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REVIEW ARTICLE

Extrusion Processing on Physical and Chemical Properties of Protein Rich Products-An Overview

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Abstract

Extrusion is a thermodynamic process which combines several unit operations including mixing, cooking, kneading, shearing, shaping and forming. The principles of operation are similar in all types: raw materials are fed into the extruder barrel and the screw(s) then convey the food along it. Further down the barrel, smaller flights restrict the volume and increase the resistance to movement of the food. As a result, it fills the barrel and the spaces between the screw flights and becomes compressed. There are number of versatile product developed through this technology which has properties like lower cost, high nutritive value and convenience food products. The review aimed to cover effect of various factor of extrusion processing that affects physical as well as chemical properties of various protein rich products.

Keywords: Protein rich product, Protein digestibility, Twin screw extruder, Physical properties.

1. Introduction

Extrusion processing is defined as the process by which moistened, expansible, starchy and proteinaceous food materials are plasticized through a die by a combination of moisture, pressure, heat mechanical shear. Extruder is equipment which is used for extrusion processing. Extruders are composed of five main parts: (i) the pre-conditioning system (ii) the feeding system (iii) the screw or worm (iv) the barrel (v) the die and the cutting mechanism which can be seen in Fig 1.

In the extrusion process, the dry or pre-conditioned material (generally between 15 and 30% moisture content) is fed to the extruder through a screw feeder, reaching the feeding zone. The screw in this zone presents greater depth and pitch of the screw flight, and has as main function the transportation and homogenizing of the raw material. The material is conducted from the feeding zone to the compression zone. In the compression zone, there is a reduction in screw depth and pitch, with a consequent increase in shear rate, temperature (110 - 180ºC) and pressure (20-30 atm). In this zone, the conversion from a solid material to a fluid melt starts to occur. In the subsequent high pressure zone, the screw has its depth and pitches reduced even more, resulting in higher shear and maximum heat generation. Thus, the extruded mass reaches maximum temperature and pressure and a reduction in viscosity immediately before exiting the extruder (Fellows, 2000; Riaz, 2000). The material, under high pressure, is expelled through the die and, in contact with ambient pressure, expands to its final format and cools rapidly through water flash-off (Fellow, 2000).

2. Types of Extruders

Two types of extruders are used for extruded food products: (i) single-screw extruders and (ii) twin-screw extruders.

2.1 Single-Screw Extruders

Single-screw extruders are the most common extruders applied in the food industry. Single-screw extruders can be defined on process or equipment parameters such as: conditioning moisture content (dry or wet), solid or segmented screw, desired degree of shear and heat source (Riaz, 2000).

2.2 Twin-Screw Extruders

Twin-screw extruders are used for high-moisture extrusion, products that include higher quantities of components such as fibres, fats, etc. and –

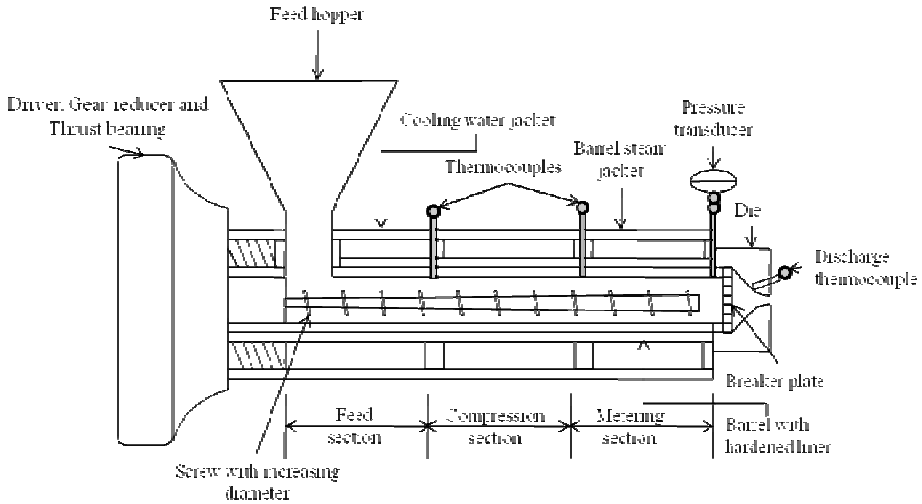

Fig 1: Schematic representation of a single screw extruder including its main parts and zones

more sophisticated products. Twin-screw extruders are composed of two axis that rotate inside a single barrel; usually the internal surface of the barrel of twin-screw extruders is smooth. Depending on the position of the screws and their direction of rotation, four different types of configurations are possible: (i) co-rotating intermeshing screws; (ii) co-rotating non-intermeshing screws; (iii) counter-rotating intermeshing screws and (iv) counter-rotating non-intermeshing screws.

3. Importance of Protein in Extrusion Processing

Extrusion is used for restructuring of protein based food materials to manufacture a range of textured convenience foods. Extrusion of texturized proteins is one of the successful applications. Meat analogues are blends of various protein sources such as isolates, glutens, albumin, extrusion-cooked vegetable proteins and others which are mixed with oils, flavours and binders before forming them into sheets, patties, strips or disks. Proteins have many functional properties. They form interfacial films that stabilize emulsions and foams, can act together to make gel networks and edible films.

Proteins are used to produce products that have meat-like characteristics and that are used either as full or partial replacements for meat in ready meals, dried foods and many pet food products (Guy, 2001). In general, physicochemical changes in protein polymers that can occur during extrusion process includes: binding, cleavage, loss of native conformation, fragment recombination and thermal degradation. Proteins undergo many changes during the extrusion process, with the most important being denaturation (Camire, 2000). Proteins are classified, according to their solubility, in albumins, globulins, prolamines and glutelins with solubility in water, saline solution, alcohol solution and acid or alkaline solutions, respectively (Pereda *et al.*, 2005).

High molecular weight proteins break into smaller subunits (Guy, 2001). One of the main applications of extrusion in protein rich foods is protein texturization. Texturization processes can be used to obtain many products that reproduce the texture, taste, and appearance, with the use of soy for the production of texturized soy products and meat analogues (Ledward and Mitchell, 1988; Mitchell and Areas, 1992). The proteins that can form a continuous structure in extrusion are globular proteins from oilseeds such as soybeans, sunflower seeds, common beans, peas and gluten proteins from cereals, especially wheat (Riaz, 2000; Strahm, 2006). The extrusion cooking, converts protein bodies into a homogeneous matrix and the process recombines storage proteins into structured fibres (Stanley, 1998). Low extrusion of vegetable protein with low moisture (up to 35%) can be used to elaborate products to partially or totally substitute meat and they are not consumed directly. On the other hand, high moisture (>50%) extruded products are consumed directly.

In the extrusion of proteins, disulfide bonds are cleaved and undergo reorganization and polymerization. Disulfide bonds, non-specific hydrophobic and electrostatic interactions are the main bonds and interactions responsible for protein -

Table 1: Protein rich extruded products and raw materials used in extrusion

Product	Raw Materials	Extruder	Product type	Reference (s)
Blended Extruded Products	Corn, soy, whey	SS	RTE	Aguilera and Kosikowski (1978)
Meat substitute like soy /nugget	Defatted soy flour	SS	RTC	Atkinson (1970); Harper, (1981)
Restructured fish/meat mince	Mince from fish/ meat/poultry and wheat	SS/TS	RTE/ RTC	Yu *et al.* (1981); Noguchi (1990); Bhattacharya *et al.* (1993)
Expanded extrudates	Legumes	SS	RTC	Balandran Quintana *et al.* (1998)
Extruded product	Rice/wheat	TS	RTE	Ding *et al.* (2005, 2006)
Blended extruded product	Cassava, pigeon pea	TS	RTE	Rampersad *et al.* (2003)
Blended extruded product	Wheat flour, corn	TS	RTE	Stojceska *et al.* (2009)
Blended Cereal pasta	Wheat, egg	SS	RTC	Zardetto and Rosa (2009)
Expanded dairy product	Whey protein concentrate starch	TS	RTC	Manoi and Rizvi (2009)
Cereal, Vegetable	Barley flour and tomato pomace	TS	RTE	Altan *et al.* (2008)
Blended extruded product	Wheat-potato/ corn–soy	TS / high protein snack	RTE	Bhattacharya *et al.* (1999); Baskaran and Bhattacharya (2004)
Extruded Confectionery	Chocolate	TS	RTE	Mulji *et al.* (2003)

SS- single screw extruder, TS- twin screw extruder, RTE- ready to eat, RTC-ready to cook

texturization by extrusion (Areas, 1992). Protein rich raw materials used for extrusion processing are whey protein concentrate, whey protein isolate, soy protein isolate, blend of soy protein and corn flour, peanut protein products, wheat proteins etc. Proteins such as wheat gluten, corn zein, soy protein, myofibrillar proteins, and whey proteins have been processed into films using thermoplastic processes such as compression molding and extrusion (Hernandez-Izquierdo and Krochta, 2008).

To human diets, especially for vegetarians, the ingestion of high protein content products has been incorporated, for example, meat extenders and meat analogues (Strahm, 2006; Macdonald *et al.*, 2009). Meat extenders (chunks or small granular pieces) are obtained at low moisture contents (20-35%) while meat analogues that have a remarkable similarity in appearance, texture and mouth feel to meats are obtained at high moisture contents (50-70%) by extrusion process. The raw materials commonly used to produce meat extenders are defatted soy flour and soy protein concentrate (SPC), and meat analogues are produced from, soy protein concentrate (SPC) and soy protein isolate (SPI). Texturization occurs between the molecules as they flow in the streamlines to form laminar cross-linked products. Evaporation of water in the mass creates gas bubbles that form alveolar structures held in place by cross-linking in the protein layers (Guy, 2001). The utilization of extrusion processing throughout the food industry has shown that a variety of products can be made on extrusion equipment. Some of these products include breakfast cereals, breading, snacks, instant rice, instant pasta, animal and aquatic feeds.

3.1 Effect of Extrusion on Physical Properties of Protein

The extruded product hardness is strongly influenced by the protein content. If raw material is high in protein content, it produces a less expanded product and form more rigid network, resulting in higher resistance to cut. However, feed moisture and barrel temperature also affect the hardness of extruded product. The hardness is the maximum force required for a probe to penetrate the extrudate. It is expected that high density and low expansion would produce harder extrudate. If moisture content in raw material increases, it enhances the breaking strength of extruded products while increasing temperature reduces the breaking strength.

Expansion occurs in both radial and axial directions, at different degrees, depending on the viscoelastic properties of the melt. Vaporization of moisture and cooling of the extrudate serve to bring the product from a molten to a rubbery state and further drying is usually used to produce the brittle, fracturable texture typical of these products. Products obtained with high temperatures and short extrusion process times normally present a porous, open structure, what provides them a "crunchy" texture (Barrett, 2003).

The increase in moisture content in raw material and simultaneously decrease in barrel temperature decreases the expansion of extruded products resulting in increased density and hardness. Temperature lower than 90°C delay expansion and layer formation (Cheftel *et al.*, 1992). The presence of wheat proteins has shown an effect on the expansion of wheat starch. A reduction in expansion was noted as gluten increased to 11% followed by an increase in expansion as the protein content increased to 16%. At a given temperature, higher moisture contents result in softer and less texturized extruded products due to reduced protein-protein interactions and lower viscosity. Increasing feed moisture leads to a sharp increase in extrudate density. However, increasing screw speed and barrel temperature causes a slight decrease in the density of extrudate.

The changes in colour could be due to the non-enzymatic browning by Millard reaction between proteins and reducing sugars that occurs due to the high temperature. (Petitot *et al.*, 2009).The process conditions used in extrusion cooking high barrel temperatures and low feed moistures are also known to favour the Millard reaction. It also decreases the nutritional availability of lysine (Camire, 2000). Increasing protein content at constant feed moisture content causes an increase in hardness, crispness and brittleness but decrease colour intensity.

Water absorption is a qualitative test for analyzing the cross-link density of protein biopolymer. Water absorption decreased and tensile properties increased with increasing molding temperature, up to 130°C. Above 130°C, the water absorption increased slightly, accompanied by a slight decrease in tensile strength and elongation at break, indicative of protein degradation. Water absorption is not only influenced by covalent cross-linking, but also by the protein's ability to interact with water. Exposing hydrophobic groups, either by chain re-arrangement or by chemical additives, may also influence water absorption.

The feed moisture and temperature have a significant effect on the water absorption index (WAI) and water solubility index (WSI) of wheat extrudate. However, feed rate and screw speed have been observed to no significant effect on WAI and WSI of extrudate. Increasing feed moisture and barrel temperature both significantly decreases the WAI of wheat extrudate. Increasing in feed moisture and barrel temperature has been observed to result in a significant increase in the extrudate WSI (Ding *et al.*, 2006). The water absorption capacity of dough depends mainly on the flour composition and increases with increasing protein, pentosan and damaged starch content (Martinez *et al.*, 2013).

Extruded whey protein isolate (WPI) under alkaline conditions have a stringy texture that could be used in meat applications. At relatively lower moisture contents, higher barrel temperatures (140 to 180°C) result in better textures. At higher moisture levels, temperature needs to be decreased as moisture flash-off may cause considerable water loss if a cooling die is not used (Thiebaud *et al.*, 1996).

3.2 Effect of Extrusion on Chemical Properties of Protein

Solubility of protein before and after processing is often regarded as a good indicator of cross-link formation during processing. Denaturation during the extrusion process of proteins results in reduction of protein solubility, cross-linking reactions also occur and possibly, some covalent bonds form at high temperatures. Increasing temperature from 140 to 180°C results in a proportional decrease in disulfide linkages formed in extruded soy protein isolates (Areas, 1992).

High temperature, screw speed and moisture resulted in more insoluble extruded products, indicative of cross-linking. Due to high temperature in extrusion hydrophobic and electrostatic interactions favour the formation of insoluble aggregates, like the fibrous structure of meat analogues (Li and Lee, 1996; Tilley *et al.*, 2000; Li-Chan, 2004; Sluimer, 2005). Denaturation of proteins at high temperature during extrusion cooking improves digestibility and inactivates anti-nutritional factors (such as antitrypsin factor, lectins, etc.). The extrusion of soy protein reduces the bitter taste and the undesirable volatile compounds (Areas, 1992; Kitabatake and Doi, 1992).

Extrusion of whey protein isolate (WPI) at 35 or 50ºC increases their gel strength, but gel strength is gone when WPI is extruded at 75 or 100ºC. On the other hand, extrusion at these high temperatures had minimal effect on foaming and digestibility of WPI. Texturizing WPI by extrusion under acidic and alkaline conditions has influenced their functional properties.

Table 2: Effect of processing parameter on protein digestibility

Processing parameter	Protein digestibility	Food source	Reference (s)
Process temperature	Increase with increasing extrusion temperature	Corn gluten-whey blends, sorghum and fish-wheat blends	Fapojuwo et al. (1987); Bhattacharya and Hanna (1985); Bhattacharya et al., (1988)
Feed ratio	Increase with increasing animal protein	Fish and wheat flour	Bhattacharya et al. (1988); Camire et al. (1990)
Screw speed	Insignificant effect increase with increasing screw speed	Fish and wheat flour Corn gluten-whey blend	Bhattacharya et al. (1988); Camire et al. (1990)
Length to diameter ratio	Insignificant effect	Fish and wheat flour	Bhattacharya et al. (1988)

Table 3: Effects of processing variables on lysine retention

Processing parameter	Effect on lysine Retention	Food source	Reference (s)
Screw speed	Increase with increasing screw speed	Defatted soy flour and sweet potato flour mixture	Iwe et al. (2004)
Die diameter	Increase with increasing die diameter	Defatted soy flour and sweet potato flour mixture	Iwe et al. (2004)
Feed rate	Increase with increasing feed rate	Wheat flour	Bjorck and Asp (1983)
Feed moisture	Increase with increasing moisture	Cowpea and mung bean	Pham and Del Rosario (1984)

Alkaline conditions increases solubility and pasting properties significantly, whereas acidic conditions increases solubility but decreases pasting properties of WPI. Protein nutritional value is dependent on the quantity; digestibility and availability of essential amino acids. Very high drying temperatures have shown to decrease in protein digestibility (Table 2) and lysine bioavailability (Table 3) (Singh *et al.*, 2007).

At the molecular level, starch and protein components undergo minor changes during extrusion. The drying step mainly affects the protein fraction. The use of high drying temperatures would allow conservation of the protein network, even after prolonged cooking. At the molecular level, the higher the drying temperature, the higher the protein in-solubilisation and aggregation occur. Moreover, depending on the moisture and drying conditions applied, very high temperature may promote the formation of protein aggregates stabilised by irreversible protein interactions, probably through inter peptide cross linking or Millard-type reactions. Structural modifications obtained especially at high drying temperatures could strengthen the protein network and therefore better preserve starch from enzymic degradation in cooked pasta. The variations in the alveogram characteristics are principally related to two factors: gluten matrix degradation and starch modification, both of which affect the extrusion process. Gluten matrix degradation increases with treatment intensity (Gomez *et al.*, 2011).

4. Conclusion

Extrusion processing provides a great versatility for the development of low cost, high nutritive and convenience food products. Texturized proteins have been successfully marketed and produced throughout the world by applying the extrusion process. The major factors during extrusion processing which affect the physical and chemical property of the final product are high barrel temperature, feed moisture, composition of raw materials (protein and starch mainly) and the screw speed. It also reduces the anti-nutritional factor present in the raw material and increases the digestibility of the final product. Extrusion processing, changes the ingredients such as protein, starch, salt and fibre, and can affect the extrusion system variables and product characteristics such as texture, structure, expansion and sensory attributes.

References

Aguilera JM and Kosikowski FV (1978). Extrusion and roll-cooking of corn-soy-whey mixtures. *Journal of Food Science,* 43: 225-227.

Altan A, McCarthy KL and Maskan M (2008). Evaluation of snack foods from barley tomato pomace blends by extrusion processing. *Journal of Food Engineering,* 84: 231-242.

Areas JA (1992). Extrusion of food proteins. *Critical Reviews in Food Science and Nutrition,* 32: 365-392.

Atkinson WT (1970). Meat-like protein food product. *US Patent,* 3488770.

Balandran-Quintana RR, Barbosa-Canovas GV, Zazueta-Morales JJ, Anzaldua-Morales A and Quintero-Ramos A (1998). Functional and nutritional properties of extruded whole pinto bean meal (*Phaseolus vulgaris* L.). *Journal of Food Science,* 63: 13-116.

Barrett A (2003). Characterization of macrostructure in extruded products. In: Characterization of cereal and flours: properties, analysis and applications (G Kaletunc and Breslauer (Eds.)), *CRC Press, Boca Raton, United States of America,* 369-386.

Baskaran V and Bhattacharya S (2004). Nutritional status of the protein of corn-soy based extruded products evaluated by rat bioassay. *Plant Foods and Human Nutrition,* 59: 101-104.

Bhattacharya M and Hanna MA (1985). Extrusion processing of wet corn gluten meal. *Journal of Food Science,* 50: 1508-1509.

Bhattacharya S, Das H and Bose AN (1988). Effect of extrusion process variables on in vitro protein digestibility of fish-wheat flour blends. *Food Chemistry,* 28: 225-231.

Bhattacharya S, Das H and Bose AN (1993). Effect of extrusion process variables on texture of blends of minced fish and wheat flour. *Journal Food Engineering,* 19: 215-235.

Bhattacharya S, Sudha ML and Rahim A (1999). Pasting characteristics of an extruded blend of potato and wheat flours. *Journal of Food Engineering,* 40: 107-111.

Bjorck I and Asp NG (1983). The effects of extrusion cooking on nutritional value. *Journal of Food Engineering,* 2: 281-308.

Camire ME (2000). Chemical and nutritional changes in food during extrusion. In: Extruders in food applications, CRC Press, *Boca Raton, United States of America,* 127-147.

Camire ME, Camire AL and Krumhar K (1990). Chemical and nutritional changes. *Critical Reviews in Food Science and Nutrition,* 29: 35-57.

Cheftel JC, Kitagawa M and Queguiner C (1992). New protein texturization processes by extrusion cooking at high moisture levels. *Food Reviews International,* 8: 235-275.

Ding QB, Ainsworth P, Plunkett A, Tucker G and Marson H (2005). The effect of extrusion conditions on the physicochemical properties and sensory characteristics of rice based expanded snacks. *Journal of Food Engineering,* 66: 283-289.

Ding QB, Ainsworth P, Plunkett A, Tucker G and Marson H (2006). The effect of extrusion conditions on the functional and physical properties of wheat-based expanded snacks. *Journal of Food Engineering,* 73: 142-148.

Fapojuwo OO, Mega JA and Jansen GR (1987). Effect of extrusion cooking on in vitro protein digestibility of sorghum. *Journal of Food Science,* 52: 218-219.

Fellows P (2000). Food processing technology: principles and practice (2nd ed.) *CRC Press, Boca Raton, United States of America,* 267-276.

Gomez M, Ruiz-Paris E and Oliete B (2011). Influence of wheat milling on low-hydration bread quality developed by sheeting rolls. *Food Science and Technology International,* 17: 257-265.

Guy RCE (2001). Raw materials for extrusion cooking, In: Extrusion cooking: *Technologies and applications, Woodhead Publishing Limited, Cambridge, England,* 5-28.

Harper JM (1981). Extrusion of Foods (Vol. 2, RJ Alexander and HF Zobel (Eds.)), *CRC Press, Boca Raton, Florida,* 37-64.

Hernandez-Izquierdo VM and Krochta JM (2008). Thermoplastic Processing of Proteins for Film Formation: A Review. *Journal of Food Science,* 73: 2-10.

Iwe MO, Van Zuilichem DJ, Ngoddy PO, Lammers W and Stolp W (2004). Effect of extrusion cooking of soy-sweet potato mixtures on available lysine content and browning index of extrudates. *Journal of Food Engineering,* 62: 143-150.

Kitabatake N and Doi E (1992). Denaturation and texturization of food protein by extrusion cooking, In: Food extrusion: Science and Technology (JL Kokini, CT Ho and MV Karwe (Eds.)), *Marcel Dekker, New York, United States of America,* 361-371.

Ledward DA and Mitchell JR (1988). Protein extrusion - More questions as answers, In: Food structure: its creation and evaluation (JMV Blanshard and JR Mitchell (Eds.)), *Butterworth Heinemann, London, United Kingdom,* 219-229.

Li M and Lee TC (1996). Effect of extrusion temperature on solubility and molecular weight distribution of wheat flour protein. *Journal of Agricultural and Food Chemistry,* 44: 763-768.

Li-Chan ECY (2004). Properties of proteins in food systems: an introduction, In: Proteins in food processing (RY Yada (Ed.)), *Woodhead Publishing Limited, Cambridge, London,* 2-26.

MacDonald RS, Pryzbyszewshi J and Hsieh FH (2009). Soy protein isolate extruded with high moisture retains high nutritional quality. *Journal of Agricultural and Food Chemistry,* 57: 3550-3555.

Manoi K and Rizvi SSH (2009). Physicochemical changes in whey protein concentrate texturized by reactive supercritical fluid extrusion. *Journal of Food Engineering,* 95: 627-635.

Martinez M, Oliete B and Gomez M (2013). Effect of the addition of extruded wheat flours on dough rheology and bread quality. *Journal of Cereal Science,* 30: 1-6.

Mitchel JR and Areas JAG (1992). Structural changes in biopolymers during extrusion, In: Food extrusion: Science and Technology (JL Kokini, CT Ho and MV Karwe (Eds.)), *Marcel Dekker, New York, United States of America,* 345-360.

Mulji NC, Miquel ME, Hall LD and Mackley MR (2003). Microstructure and mechanical property changes in cold-extruded chocolate. *Food and Bio-products Processing,* 81: 97-105.

Noguchi A (1998) Extrusion cooking of high-moisture protein foods, In: Extrusion cooking (C Mercier, P Linko and JM Harper (Eds.)), *American Association of Cereal Chemists, Saint Paul, United States of America,* 343-370.

Pereda JAO, Rodriguez AIC, Alvarez LF, Sanz MLG, Minguillon GDGF, Perales LH and Cortecero MDS (2005). *Food technology:* food components and processes. New Haven Porto, Alegre, Brazil.

Petitot M, Abecassis J and Micarda V (2009). Structuring of pasta components during processing: impact on starch and protein digestibility and allergenicity. *Trends in Food Science and Technology,* 20: 521-532.

Pham CB and Del Rosario RR (1984). Studies on the development of texturized vegetable products by the extrusion process. *Journal of Food Technology,* 19: 549-559.

Rampersad R, Badrie N and Comissiong E (2003). Physicochemical and sensory characteristics of flavored snacks from extruded cassava/pigeon pea flour. *Journal of Food Science,* 68: 363-367.

Riaz MN (2000). Introduction to extruders and their principles, In: Extruders in food applications (MN Riaz (Ed.)), *CRC Press, Boca Raton, United States of America,* 1-23.

Singh S, Gamlath S and Wakeling L (2007). Nutritional aspects of food extrusion: a review. *International Journal of Food Science and Technology,* 42: 916-929.

Sluimer P (2005). Principles of bread making: functionality of raw material and process steps, *American Association of Cereal Chemists, Saint Paul, United States of America.*

Stojceska V, Ainsworth P, Plunkett A and Ibanoglu S (2009). The effect of extrusion cooking using different water feed rates on the quality of ready-to-eat snacks made from food by products. *Food Chemistry,* 114: 226-232.

Strahm BS (2000). Preconditioning, In: Extruders in food applications (MN Riaz (Ed.)) *CRC Press, Boca Raton, United States of America,* 115-126.

Thiebaud M, Dumay E and Cheftel JC (1996). Influence of process variables on the characteristics of a high moisture fish soy protein mix textured by extrusion cooking. *Journal of Food Science and Technology,* 29: 526-535.

Tilley KA, Benjamin RE, Bagorogoza KE, Okot-Kotber BM, Prakash O and Kwen H (2001). Tyrosine cross-links: molecular basis of gluten structure and function. *Journal of Agricultural and Food Chemistry,* 49: 2627-2632.

Yu SY, Mitchell JR and Abdullah A (1981). Production and acceptability testing of fish crackers (keropok) prepared by the extrusion method. *International Journal of Food Science and Technology,* 16: 51-58.

Zardetto S and Rosa MD (2009). Effect of extrusion process on properties of cooked, fresh egg pasta. *Journal of Food Engineering,* 92: 70-77.