egg supplement was prepared and appeared suitable as a substitute for fish meal in *L. vannamei* diets (Samocha et al., 2004). Nayak et al. (2011) demonstrated puffed extruded food products with the improved antioxidant content from purple potato and yellow pea flours using a co-rotating twin screw extruder. Browning indices and color attributes such as brightness, chroma and hue angle agreed with degradation of

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anthocyanins in the extruded products. However, extrusion cooking retained antioxidant capacities of the raw formulations in the extruded products either in their natural forms or degraded products with radical scavenging activity

Pet food and animal feed products

Extrusion technology is extensively being used for pet food and animal feed products. The nutritional effects of expansion and short time extrusion on feeds for broilers was studied by Plavnik and Wan (1995). They found that the effect of short time extrusion or expansion on digestibility and energy of feeds and grains was determined in 18-21 day old broiler chicks. Untreated corn-based feed or wheat or barley were compared with the same material treated by expansion or extrusion, and milled to equal size. Extrusion of whole feeds enhanced gross energy digestion and increased the apparent metabolisable energy, by 1.5 and 3.5%. Barley was less well digested than wheat. High temperature short time extrusion and expansion processes appear to enhance energy of common feeds for broilers. Mathew et al. (1999) applied this concept for extruded pet food with high protein content and found that injection of water into the preconditioner resulted in better quality parameters.

Marsman et al. (1995) investigated the effect of shear forces and addition of a mixture of a protease and a hemicellulase on chemical, physical and physiological parameters during extrusion of soybean meal. Chemical analysis showed a decrease of 25-41% in trypsin inhibitor activity and a decrease in lectin content below the detectable level as a result of extrusion. The in-vitro protein digestibility increased from 60.7% in toasted soybean meal to 81.1% after extrusion with 2 twin lead slotted screws and seemed negatively correlated with trypsin inhibitor activity. The protein dispersibility index and nitrogen solubility index decreased as a result of

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extrusion but both failed to differentiate between the different shear levels. Using nitrogen solubility index as a quality parameter of soybean meal extrusion, it was concluded that nitrogen solubility index levels of 50-558 improved in-vitro protein digestibility and feed conversion of broiler chickens.

Pet foods extruded at 300 rpm had a significantly higher lipid oxidation rate than the ones produced at 200 and 400 rpm. Feed moisture content had the same effect as the fat content; the extrudates with a higher moisture content resulted in a lower lipid oxidative rate (Hsieh and Huff, 1998).

VALUE ADDITION AND BY PRODUCT WASTE UTILIZATION IN EXTRUDED PRODUCTS

Value addition of extruded products involves incorporation of ingredients into the extruded products in order to enhance their textural or nutritional quality. Extrusion technology to some extent may improve bioavailability of bioactive compounds by forming complex with protein which could be broken down in human body thus yielding antioxidant activity per sec. Enrichment of extruded snacks with several fruit and vegetables by-products are being developed to increase the level of bioactive in extrudates (Brennan et al., 2011).

A lot of research work has been reported using rice flour for extrusion for good extrusion characteristics. Rice flour incorporated cauliflower by-products as a new source of dietary fibre, antioxidants and proteins in cereal based ready-to-eat expanded snacks. Rice flour was added with different proportions of dehydrated carrot pomace and pulse powder mixture having equal ratio at different moisture content, screw speed and die temperature (Navneet et al., 2010). Stojceska et al. (2008a) observed cauliflower by-products as a new source of dietary fibre,

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antioxidants and proteins in cereal based ready-to-eat expanded snacks. It was found that addition of cauliflower significantly increased the dietary fibre and levels of proteins. Extrusion cooking increased the level of phenolic compounds and antioxidants but decreased protein in vitro digestibility and fibre content in the extruded products. Altan et al. (2008c) processed the blends of barley flour and tomato pomace; barley flour and grape pomace and corn flour and tomato pomace in a co-rotating twin-screw extruder. Bhattacharya (1997) investigated twin-screw extrusion of rice-green gram blend. The torque during extrusion was highest at the highest temperature levels. The specific mechanical energy linearly increased with screw speed. The maximum breaking (shear) stress of the product was highly sensitive to the levels of the extrusion variables and varied up to 25-fold. Temperature and screw speed also imparted curvilinear effects on the extrusion and extrudate characteristics. Extrusion of partially defatted hazelnut flour, fruit waste and durum clear flour in combination with rice grit an acceptable extruded snack was produced by Yagci and Gogus (2008). Increasing partially defatted hazelnut flour content caused increase in bulk density and water solubility index, but decrease in porosity and water absorption index of the extruded snacks. Pastor-Cavada et al. (2011) studied the effects of the addition of wild legumes (Lathyrus) on the physical and nutritional properties of extruded products based on whole corn and brown rice. Addition of legumes produces a decrease of expansion and an increase in solubility in both rice-containing and corn-containing samples. With only 15% of legume replacement, a significant increase in protein content and quality, fibre, and mineral content was obtained. The performance of each mixture during extrusion and the physical properties of the extruded products were considered to be in the range of those expected for snack type products. The materials were added at the level of 30% into the gluten-

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free balanced formulation (control) made from rice flour, potato starch, corn starch, milk powder and soya flour (Stojceska et al., 2010).

Shoar et al. (2010) explained the addition of tomato derivatives to traditional starchy extruded snacks and improved nutritional properties by adding lycopene and fibre. Lycopene retention was higher in products containing tomato skin powder and significantly lowers when wheat flour was used to make the snacks. The energy bar made from extruded flour i.e. mixing defatted and whole hemp powders with rice flour at varying hemp levels (Norajit et al., 2011). Corn-based extruded product blended with apple pomace was studied by Karkle et al. (2012). He postulated that hydration to 17.2% by adding water either into the preconditioner the extruder or dividing half in each was key factor in defining extrudate microstructure, texture and digestibility patterns. Stojceska et al. (2009) suggested that increasing the water feed to 15% increased the level of total dietary fibre in the extrudates and also increased the level of total antioxidant capacity and total phenolic compounds. Mixtures of semi-defatted sesame cake (0–20%) and corn grits were processed in a single screw extruder which improved the nutritional value of corn expanded extrudates. The addition of semi-defatted sesame cake increased protein, fat and ash content of corn extrudates, whereas carbohydrate content was reduced. The addition of semi-defatted sesame cake reduced the sectional expansion of the corn extrudates and increased puncture force (Nascimento et al., 2011).

Anton et al. (2009) studied physical and nutritional impact of fortification of corn starch-based extruded snacks with common bean (Phaseolus vulgaris L.) flour: Effects of bean addition and extrusion cooking. Fortification of corn starch with small red bean flour yielded extrudates with higher nutritional functionality compared to navy bean flour substitution. In another study,

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Berrios et al. (2002) reported that by adding increasing levels of sodium bicarbonate to black bean flour they could produce more expanded bean extrudates. This observation was attributed to the release of CO_2 from $NaHCO_3$ facilitated through the heat and moisture provided by the extrusion process. In comparison to raw flours, extrusion significantly decreased concentration of phenolics, antioxidants, TI, and phytic acid.

The effects of emulsifiers have been attributed to their ability to form inclusion complexes with starch, particularly with amylose (Galloway et al., 1989). The ability of MG to form complexes with amylose depends upon their physical state (Krog and Nybo-jensen, 1970). Singh et al. (2000) reported the effect of sodium bicarbonate and glycerol monostearate addition on the extrusion behaviour of maize grits. The effect of $NaHCO_3$ on expansion, WAI, WSI and viscosity of extrudates was observed to be temperature-dependent. $NaHCO_3$ at lower extrusion temperature (125°C) increased expansion, WAI and WSI while at higher extrusion temperature (175°C), a reverse effect of $NaHCO_3$ on these characteristics was observed. Addition of $NaHCO_3$ decreased the lightness and increased the redness and yellowness of extrudates in a study by Chinnaswamy and Hanna (1990). Addition of emulsifiers resulted in a product of more uniform appearance and homogenous structure and reduced surface stickiness in the warm extrudates (Harper, 1981; Guy, 1993).

Stojceska et al. (2009) determined the effect of extrusion cooking using different water feed rates on the quality of ready-to-eat snacks made from food by-products. Extrusion cooking and increased feed moisture content significantly increased total dietary fibre level of the extrudates except wheat flour and red cabbage blend, which was more evident up to 15% water feed level. Extrusion cooking increased the level of total antioxidant capacity and total phenolic compounds

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in samples containing red cabbage but had no effect on phytic acid. Water feed level also affected the expansion ratio, bulk density, hardness, WSI, SME and colour of finished products.

Reactions in extruders, such as gelatinisation, melting, degradation as well as complexations between ingredients are influenced by the form and the intensity of energy inputs (Zheng and Wang, 1994). Extrusion cooking of starch leads to a degradation of amylose and amylopectin by chain splitting (Colonna and Mercier, 1983; Colonna et al., 1983; Davidson et al., 1984b) due to effects of shear (Della Valle et al., 1989; Davidson, 1991). Extrusion, under the conditions reported, partially solubilised sago without major breakdown of the macromolecules. Solubility did not increase at the expense of water absorption capacity (Smith, 1991). It is postulated that starch granules are either split into smaller pieces or the surfaces are sheared but that, the crystalline structure is wholly or partially preserved within each fragment. High moisture twin-screw extrusion of sago starch: Influence on granule morphology and structure was studied by Govindasamy et al. (1996). Thermomechanical processing of sago starch in the twin-screw extruder at the high moisture system led to shear induced limited degradation and starch phase transitions (a composite melting gelatinisation process).

Further, Stojceska et al. (2008a) and Chung (2007) reported the addition of eggshell powder with rice flour resulted in increased water solubility index, decrease moisture content and cross-sectional expansion but increased longitudinal expansion of extrudates. The addition of eggshell powder could also increase the specific volume and decrease shear force of extrudates; moreover, the highest specific volume and the lowest shear force of extrudates were observed for 1% eggshell powder added.

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Hwang et al. (1997) investigated the effect of cysteine addition on the volatile compounds released at the die during twin-screw extrusion of wheat flour. There was significant flavor generation by using cysteine as a flavor precursor in extrusion cooking. Most of the volatile compounds released at the extruder die were sulfur-containing compounds. A comparison of volatiles from the condensate and recovered from the extrudate shows that more thiophenes were identified from the extrudate while more thiazolines, thiazolidines, and dithiazines were identified in the condensate.

In studies of direct oil addition Harper and Tribelhorn (1992) added corn oil to manipulate three corn flours to the same oil level, Mohamed (1990) added up to 4% corn oil to maize grits and Pan et al. (1992) added 3% soybean oil to rice. Chang et al. (2011) evaluated extrusion-modified fenugreek gum. The results suggested that extrusion processing of fenugreek gum could lead to some changes in the structure and functional groups, including disruption of the cell-wall structures and unfolding of the polysaccharide molecules, which could lead to the exposure of functional groups, such as hydrophilic groups, from inside, thereby improving the hydration properties. Sereno et al. (2007) examined the effects of extrusion processing on the hydration properties (water dispersibility and water hydration viscosity) of xanthan gum, and reported that the extrusion process can enhance the dispersibility and hydration viscosity of the gum.

Politz et al. (1994) suggested that the amylose/amylopectin ratio is the primary factor affecting the fragmentation of corn starch in a twin-screw extrusion at temperatures higher than 140°C due to the insignificant correlation between specific mechanical energy and the changes of molecular size. Faubion and Hosney (1982) reported that the expansion of wheat starch with

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1–8% soy protein isolate was higher than that of pure starch. However, at 10% soy protein isolate, expansion decreased. Ghorpade et al. (1997), on the other hand, showed that increasing the percentage of soy protein isolate from 10% to 30% in corn starch extrudates did not significantly affect bulk density and the percentage of open pores. De-Mesa et al. (2009) studied soy protein-fortified expanded extrudates using normal corn starch. Screw speed and soy protein concentrate levels affected the expansion, mechanical, and macromolecular properties of corn starch-soy protein concentrate (CS–SPC) extrudates and found that the effect of increasing soy protein concentrate content was greater than the effect of screw speed on starch degradation (WAI, WSI and starch molecular weight shifts).

Sucrose is a common additive in commercially extruded foods, particularly breakfast cereals, and is incorporated into these products in concentrations up to 50% by weight (Hsieh et al., 1990). In corn meal extrudates, very high concentrations of sucrose (2-50%) together with 25% processing moisture were found to reduce expansion progressively and to facilitate product collapse (Sopade and Le Grys, 199la). Later, Jin et al. (1994) found that even low concentrations of sucrose (2-12%) in the presence of 20% moisture in feed resulted in an increase in bulk density and a reduction in expansion of corn meal extrudates. In wheat flour extrudates, Moore et al. (1990) noted an increase in apparent density with sucrose concentration (3-18%). Ryu et al. (1993b) also reported that increasing sucrose concentration from 5 to 10% by weight significantly affected the expansion and cell structure by reducing expansion, increasing bulk density, increasing the number of cells per unit area, and also resulted in an increase in mechanical strength.

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Brewer's spent grain is the main by-product of the brewing industry. contains a high level of dietary fibre and has a strong potential for being recycled and upgraded for use within the food chain. Stojceska et al. (2008b) studied the recycling of brewer's processing by-product into ready-to-eat snacks using extrusion technology. It was found that addition of brewer's spent grain significantly increased protein content, phytic acid and bulk density, decreased sectional expansion index, individual area and total area of the cells. The higher level of brewer's spent grain resulted in cells with thicker walls with a rougher surface.

Fenugreek polysaccharide mainly contains 75% soluble dietary fiber and 15% insoluble dietary fiber of its composition. In view of the promising health benefits of fenugreek polysaccharides, fenugreek flour and debittered fenugreek polysaccharide were incorporated as natural functional ingredients in chickpea– rice blends to develop acceptable snack products utilizing extrusion technology (Shirani and Ganesharanee, 2009). Wheat flour was supplemented with wheat bran to achieve two levels of fibers (12.6% and 22.4%) (Robin et al., 2011b). Increasing the bran concentration decreased sectional and volumetric expansions and increased longitudinal expansion. The reduction in volumetric expansion was associated with an increase in shear viscosity only at the highest bran concentration. This may induce a decrease in the viscosity of the starch phase and counteract the matrix viscosity increase linked to the properties of bran. A higher surface porosity was observed in the bran containing recipe due to earlier burst of the bubbles during growth. Zhang et al. (2011) elucidated the effects of extrusion processing on soluble dietary fiber in oat bran. Soluble dietary fiber in extrude oat bran had higher swelling capacity, solvent retention capacity, foam ability, apparent viscosity and consistency coefficient, and lower flow behavior index than those of soluble dietary fiber in untreated oat bran. The

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extrusion process also improved some properties of soluble dietary fiber from oat bran. The level of total dietary fibre was increased in gluten-free products by using extrusion technology and by incorporating a number of different fruits and vegetables, such as apple, beetroot, carrot, cranberry and gluten-free teff flour cereal.

EFFECT OF EXTRUSION PROCESS PARAMETERS ON QUALITY CHARACTERISTICS OF DEVELOPED PRODUCTS

Physiological quality attributes

Physical characteristics such as expansion, density, and hardness are important parameters to evaluate the consumer acceptability of the final product (Patil et al., 2007). It has been shown that SME correlates well with extrudate properties such as expansion, density and texture characteristics (Altan et al., 2008a; Dogan and Karwe, 2003; Ilo et al., 1996; Meuser and Van Lengerich, 1992; Onwulata et al., 2001b).

Grenus et al. (1993) studied the physical properties of extruded rice flour mixed with rice bran using the Instron machine and the Warner-Bratzler cutting device. The authors calculated the ratio between the shear force and cross-sectional area of the product to verify the hardness of the extrudates. Onwulata et al. (2001a) studied the breaking strength index of extruded corn, potato or rice snacks incorporated with whey. The authors observed that as the whey concentration increased (either sweet whey solids or whey protein concentrate) the quality parameters for expansion and breaking force decreased significantly.

WAI and WSI

The WAI and WSI characterize how extruded products will interact with water and are often important in predicting how the extruded materials may behave if further processed. Also, the

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degree of conversion of starch from granule form during processing can be assessed via WAI and WSI (Sriburi *et al*., 1999). Oikonomou and Krokida (2012) determined water absorption index and water solubility index prediction for extruded food products. It was observed that in most cases, the modeling of the WAI of food products showed that the power law equation is fitted satisfactory to the available experimental values. In contrast, when modeling WSI the fit of the power law equation to experimental data is adequate. Gonzalez et al. (2006) determined the effects of extrusion conditions and structural characteristics on melt viscosity of starchy materials. It was concluded that ‘‘Bagleys method’’ should not be used to estimate melt viscosity in cases where pressure and mass output pairs of data obtained do not correspond to samples differing excessively in degree of cooking. These results confirm that most of the responses in extrusion process (specific mechanical enegy, degree of cooking, among others) are combined responses that depend on several factors such as extrusion conditions and types of material structure.

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Colour change

Comparison of colour change before and after extrusion cooking helps in determining the impact of extrusion cooking on product ingredients. Ilo and Berghofer (1999) determined kinetics of colour changes during extrusion cooking of maize grits. In this study, the kinetics of colour changes during extrusion cooking of yellow maize grits were investigated using the CIE Lab colour system and a zero-order kinetic model. The lightness of extrudate (L*) and the redness (a*) were mostly dependent on barrel temperature, feed moisture, and feed rate. The yellowness parameter (b*) was only slightly dependent on extrusion variables. The lightness parameter (L*) showed marked changes due to extrusion cooking and was the best parameter in the modelling of extrudate browning kinetics. Wojtowicz and Moscicki (2011) also showed lower L* values for both raw and hydrated products with higher bran addition.

Bulk density and expansion ratio

Bulk density and expansion ratio are dependent physical attributes. The increase in bulk density corresponds to decrease in expansion ratio and vice-versa. Extrudate expansion has been reported to be the most dependent on material moisture content and extrusion temperature. Several theoretical considerations for extrudate expansion have been published (Alvarez-Martinez et al., 1988; Ilo et al., 1996; Kokini et al., 1992; Kumagai and Yano, 1993; Padmanabhan and Bhattachayrya, 1989). A general model of extrudate expansion was developed including the radial, longitudinal and volumetric expansion (Alvarez-Martinez et al., 1988). Most of these studies used radial expansion as a measure of quality for extrudate expansion. However, studies by Launay and Lisch (1983) and Lai et al. (1989) showed that extrudate expansion occurred in both the longitudinal and lateral directions during extrusion cooking. A systematic increase in bulk density and a decrease in expansion were reported by several authors when adding sucrose to extruded cereals (Barrett et al., 1995; Ryu et al., 1993b). Hsieh et al. (1990) reported reduced bulk density and enhanced expansion for corn meal extrudates with added sucrose (2-8% wt). The structural changes in extrudates with the addition of sucrose have been attributed to competition for moisture (Hsieh et al., 1990) and inhibition of gelatinization (Sopade and Le Grys, 1991) during expansion. A bulk density increase and a sectional expansion reduction with sucrose addition were observed by Fan et al. (1996a). In addition Barrett et al. (1995) noticed a cell size reduction with sucrose addition. The influence of physical structure of

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extrudates on strength of these materials was reported by various investigators (Barrett and Peleg, 1992). Ollette et al. (1991) observed progressive reduction in the stress-strain functions of extruded wheat starch during bending tests. Thymi et al. (2005) reported structural properties of extruded corn starch. The effect of extrusion conditions (temperature, feed moisture content, residence time and rotation speed) on the structural properties of extruded corn starch was investigated. The apparent density increased slightly as the residence time increased for all temperature and moisture contents, while the porosity and the expansion ratio of extruded products decreased with the residence time.

Higher water feed level during extrusion process decrease the radial expansion (Chinnaswamy and Hanna, 1988; Faubion and Hoseney, 1982; Fletcher et al., 1985; Singh et al., 2007a) decrease volumetric expansion (Alvarez-Martinez et al., 1988) and increase bulk density of the extrudates. Zhu et al. (2010) investigated mechanical and microstructural properties of soy protein–high amylose corn starch extrudates in relation to physiochemical changes of starch during extrusion. Results from the current study indicated that high amylase corn starch-soy protein concentrate extrudates did not expand very well, but had substantially lower mechanical strength. High amylase corn starch-soy protein concentrate gave a much lower expansion compared with normal corn starch during extrusion. However, the expansion of normal corn starch was significantly reduced when 10% or 20% SPC was added (De Mesa et al., 2009) whereas the expansion of high amylase corn starch-soy protein concentrate was not significantly impacted.

Foods with lower moisture contents tend to be more viscous, therefore, the pressure differential would be smaller for higher moisture extruded foods, leading to a less expanded

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product (Singh et al., 2007a). The increase in feed moisture content at the same extrusion temperature reduced the degree of starch conversion (Kokini et al., 1992) and increased the apparent density values (Thymi et al., 2005). Ding et al. (2006) investigated the effect of extrusion conditions on the functional and physical properties of wheat-based expanded snacks. During the extrusion process, the dough viscosity, elastic swell effect and bubble growth effect contribute to the structure change of the extrusion mix. The degree of starch gelatinization and extrudate expansion was found to be reduced as the feed moisture increased.

Texture

In extruded foods, texture is of major importance, with crispness being often a desirable attribute. Among other tests, the texture analysis of expanded snacks has been performed through compression, penetration, acoustic procedures and texture profile analysis. The main component which determines the texture of extruded product is flour composition. Many ingredients have pronounced effect on overall texture of extruded product. Mezreb et al. (2006) evaluated the effect of sucrose on the textural properties of corn and wheat extrudates. Sucrose exerted pronounced effects on both the structure and the ability to process corn and wheat extrudates. Sucrose induced a reduction in product expansion, probably reflecting the decrease in glass transition temperature. However, independently of the flour type, an increase in sucrose leads to crisper products until an optimal content has been reached, beyond which crispness decreases.

Moisture content plays a significant role on the texture of ready-to-eat snacks as it directly affects the crisp behavior, the key factor related to their acceptance. The texture parameters of extruded rice crisps which were adjusted to water activities in the range of 0.05 and 0.65 were studied by Heidenreich et al. (2004). The general conclusions were derived from studies were

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that the crispness was affected when the sample exceeded a critical water activity value which had been reported to be above 0.5. Mazumder et al. (2007) reported textural attributes of a model snack food at different moisture contents.

Texture evaluation of extruded snacks is a complex subject, where the combination of techniques involving sensory, instrumental and microstructure analysis would certainly be the best practice. Anton and Luciano (2007) studied a review on instrumental texture evaluation of extruded snack foods. Katz and Labuza (1981) evaluated the crispness and shear resistance of several products, including extruded snacks, by a sensory test and by the Instron machine. Different types of cutting devices were used and they found that the initial slope of the force-deformation curve correlated with crispness, stating that the mechanical shear force can be used as indicator of crispness in expanded cereals. In 1986, Stanley found a good negative relationship between the shear force needed to fracture and the expansion of puffed cereal. Using a universal texture analyzer with a Warner-Bratzler device, the author associated the force deformation curve to the microstructure.

Physical properties of extruded rice flour mixed with rice bran using the Instron machine and the Warner-Bratzler cutting device were studied by Grenus et al. (1993). The authors calculated the ratio between the shear force and cross-sectional area of the product to verify the hardness of the extrudates. Onwulata and Veronica et al. (2006) conducted a TPA using a TA-XT2i texture press. Whereas Liu et al. (2000) performed a TPA of extruded oat-corn puffs and found a high correlation with human sensory perception of specific textural attributes. The effect of extrusion conditions on the functional and physical properties of wheat-based expanded snacks has been investigated by Ding et al. (2006).

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Mazunder et al. (2007) investigated the textural attributes for a model snack food at different moisture contents and used uniaxial compression to evaluate texture. Furthermore, the relationship that acoustic sensations have with the perception of texture has been studied for crisp, crunchy and crackly products by Duizer (2001). This has involved evaluating the contribution of chewing sounds to the perception of these textures or recording noises produced during mastication and evaluating various acoustic parameters from the resulting amplitude–time curves. Briefly, it has been reported that both crisp and crunchy foods exhibit a crunchy sound (Szczesniak, 1988). The description and interpretation of various methods of acoustic analysis of crispness and crunchiness is well described by Duzier (2001).

Recently, research has been conducted in order to correlate the results of some of the described methods with microstructure of extruded snacks (Chaunier et al., 2007; Mazunder et al., 2007; Onwulata and Konstance, 2006). Saeleaw et al. (2012) studied the effect of extrusion conditions on mechanical-sound and sensory evaluation of rye expanded snack. The results showed with increasing extrusion cooking temperature increasing number of force and number of sound peaks but decreasing maximum forces. Wojtowicz and Moscicki (2011) studied the effect of wheat bran addition and screw speed on microstructure and textural characteristics of common wheat precooked pasta-like products. Higher screw speed applied during processing improved sensory attributes and firmness of the products. The best pasta-like products were obtained by extrusion-cooking at 100 and 120 rpm when moisture content of dough reached 30% and bran addition did not exceed 20%.

Critical extrusion process variables such as temperature, screw speed, and moisture content may induce desirable modifications, thus improving palatability and technological properties of

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extruded products (Brennan et al., 2008). Robin et al. (2011c) explained extrusion, structure and mechanical properties of complex starchy foams. The fair agreement of extrusion simulation results with measured pressure, temperature and energy suggests that it would be possible to design a target foam structure by computing die pressure before extensive extrusion trials. Meng et al. (2010) studied the effects of extrusion conditions on system parameters and physical properties of a chickpea flour-based snack. It was observed that change of extrusion conditions, feed moisture content, screw speed, and barrel temperature, affected the extruder system parameters and physical properties of the chickpea flour-basedsnack. High specific mechanical enegy was observed at high screw speed and low barrel temperature. High level of feed moisture alone, or in combination with high temperature resulted in dense and hard extrudates with poor expansion.

Jin et al. (1995) suggested that crispness of food is affected by the size of the air cells and thickness of the cell walls. Structure has a large impact on the sounds produced when biting into products with crisp, crunchy and crackly textures (Duizer, 2001). The relation between cellular structure, mechanical strength and fracturability and sensory attributes have been studied for some extruded food models by Dogan and Kokini (2007); Luyten et al. (2004).

Anti-nutrientional quality attributes

Extrusion cooking is a high-temperature short-time process where the raw material is subjected to severe shear resulting in molecular transformations and chemical reactions. These changes include gelatinization of starch, denaturation of proteins, inactivation of many food enzymes and reduction of microbial counts (Harper, 1988). During processing through the extruder, a dough-like mixture is forced through a stationary metal tube or barrel by a rotating

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screw shaft. As this occurs, heat can be added in the form of steam and is also generated by the mechanical energy of the turning screw and the friction of the barrel. As a result, very high temperatures (>150^{0}C) can be reached (Harper, 1992a).

Castells et al., 2005 compiled a review on the fate of mycotoxins in cereals during extrusion cooking. Mycotoxins are secondary metabolites produced by fungi colonizing cereals in the field and in storage and are harmful to both humans and animals (Bennett et al., 1996). Five mycotoxins are considered to be economically and toxicologically important worldwide: fumonisins (FB), aflatoxins (AF), deoxynivalenol (DON or sometimes called vomitoxin) and derivatives, zearalenone (ZEA) and derivatives and ochratoxins (Chelkowski, 1998), although there are many others of worldwide interest such as moniliformin (MON), patulin, T-2 toxin and HT-2 toxin. Mukhopadhyay and Bandyopadhyay (2003) employed extrusion cooking technology to reduce the anti-nutritional factor tannin in sesame (Sesamum indicum) meal. Extrusion cooking was used to reduce tannin in sesame oilseed meal. A single screw cooking extruder, designed and fabricated at the Institute was used for the study. At the end it was found that extrusion cooking technology was very effective in reducing the anti-nutritional factor, tannin from sesame meal.

Fumonisin B_1,Hydrolysed B_1 and Fumonisin B_2

In studies on the heat stability of FB1, it has been demonstrated that the higher the temperature of the process the greater the inactivation of FB1 (Dupuy et al., 1993; Jackson et al., 1996; Katta et al., 1999). Temperatures ≥160^{0}C have been reported to reduce FB1 content by 46–76% (Katta et al., 1999), 50–68% (Meister, 2001) and 66–92% (Pineiro et al., 1999), and when corn grits plus glucose were extruded, by 45–71% (Castelo et al., 2001). A study by Castelo et al.

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(1998) showed that In spite of expecting greater FB1 decontamination with high temperature, losses of the mycotoxin was greater at 120° C than those resulting from processing at 140^0C with a mixing screw. Extrusion cooking resulted in more apparent loss of FB1 when the extruder was equipped with mixing (30–68%) screws than with non-mixing ones (16–50%) since residence time and shear rate are both higher when extruding with mixing screws. In another study, no hydrolysis products of FB1 were observed (HFB1 or partially HFB1) in extruded samples, therefore it was concluded that hydrolysis was not the mechanism for destruction of the mycotoxin. (Castelo et al., 1998, 2001, Pineiro et al., 1999).

Fumonisin B1 was reduced in a study by Girolamo et al. (2001)less than 30% when the raw material was extruded at temperature levels of 70–105°C but the decontamination rate with respect to the amount present in the initial corn material reached a 71% when the extruded samples were then roasted (170–220°C) to produce commercial cornflakes. The same trend was observed when reporting on FB2 stability since greater inactivation of the mycotoxin also occurred at higher temperatures. FB2 was lost from 44–66 and 72–100% when the cooking temperature was raised to 160–180 and 180°C, respectively (Pineiro et al., 1999; Meister, 2001). In contrast, some authors (Meister, 2001) found that the greatest reduction of FB2 content resulted from the combination of high temperature, high speed and low moisture content.

Total aflatoxins, aflatoxin B1, B2, M1, G1 and B1-dihydrodiol

Aflatoxins are one of the most potent toxic substances that occur naturally. Diet is the major way through which humans as well as animals are exposed to aflatoxins. Extrusion has been proven to be effective against reduction of total aflatoxin contenbt in many foods. AFB1 and AFG1 levels were influenced by both moisture content and temperature when rice flour was

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extrusion cooked (Cheftel, 1989). In another study carried out at 105°C by Hameed (1993), it was demonstrated that the extrusion process alone reduced total aflatoxins (AFt) content by 50–80%. Contrary to Hameed (1993), Elias-Orozco et al. (2002) found that both calcium hydroxide (lime) and hydrogen peroxide significantly lowered the levels of AFB1, AFM1 and AFB1-dihydrodiol when extruding corn flour. Extrusion cooking alone as well as all lime and hydrogen peroxide reduced the initial contents of aflatoxins.

Extrusion cooking has also been used as a kind of bioreactor to decontaminate aflatoxins in peanuts (Grehaigne et al., 1983), glucosinolates in rapeseeds (Barrett et al., 1997), and canavanine in jack beans (Tepal et al., 1994). Giddey et al. (1977) reduced aflatoxins B1 concentration in peanut cake from 2000 mg/kg to less than 50 mg/kg by mixing with a combination of methylamine (0.5 g/100 g) and calcium hydroxide (2 g/100 g) and extruding at 11-25 g/100 g dry matter moisture content, and 100-110^{0}C. Grehaigne et al. (1983) attained 87% degradation of aflatoxins by co-extruding contaminated peanut meal with ammonium hydroxide in a twin-screw extruder. Saalia and Phillips (2011) evaluated reduction of aflatoxins in peanut meal by extrusion cooking in the presence of nucleophiles.

Lysine showed comparable efficacy with methylamine in mediating aflatoxin reduction during extrusion cooking. The feed moisture, pH, and temperature of the extruder barrel were the most influential variables in reducing aflatoxins. It is suspected that frictional heat as a result of viscous dissipation of mechanical energy greatly enhanced aflatoxin degradation during low moisture extrusion. At high moisture aflatoxin reduction was probably promoted by hydrolysis of the lactone ring in the aflatoxin molecule.

Deoxynivalenol, Moniliformin, Zearalenone and Ochratoxin A

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Extrusion cooking turned out to be an effective process in reducing DON levels when a moisture content of 15 and 30%, a temperature of 150 and 180^{0}C and a sodium metabisulphite addition of 1% were set up as factors affecting the initial mycotoxin content (Cazzaniga et al., 2001). In the case of whole meal and flour (soaked in water or in 5 or 10% sodium bisulphite), extrusion slightly increased DON content, especially when a high temperature (170°C) was used; this could be because of the disruption of the DON-sulphonate adduct, which is unstable at higher temperatures (Accerbi et al., 1999). Both screw type and moisture content showed a significant effect in lowering MON content whereas no statistical effect was found for temperature (140–180°C) in an experiment conducted by Pineda-Valdes et al. (2003). As reported by Castelo et al. (1998), theoretically greater losses of MON would be expected at 26% because of the better heat transfer.

In comparison with other methods of thermal processing, extrusion cooking was more effective for reducing ZEA concentrations since greater reductions were achieved at temperatures of 120 and 140°C (73–83%) (Ryu et al., 1999) with extrusion cooking than those resulting from heating wheat flour at 200^{0}C for 60min (69%) (Bennett et al., 1980; Matsuura et al., 1981).Both temperature and initial moisture con According to Scudamore et al. (2004) tent showed significant influence in reducing OTA content from wheat wholemeal with extrusion cooking.

Nutritional quality attributes

Antioxidant activity

Extrusion conditions have an important impact on the antioxidant activity of various food materials. Many researchers have studied the effect on antioxidant capacity of various

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ingredients used for extrusion cooking. Sharma et al. (2012) predicted the antioxidant activity of barley as affected by extrusion cooking. Extrusion cooking exhibited a significant effect on the antioxidant properties of barley extrudates. Total phenolic content, total flavonoid content and reducing power decreased upon extrusion while the non-enzymatic browning index, metal chelating activity and DPPH radical scavenging activity increased significantly. The feed moisture and extrusion temperature significantly affected the antioxidant properties of barley. Among the extrudates, the highest total phenolic content (TPC) and antioxidant activity (AOA) was exhibited by extrudates prepared by the LTHM process.

The effects of extrusion cooking on the polyphenol content and antioxidant activity in rye bran has been reported by Gumul and Korus (2006) and in a snack bar composed of chickpea, corn, oat carrot and hazelnut by Ozer et al. (2006). In another experiment, Korus et al. (2006) studied the effects of extrusion on the phenolic composition and antioxidant activity of kidney beans. A maize bran/oat flour extruded breakfast cereal was developed by Holguin-Acuna et al. (2008) as a novel source of antioxidant and complex polysaccharides. An increase in the total phenols and DPPH radical scavenging activity in corn starch/common bean extrudates was reported by Anton et al. (2009). While, Shih et al. (2009) investigated the effects of drying and extrusion on the antioxidant activity of sweet potato and reported that the scavenging effect on DPPH radicals and total phenolic compounds increased. The effects of extrusion on the polyphenols, vitamins and antioxidant activity of foods was studied by Brennan et al. (2011). Viscidi et al. (2004) observed that the addition of ferulic acid and benzoin at levels of 1.0 g/kg or higher generally resulted in delayed onset of oxidation in oats based extrudates.

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Antioxidant activity and antiradical activity of extruded products is dependent not only on the level of bioactive compounds but also on the composition of bioactive compounds. Korus et al. (2007) observed a lower antioxidant activity for dark-red beans compared to black brown and cream coloured beans, even though dark-red beans extrudates exhibited higher total phenolic content compared to black brown and cream coloured beans extrudates. White et al. (2010) observed an increase in ORAC values (16-30%) with an increase in barrel temperature. The increase in ORAC values might be due to the products formed during Maillard reaction. Gujral et al. (2012) determined total phenolic content and antioxidant activity of extruded brown rice. The study revealed that both the total phenolic content and antioxidant activity increased significantly with the increase in germination duration in all the cultivars. Extrusion and rise in extrusion temperature lowered both the TPC and AOA. The results also suggested that the physical characteristics, such as bulk density, decreased with increase in germination duration and rise in extrusion temperature.

Delgado-Licon et al. (2009) observed a significant decrease in the total polyphenols and antioxidant activity during extrusion of bean/corn mixture. They observed that the decrease in bioactive compounds was dependent on process condition. Shih et al. (2009) observed a significant decrease in β-carotene and anthocyanin for both yellow and orange sweet potatoes after extrusion. Yagci and Gogus (2010) also observed that both feed moisture content and barrel temperature causes significant decrease in total phenolic content. While in another study, El-Hady and Habiba (2003) studied the effects of extrusion process variables such as barrel temperature and feed moisture on total phenols content of whole meal of peas, chickpeas, faba and kidney beans. They observed a significant decrease in total phenol in extruded products. This

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decrease was mainly attributed to individual effect of both temperature and moisture. Extruded products prepared from purple potato and dry pea flours had significantly higher content of total phenolics antioxidant activity, and flavonoids, compared to the raw formulations.

Anthocyanins

Anthocyanin pigments are responsible for the red, purple, and blue colors of many fruits, vegetables, cereal grains, and flowers. The interest in anthocyanin pigments has intensified because of their possible health benefits as dietary antioxidants. Extrusion parameters effect the levels of antioxidants in food ingredients and thus has been studied by many researchers. In a study, a significant decrease in β-carotene and anthocyanin for both yellow and orange sweet potatoes after extrusion was observed by Shih et al. (2009). Reports on loss of indigenous anthocyanins (55%) in blue and red pigmented maize during extrusion processing was given by Mora-Rochin et al. (2010). Anthocyanins present in cranberry pomace added to corn starch (White et al., 2010) or grape pomace (Khanal et al., 2009a) was studied in order to know the influence of extrusion on anthocyanin contents. Use of ascorbic acid to reduce the loss of anthocyanins during extrusion was studied by Chaovanalikit et al. (2003).

Durge et al. (2011) predicted stability of anthocyanins as pre-extrusion colouring of rice extrudates. The retention of anthocyanin increased with an increase in the moisture content of feed material and screw speed, but decreased with an increase in the die temperature. The effect of citric acid and sodium bicarbonate on colour stability of extrudates during processing, and that of light and packaging materials during storage at ambient conditions (30±2 °C) were evaluated. Addition of 1% citric acid increased the retention of anthocyanin up to 18.2% which could reduce the requirement of pre-extrusion colouring by almost 25%.

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Significant losses are reported for anthocyanins during extrusion cooking which is mainly due to high temperature employed and anthocyanins are quiet sensitive to high temperature. Total anthocyanin content during extrusion was reported to decrease however an increase in the biologically important monomer and dimmers were reported due to disruption of food matrix by Khanal et al. (2009b). Extrusion variables such as extrusion temperature, screw speed and residence time are considered critical for the level of monomer, dimer and trimers in extruded products (Khanal et al., 2009b; White et al., 2010). Despite losses during extrusion, Camire et al. (2002); Camire et al. (2003) observed a sufficient amount of the colorants remained to produce a purple colour corn meal extruded product. Chaovanalikit et al. (2003) investigated the effect of added ascorbic acid and blueberry concentrate on the retention of anthocyanins and ascorbic acid in Corn meal extruded products. They observed that addition of ascorbic acid during extrusion did not provide protection to anthocyanins and had no contribution in inhibition of browning reactions. Anthocyanin losses of low magnitudes (10%) are also reported for extrusion cooking of blueberry, cranberry, raspberry, grape powders and corn blends (Camire et al., 2007) and losses upto 32% are also reported for blueberry-corn blends (Chaovanalikit et al., 2003).

Phenols

Natural phenols are a class of natural organic compounds. They are small molecules containing one or more phenolic group. Extrusion influences natural phenolic content in many foods. Some studies show a decrease up to 80.3% in the level of total phenolic acid after extrusion of kiwicha (Amaranthus caudatus) (Repo-Carrasco-Valencia et al., 2009a; Repo-Carrasco-Valencia et al., 2009b). This decrease may be due to decarboxylation of phenolic acids during extrusion. Yagci and Gogus (2009) also observed that both feed moisture content and barrel temperature causes significant decrease in total phenolic content. The level of bioactive compounds in extruded products may increase in extrudates for example ferulic acid content is reported to increase by three times in extruded cereal grains (Zielinski et al., 2001). A similar increase in total phenolic compounds is reported after extrusion cooking of sweet potato by Shih et al. (2009) and for cereals in combination with vegetables by Stojceska et al. (2008a). The increase in the levels of certain phenolic acids in extruded products is generally due to the release from the cell wall matrix. El-Hady and Habiba (2003) studied the effects of extrusion process variables such as barrel temperature and feed moisture on total phenols content of whole meal of peas, chickpeas, faba and kidney beans. They observed a significant decrease in total phenol in extruded products. This decrease was mainly attributed to individual effect of both temperature and moisture.

Extrusion of common beans with corn starch blend is reported to increase total phenol, and antioxidant potential of extruded snacks (Anton et al., 2009). They observed a significant increase in total phenol content and antioxidant activity of extruded snacks obtained from blends of corn starch and navy/small red beans. They observed significantly higher total phenol in snacks prepared from small red bean cultivars compared to navy bean. This increase was evident because coloured dry beans are reported to possess strong in vitro antioxidant activity (Anton et al., 2009; Beninger and Hosfield, 2003). Dlamini et al. (2007) studied the effect of extrusion cooking on the total phenols, tannin content and antioxidant activity of both whole and decorticated sorghum grains. They observed that extrusion cooking significantly reduces total phenols and tannins for both whole and decorticated sorghums. Korus et al. (2007) studied the effect of extrusion on several polyphenols such as myricetin, quercetin, kaempferol, cyanidin,

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chlorogenic acid, caffeic acid, ferulic acid and p-coumaric acid in raw and extruded beans. Interestingly they observed an increase of 14% in the amount of phenolics in extrudates compared to raw dark-red beans, whereas they observed a decrease of 19% and 21% in black brown and cream coloured beans respectively. The overall increase of 14% observed in dark-red beans during extrusion was mainly due to increase in quercetin (by 84%) and ferulic acid (by 40%) along with a significant decrease in chlorogenic and caffeic acids by 33 and 9% respectively (Korus et al., 2007). Zielinski et al. (2006) reported a significant increase in free/bound phenolic acid such as syringic, ferulic, coumaric, except vanillic acid during extrusion of buckwheat.

Lycopene, Ascorbic acid, Flavonoids and Carbohydrates

Lycopene is heat-labile and degrades rapidly at temperatures higher than 100°C and consequently, a greater proportion of lycopene may be lost as the severity of the extrusion process is increased. To compensate, severe extrusion processing at high temperature and shear is needed to decrease the melt viscosity and produce well expanded products enriched with tomato derivatives (Altan et al., 2008c; Yagci and Gogus, 2008). According to Shoar et al. (2010) adding tomato derivatives to traditional starchy extruded snacks can improve their nutritional properties by adding lycopene and fibre. A crisp low density extruded snacks were manufactured from corn, wheat and rice, with or without dried tomato skin or paste powder extruded at temperatures of 140, 160 or 180°C. Lycopene retention was higher in products containing tomato skin powder and significantly lower when wheat flour was used to make the snacks.

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The influence of screw speed, compression ratio and die diameter on ascorbic acid retention was studied by Maga and Cohen (1978), who reported losses of between 9% and 57% when extruding fortified potato flakes. It was found that losses were lower with a larger die diameter, reduced screw compression ratio and lower temperatures. Increases in the screw speed were found to result in a reduction in the ascorbic acid retention. Plunkett and Ainsworth (2007) studied influence of barrel temperature (75–150°C) and screw speed on the retention of L-ascorbic acid in a rice based extrudate. At all screw speeds used greater losses of L-ascorbic acid occurred as barrel temperature increased. As screw speed increased from 100 rpm to 200 rpm at each temperature, an increase in L-ascorbic acid loss was observed. In an earlier study by Maga and Sizer (1978), similar effects were observed when extruding potato flakes enriched with 0.005% L-ascorbic acid. Losses of L-ascorbic acid during this study were reported to be between 14% and 68%, with greatest retention occurring at high moisture content (59%) and low barrel temperature (70°C). However, it was found that at high barrel temperatures (130–160°C) retention of L-ascorbic acid was greatest at low moisture contents (25%). Additionally, it was noted that screw wear due to high shear conditions could significantly increase the concentration of iron in the extrudate resulting in greater destruction of L-ascorbic acid.

Extrusion cooking of soybean alone or blends with other cereal have little change in isoflavone content with significant changes in isoflavone profile. White et al. (2010) investigated the changes in the anthocyanin, flavonol, and procyanidin contents of cranberry pomace/corn starch blends during extrusion cooking. They observed significant losses (46-64%) in anthocyanin content of extrudates and losses were higher at higher barrel temperature. However,

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the observed a significant increase (30-34%) in total flavonols in extruded products compared to control.

Berrios et al. (2010) determined carbohydrate composition of raw and extruded pulse flours. Dry pea showed the highest concentration of TAC, followed by chickpea and lentil. Formulated pulse flours demonstrated a beneficial increase in dietary fiber. This research indicates that value-added, nutritious snacks with reduced levels of flatulence factors and higher contents of dietary fiber can be fabricated successfully by extrusion processing of formulations based on lentil, dry pea or chickpea, and represent good alternatives to traditional cereal-based snacks.

Dietary fibre

Dietary fiber is defined as "edible carbohydrate polymers with ten or more monomeric units which are not hydrolyzed by the endogenous enzymes in the small intestine of humans" (Codex, 2009b). During extrusion, dietary fiber may be significantly modified. This leads to changes in its total dietary fiber content and solubility. Ralet et al. (1991) investigated the effect of extrusion on a wide variety of dietary fiber-containing ingredients such as sugar beet pulp, lemon fiber (Ralet et al., 1994; Ralet and Thibault, 1994), wheat bran (Ralet et al., 1990) or pea hulls (Ralet et al., 1993a; Ralet et al., 1993b). They reported that the water solubility of dietary fiber can be significantly increased when increasing the specific mechanical energy during extrusion. Kahlon et al. (1998) reported no significant effect of extrusion on the solubility of rice, oat or corn bran. The decrease in total dietary fiber content after extrusion was associated to an increase in low molecular weight soluble fiber, not recovered by alcohol precipitation (Gajula et al., 2008; Wang and Klopfenstein, 1993a).

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The morphology (i.e. size, shape, aspect ratio) of fiber is also modified during extrusion. Redgwell et al. (2011) using light microscopy observed that under extrusion, the particle size of citrus fiber was reduced. The decrease in sectional expansion when increasing insoluble dietary fiber content often leads to an increase in longitudinal expansion (Lue et al., 1990; Jin et al., 1995; Robin et al., 2011a; Stojecska et al., 2008b). The bulk density of extruded products was usually increased when adding insoluble fiber (Ainsworth et al., 2007; Andersson et al., 1981; Blake, 2006; Brennan et al., 2008; Jin et al., 1995; Lue et al., 1990; Moore et al., 1990; Stojecska et al., 2008b; Yanniotis et al., 2007). As visually observed, the addition of insoluble fiber such as wheat or corn bran fiber lead to cellular structures with lower cell sizes and a higher cell density (Guy and Horne, 1988; Moore et al., 1990; Yanniotis et al., 2007).

The difference in expansion properties between soluble and insoluble fibers was well illustrated by the study of Brennan et al. (2008). In this work it was shown that, compared to the control flour sample containing no added fiber, increasing up to 15% the wheat bran content significantly decreased the sectional expansion of extruded corn flour. This decrease in sectional expansion with wheat bran was associated with an increase in bulk density. Increasing cereal bran fiber decreased the water solubility and absorption properties of extruded cereals (e.g. Robin et al., 2011b). This is due to their insolubility and higher hydrophobicity compared to starch. The effect of fiber on the elastic properties of the melt may also explain the decreased expansion volumes with insoluble fiber (Guy and Horne, 1988; Moore et al., 1990; Yanniotis et al., 2007). Insoluble fiber tends to reduce the sectional expansion and increase the density of the extruded cereals. This induces harder structures to break. This was for instance demonstrated by Brennan et al. (2008) who reported an increased breaking force when increasing wheat bran

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content up to 15% in extruded breakfast cereals. Similar results were reported for wheat bran by Moore et al. (1990) or for wheat fiber by Onwulata et al. (2001) and Yanniotis et al. (2007).

Ostergard et al. (1989) reported that dietary fiber content of barley increased upon extrusion cooking, accompanied by a decrease in total starch content. Vasanthan et al. (2002) investigated the dietary fiber profile of barley flour as affected by extrusion cooking. Extrusion cooking increased the total dietary fiber of barley flours. The total dietary fiber increase in waxy-CDC-candle barley was mainly due to an increase in soluble dietary fiber. For Phoenix, the increase in both insoluble and soluble dietary fiber contributed to the increased total dietary fiber content. The change in dietary fiber profile during extrusion of barley flour may be attributed, primarily, to a shift from insoluble to soluble dietary fiber, as well as the formation of RS3 and 'enzyme resistant indigestible glucans' formed by transglycosidation. An improvement of the nutritional properties of food during extrusion processing is often a consequence of the breakdown of phytic acid and reorganization of total dietary fibre components, changing the chelating properties of these materials.

Recently, it was shown that extrusion technology increases the level of dietary fibre in non-gluten-free ready-to eat expanded snacks made from cereal and vegetable co-products (Stojceska et al., 2009; Stojceska et al., 2008). Stojceska et al. (2010) reported the advantage of using extrusion processing for increasing dietary fibre level in gluten-free products. The formation of gluten-free expanded products with high dietary fibre levels can be achieved by controlling extrusion conditions, such as temperatures, solid feed rate and screw speed combinations and the selection of appropriate raw ingredients. Zhang et al. (2011) confirmed that extrusion process improves the functionality of soluble dietary fiber in oat bran. The yield, composition, thermal

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properties, rheological behavior and functionality of soluble dietary fiber in extruded oat bran were compared with those of soluble dietary fiber in untreated oat bran. The results showed that soluble dietary fiber in extrude oat bran had higher yields (14.2%), mean particle diameter (1718.1 nm), peak temperature (T_p = 69.0° C), solubility, swelling capacity, solvent retention capacity, foam ability, apparent viscosity and consistency coefficient, and lower flow behavior index than those of soluble dietary fiber in untreated oat bran.

Extrusion has been applied successfully to increase the soluble dietary fiber fraction of fiber-rich plant food by-products such as sugar beet pulp (Rouilly et al., 2006) and potato peels (Camire et al., 1997). During extrusion processing, the extent of soluble dietary fiber increment largely depended on the temperature and pressure in the extruder barrel. The higher the temperature and pressure, the higher the success of breakdown of polysaccharides glucosidic bonds was. This led to the release of oligosaccharides and eventually to the increase in soluble dietary fiber (Bjorck et al., 1984; Esposito et al., 2005; Guha et al., 1997). However, very high temperature (≥200 °C) deteriorates the nutritional and sensory quality of the extrudate. The high temperature is limited in the improvement of extrusion product (Singh et al., 2007b). Robin et al. (2012) studied dietary fiber in extruded cereals. Dietary fiber has positive effects on cardiovascular health, diabetes, weight management and on the immune system (Anderson et al., 2009).

Protein

During extrusion cooking shear forces are suspected to play an important role in changing the nutritional value of proteineous materials (Bhattacharya and Hanna, 1988b; Marsman et al., 1993). Normally, shear forces during extrusion are varied by changing the screw-speed.

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However, by changing the screw-speed also the residence time is largely affected (Van Zuilichem et al., 1988). Batterman-Azcona and Hamaker (1998) have shown that extrusion disrupts maize protein bodies, which are homologous to sorghum proteins. Moreover, as reported in other sorghum based applications (Dahlin and Lorenz, 1993; Fapojuwo et al., 1987; Hamaker et al., 1994; MacLean et al., 1983; Mertz et al., 1984), mechanical shear during extrusion improves protein digestibility. While extrusion-enzyme liquefaction has been used to produce sugars from cereal starches and tubers for ethanol production (Chouvel et al., 1983; Curic et al., 1998; Govindasamy et al., 1997a; Meagher and Grafelman, 1999; Solihin et al., 2007; Zhan et al., 2006), this process has not been utilized in the past for protein concentration.

Chen et al. (2011) determined chemical cross-linking and molecular aggregation of soybean protein during extrusion cooking at low and high moisture content. The results showed that, regardless of the location and moisture level in the extruder, hydrophobic interactions, hydrogen bonds, disulfide bonds and their interactions collectively hold the structure of protein extrudate, and the contribution of non-covalent bonds outweighs covalent bonds.

Starch and Mineral bioavailability

The extrusion of starchy foods results in gelatinization, partial or complete destruction of the crystalline structure and molecular fragmentation of starch polymers, as well as protein denaturation, and formation of complexes between starch and lipids and between protein and lipids (Colonna and Mercier, 1983; Ho and Izzo, 1992; Mercier and Feillet, 1975; Mercier et al., 1980). The transformations included during extrusion process are: loss of starch crystalline structure, destruction of granular structure, rupture of glycosidic bonds and new molecular interactions. (Davidson, 1992; Gonzalez et al., 2002; Mitchell and Areas, 1992). Robin et al.

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(2011b) investigated starch transformation in bran-enriched extruded wheat flour. Cooking extrusion of wheat flour enriched with wheat bran significantly modified the physicochemical properties of the starch. In the tested extrusion conditions, starch crystallites were fully dissociated. However, a remaining amorphous starch structure that could hydrate, swell and burst under shear in hot water was observed. The estimated starch solubility was only increased at the highest bran concentration. It showed that higher bran levels led to a higher amount of free water and a decrease in starch glass and melt temperatures.

Starch undergoes structural changes including gelatinization, melting, and fragmentation during the extrusion process and the extent of the transformation depends upon moisture content, pressure, temperature and shearing force. Granular starch may remain almost unchanged and result in a low expansion ratio at low temperature and high moisture (Noguchi et al., 1982; Richmond and Smith, 1985). With increasing severity of thermal treatment (temperature higher than 150°C), starch granules lose their original structure (Richmond and Smith, 1985). Harper (1992b) pointed out that depolymerization of starch molecules occurs simultaneously with the loss of crystallinity during extrusion cooking. The extent of starch degradation is a function of extrusion parameters, temperature, moisture content, and screw speed (Wen et al., 1990).

Cespedes et al. (2010) studied the effect of extruded orange pulp on enzymatic hydrolysis of starch and glucose retardation index. The apparent density and apparent viscosity values of the extruded orange pulp increased during extrusion, while the oil absorption index decreased, in comparison with the values for raw orange pulp. Extruded samples had a higher glucose retardation index: 16.04–25.92% after 30 min of dialysis and 11.66% and 18.33% after 60 min, while raw orange pulp showed a value of 8.33%.

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Effect of extrusion cooking on mineral bioavailability in pea and kidney bean seed meals was studied by Alonso et al. (2001). Moisture content decreased and iron increased in extruded compared with non-treated seed meals. Starch and NSP were reduced in both pea and kidney bean seed meals. Raffinose, stachyose and verbascose also dropped in kidney bean meal after extrusion, but only stachyose was reduced by thermal treatment in pea flours. The apparent absorption of Fe, Ca and P from unsupplemented pea-based diets significantly increased in extruded compared with raw seed meals.

Vitamins

Extrusion cooking have profound effect on the stability of vitamins in extruded snack food for example higher barrel temperatures and low feed moistures favour ascorbic acid degradation during extrusion (Killeit, 1994). Athar et al. (2006) studied the effect of extrusion processing conditions on the stability of vitamins. They observed that extrudates obtained from short barrel (90 mm) extruders had a higher retention rate of B vitamin group (44-62%) compared to 20% for long barrel extruders. Anuonye et al. (2010) studied the stability of vitamins during extrusion of Acha (Digitaria exilis)/ soy bean blend and observed a 6% decrease in Riboflavin (B2), a 86.36% decrease in pyridoxine (B6), and no significant change in ascorbic acid content. Athar et al. (2006) observed that the retention of vitamins during the extrusion process is not related to initial levels of the vitamins and varies with the cereal type. High temperature, short-time extrusion cooking is also reported to influence the stability of fat soluble vitamins such as vitamin A and E (Tiwari and Cummins, 2009). For example Zielinski et al. (2006) observed a significant decrease (about 63%) in vitamin E content of buckwheat during extrusion cooking. Sensitivity of various forms of vitamin E varies with extrusion process variables for example a significant decrease in

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a-tocopherol was reported with an increase in extrusion temperature and a significant decrease in g-tocopherol with increase in moisture content during extrusion of grass peas was reported by Grela et al. (1999). Similarly, Harper (1988) reported a decrease in Riboflavin with increase in feed moisture content and high screw speed.

Boyaci et al. (2012) explained the effects of cold extrusion process on thiamine and riboflavin contents of fortified corn extrudates. There was no significant difference between riboflavin contents of conventional extrudates produced at both feed moistures at 80 and 110°C barrel temperatures. However, riboflavin content of extrudates produced at 20% feed moisture was higher than the one produced at 25% feed moisture at 130° C. In cold extrusion, there was no significant difference between riboflavin contents of samples.

The temperature range had little differential effect on the retention of any of the vitamins. Thiamin and pyridoxine, reported earlier to be the most thermosensitive, decreased during extrusion along with niacin. However, they decreased by the same amount at all temperatures. It was possible to retain up to 80% of the vitamin C through the extrusion process but it was found to be rapidly lost during subsequent storage in a study by Lorenz and Jansen (1980). In contrast, other studies (Beetner et al., 1974; Harper, 1979; Camire et al., 1990; Killeit, 1994) have shown that the percentage of thiamine retained decreased from 40% to 60% to between 50% and 20% as temperatures increased from 140 to 190°C. Crisp extruded snack food products were produced from a range of cereal products using a short barrel, single screw snack food extruder (Athar et al., 2006) and retention of B group vitamins between 44% and 62% which was considerably higher than the 20% retention for maize reported previously for long barrel extruders was the least stable during extrusion.

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Lipids

The lipid binding to starch brings about changes in physico-chemical properties of extrudates. However, these are complex and have been shown to vary with the type, amount and the hydrophilic-lipophilic balance of lipids and the materials being extruded (Faubion et al., 1982). Mercier et al. (1980) reported that extrusion cooking of maniac starch produced different water solubilities depending on the molecular size and saturation of added lipids or fats. Badrie and Mellowes (1992) added soybean oil up to 7% to cassava flour and Bhattacharya and Hanna (1988a) reported that decreasing the lipid content resulted in a more expanded extrudate that had higher water holding capacity for the extrusion of corn gluten with defatted soy protein concentrates.

High temperature reduces the lipase and lipoxygenase activity and moisture level, thereby decreasing the factors favoring free fatty acid development and oxidation of fatty acids. The factors affecting the rate of lipid oxidation indicated by Nawar (1985) can also be applied to extrusion-cooked foods. The increase of lipids oxidation was observed with the increase in extrusion temperature (Rao and Artz, 1989). Mustakas et al. (1964) examined the effects of retention time, moisture and die temperature on the peroxide values of extruded full-fat soy flour after extrusion and 1 yr of storage at 25^0C in the dark. The highest peroxide values were found in the samples extruded at the highest moisture level, temperature and retention time. Rao and Artz (1989) suggested that some of the increase in lipid oxidation may be due to the increase in surface area from increased expansion. It was also found that the lipid oxidation of the extrudates could be intensively enhanced by exposure to light (Saxena and Chauhan, 1985). Similar results

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were also found by Hsieh and Huff (1998) that lipid oxidation of the dry pet extrudates appeared to be affected mainly by the degree of extrudate expansion.

Rheological quality attributes

The thermal and mechano-chemical reactions that occur during extrusion change the rheological properties of the raw food material as well as the functional properties of the extruded food products (Davidson, 1992). It has been shown that the starch pasting characteristics change considerably when the compression ratios of the screws are varied (Conway, 1971). The effects of the moisture content of the raw materials (Anderson et al., 1969b), on different additives (Ryu et al., 1993a, 1993b), and operating conditions of the extruder (Anderson et al., 1969b; Mason and Hoseney, 1986, Lawton et al., 1972; Davidson et al., 1984a; Van Lengerich, 1990; Davidson, 1992a) on the pasting characteristics of the extrudates have also been studied.

Bhattacharya et al. (1999) determined the pasting characteristics of an extruded blend of potato and wheat flours. High moisture content of the blend changed the pasting characteristics of the extruded material to a great extent when the screw speed was between 200 and 300 rpm. The net specific mechanical energy was negatively related to the viscosity-related parameters.

Cheyne et al. (2005) reported extrusion behaviour of cohesive potato starch pastes and its Rheological characterization. Application of the Benbow–Bridgwater approach to annular dies in an a priori fashion was less successful, owing to the challenge in describing flow in the narrow annular duct. The wall slip model obtained from the more laborious capillary flow analysis gave better agreement, as it featured contributions from small D experiments. The Benbow–Bridgwater approach has thus been shown to give reasonable predictions of extrusion pressure

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for even annular dies, but it should be noted that the validity of this continuum approach is compromised when particle–process interactions are significant.

CONCLUDING REMARKS

Extruded products are one of the fastest-growing segments of the food industry, and for years, extrusion has been a mainstay of producing new and creative products. Extrusion cooking produces a wide range of finished products from inexpensive raw materials with minimum processing time. Extrusion is a highly versatile unit operation that can be applied to a variety of food processes. Extruders can be used to cook, form, mix, texturize and shape food products under conditions that favor quality retention, high productivity and low cost. This paper provides the evident knowledge as to how the various products and waste by products can be utilized in an efficient manner for manufacturing a nutritional product with primary emphasis on changes that are experienced during the extrusion process at the physical and nutritional level. Thus, extrusion cooking will remain as an integral part of manufacturing of wholesome processed foods. In future, research should be emphasized in the area of development of improved extrusion technology which is less dependent on the nature of raw materials being used. Also, value addition and by product waste utilization in the extrusion should be encouraged in future in order to produce healthy extruded products. Extrusion cooking has a potential for becoming the most important food processing technology in future.

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