

Original article

Nutritional aspects of food extrusion: a review

Shivendra Singh, Shirani Gamlath* & Lara Wakeling

School of Science & Engineering, Mount Helen Campus, University of Ballarat, Victoria 3353, Australia

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Summary Extrusion cooking, as a multi-step, multi-functional and thermal/mechanical process, has permitted a large number of food applications. Effects of extrusion cooking on nutritional quality are ambiguous. Beneficial effects include destruction of antinutritional factors, gelatinisation of starch, increased soluble dietary fibre and reduction of lipid oxidation. On the other hand, Maillard reactions between protein and sugars reduce the nutritional value of the protein, depending on the raw material types, their composition and process conditions. Heat-labile vitamins may be lost to varying extents. Changes in proteins and amino acid profile, carbohydrates, dietary fibre, vitamins, mineral content and some non-nutrient healthful components of food may be either beneficial or deleterious. The present paper reviews the mechanisms underlying these changes, as well as the influence of process variables and feed characteristics. Mild extrusion conditions (high moisture content, low residence time, low temperature) improve the nutritional quality, while high extrusion temperatures (≥ 200 °C), low moisture contents ($< 15\%$) and/or improper formulation (e.g. presence of high-reactive sugars) can impair nutritional quality adversely. To obtain a nutritionally balanced extruded product, careful control of process parameters is essential.

Keywords Carbohydrates, dietary fibre, extrusion, Maillard reaction, minerals, protein, vitamins.

Introduction

Health and nutrition is the most demanding and challenging field in this era and would continue to be in the future as well. Maintaining and increasing the nutritional quality of food during food processing is always a potentially important area for research. Deterioration of nutritional quality, owing to high temperature, is a challenging problem in most traditional cooking methods. Extrusion cooking is preferable to other food-processing techniques in terms of continuous process with high productivity and significant nutrient retention, owing to the high temperature and short time required (Guy, 2001). Extrusion cooking is a high-temperature, short-time process in which moistened, expansive, starchy and/or protenacious food materials are plasticised and cooked in a tube by a combination of moisture, pressure, temperature and mechanical shear, resulting in molecular transformation and chemical reactions (Havck & Huber, 1989; Castells *et al.*, 2005). This technology has some unique positive features compared with other heat processes, because the material is subjected to intense mechanical shear. It

is able to break the covalent bonds in biopolymers, and the intense structural disruption and mixing facilitate the modification of functional properties of food ingredients and/or texturizing them (Asp & Bjorck, 1989; Carvalho & Mitchell, 2000). In addition, the extrusion process denatures undesirable enzymes; inactivates some antinutritional factors (trypsin inhibitors, haemagglutinins, tannins and phytates); sterilises the finished product; and retains natural colours and flavours of foods (Fellows, 2000; Bhandari *et al.*, 2001).

The process has found numerous applications, including increasing numbers of ready-to-eat cereals; salty and sweet snacks; co-extruded snacks; indirect expanded products; croutons for soups and salads; an expanding array of dry pet foods and fish foods; textured meat-like materials from defatted high-protein flours; nutritious precooked food mixtures for infant feeding; and confectionery products (Harper, 1989; Eastman *et al.*, 2001).

Parallel to the increased applications, interest has grown in the physico-chemical, functional and nutritionally relevant effects of extrusion processing. Prevention or reduction of nutrient destruction, together with improvements in starch or protein digestibility, is clearly of importance in most extrusion applications. Nutritional concern about extrusion cooking is reached at its

*Correspondent: Fax: +61353279240;
e-mail: s.gamlath@ballarat.edu.au

highest level when extrusion is used specifically to produce nutritionally balanced or enriched foods, like weaning foods, dietetic foods, and meat replacers (Cheftel, 1986; Plahar *et al.*, 2003). Many researchers have reported the positive and negative effects of the extrusion process on the nutritional quality of food and feed mixtures using different extruder conditions (temperature, feed moisture, screw speed and screw configuration) and raw-material characteristics (composition, particle size). Reviews of various chemical changes affecting the nutritional quality of food during extrusion cooking have been published by Cheftel (1986), Asp & Bjorck (1989), Camire *et al.* (1990) and Areas (1992). However, none of the publication offers a comprehensive review of all nutritional aspects.

The present paper reviews the updated and more advanced mechanisms and new concepts about the nutritional changes during the extrusion process. The effect on proteins and amino acid profile, carbohydrates, dietary fibre, vitamins, mineral content and some non-nutrient healthful components of food are discussed. This paper also indicates the gaps in the available extrusion literature and some of the future opportunities for research to make extrusion processes more efficient in terms of retention of nutritional quality of food.

Nutritional changes

Protein

Every animal, including humans, must have an adequate source of protein in order to grow or maintain itself. Proteins are a group of highly complex organic compounds that are made up of a sequence of amino acids. Among the twenty-two amino acids that make up most proteins, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine are considered as essential amino acids.

Protein nutritional value is dependent on the quantity, digestibility and availability of essential amino acids. Digestibility is considered as the most important deter-

minant of protein quality in adults, according to FAO/WHO/UNU (1985). Protein digestibility value of extrudates is higher than nonextruded products. The possible cause might be the denaturation of proteins and inactivation of antinutritional factors that impair digestion.

The nutritional value in vegetable protein is usually enhanced by mild extrusion cooking conditions, owing to an increase in digestibility (Srihara & Alexander, 1984; Hakansson *et al.*, 1987; Colonna *et al.*, 1989; Areas, 1992). It is probably a result of protein denaturation and inactivation of enzyme inhibitors present in raw plant foods, which might expose new sites for enzyme attack (Colonna *et al.*, 1989). All processing variables have different effects in protein digestibility. The findings are summarised in Table 1.

Among the process variables, the feed ratio has the maximum effect on protein digestibility, followed by process temperature in the extrusion of fish-wheat flour blend. Tripling the ratio of fish to wheat increases the digestibility of the extrudates by 2–4% (Bhattacharya *et al.*, 1988; Camire *et al.*, 1990). Increase in extrusion temperature (100–140 °C) enhances the degree of inactivation of protease inhibitors in wheat flour, and consequently, the protein digestibility values are increased. Extrusion, even at 140 °C, does not have any adverse effect on protein digestibility, which might be attributed to the lesser residence time of food dough within the extruder. The effect of other process variables, such as length to diameter ratio and screw speed on protein digestibility values appears to be insignificant ($P = 0.05$) (Bhattacharya *et al.*, 1988). Increased screw speed may have increased the protein digestibility of extruded corn-gluten, because the increase in shear forces in the extruder denatures the proteins more easily, thus facilitating enzyme hydrolysis (Bhattacharya & Hanna, 1985).

An advantage of extrusion cooking is the destruction of antinutritional factors, especially trypsin inhibitors, haemagglutinins, tannins and phytates, all of which inhibit protein digestibility (Bookwalter *et al.*, 1971; Lorenz & Jansen, 1980; Armour *et al.*, 1998; Alonso

Table 1 Effect of processing parameter on protein digestibility

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

↑, increase.

et al., 1998, 2000a). The destruction of trypsin inhibitors increases with extrusion temperature and moisture content (Bjorck & Asp, 1983). At constant temperature, inactivation increases with increasing product residence time and moisture content. The highest protein quality (as measured by protein efficiency ratio), corrected for a value for casein of 2.5 is 2.15 in extruded soy flour, obtained at a barrel temperature of 153 °C, 20% moisture and 2 min residence time, coinciding with 89% reduction of trypsin inhibitors (Bjorck & Asp, 1983). Extrusion (300-r.p.m. screw speed, 27-kg h⁻¹ feed rate, 5/32 inches die size and 93–97 °C outlet temperature) causes complete destruction of trypsin inhibitor activity in extruded blends of broken rice and wheat bran containing up to 20% wheat bran (Singh *et al.*, 2000). However, in blends containing bran beyond 20%, the inactivation of trypsin inhibitor decreases from 92 to 60% (Singh *et al.*, 2000). This may be correlated to a lower degree of expansion of extrudate with an increased proportion of bran in the blends, which probably reduced the effect of heat, resulting in a lower degree of inactivation of trypsin inhibitor. In another study, without preconditioning prior to extrusion cooking (Lorenz & Jansen, 1980), a temperature of 143 °C, at 15–30% moisture and residence time of 0.5–2 min, produced a product of maximum protein efficiency ratio, despite the finding that only 57% of trypsin inhibitors are destroyed. An increase in feed rate, with similar process conditions, has been reported to result in less destruction of trypsin inhibitors (Asp & Bjorck, 1989), presumably because of reduced residence time. In conclusion, high extrusion temperature, longer residence time and lower feed moisture content are the key variables for the destruction of trypsin inhibitors.

Lectin (haemagglutinating) activity is relatively heat resistant. An aqueous heat treatment, at 60 or 70 °C for up to 90 min, does not alter the lectin activity in soybeans. Lectin activity is reduced, but not abolished by heating at 80 ° or 90 °C. However, as found with

kidney bean (Grant *et al.*, 1982, 1994), the lectin activity in the fully imbibed seed could be completely abolished by heating them for 5 min at 100 °C. Extrusion has been shown to be very effective in reducing or eliminating lectin activity in legume flour (Alonso *et al.*, 2000a,b). Thus, extrusion cooking is more effective in reducing or eliminating lectin activity as compared with traditional aqueous heat treatment.

The enzyme hydrolysis of protein is improved after extrusion cooking as a result of the inactivation of antitrypsin activity in extruded snacks. The higher susceptibility of protein to pepsin, as compared with trypsin, further suggested the presence of antitrypsin activity. The improvement in pepsin hydrolysis might be the result of the denaturation of proteins during extrusion cooking, rendering them more susceptible to pepsin activity. This suggests that extrusion considerably improved the nutritive value of proteins (Singh *et al.*, 2000).

Amino acid profile

Among all essential amino acids, lysine is the most limiting essential amino acid in cereal-based products, which are the majority of extruded products. Thus a focus on lysine retention during the extrusion process is of particular importance. The effects of various processing variables on lysine retention are summarised in Table 2.

The available lysine in the extrudates of defatted soy flour and sweet potato flour mixture ranged from 68 to 100% (Iwe *et al.*, 2004). Increase in screw speed (80–140 r.p.m.) and a reduction of die diameter (10–6 mm) enhance lysine retention. Even though an increase in screw speed increases shear, leading to more severe conditions, the corresponding reduction in residence time (as a result of increase in screw speed) limits the duration of heat treatment, resulting in high lysine retention. An increase in the level of sweet potato increases lysine retention, which can be attributed to the

Processing parameter	Effect on lysine retention	Food source	References
Screw speed	↑ with increasing screw speed	Defatted soy flour and sweet potato flour mixture	Iwe <i>et al.</i> (2004)
Die diameter	↓ with increasing die diameter	Defatted soy flour and sweet potato flour mixture	Iwe <i>et al.</i> (2004)
Feed rate	↑ with increasing feed rate	Wheat flour	Bjorck & Asp (1983)
Feed moisture	↓ with increasing moisture	Cowpea and mung bean	Pham & Del Rosario (1984)

Table 2 Effects of processing variables on lysine retention

↑, increase; ↓, decrease.

lower levels of lysine in the sweet potato raw material, as the losses are more pronounced at increasing levels of soy addition, which apparently has higher lysine content. Optimum available lysine was estimated at a feed composition of 98.49%, screw speed of 118.98 r.p.m., and die diameter of 2.25 mm in the extrusion of mixtures of defatted soy flour and sweet potato flour (Iwe *et al.*, 2004). In the extrusion of wheat flour (150 °C mass temperature, 5-mm die diameter, 150-r.p.m. screw speed), an increase in feed rate (from 200 to 350 g min⁻¹) significantly improved lysine retention (Bjorck & Asp, 1983).

Moisture content also effects lysine retention, but conflicting results have been found. To minimise lysine loss, product temperature should be kept below 180 °C, particularly at low moisture content below 15% (Chef-tel, 1986). A number of studies suggest that higher moisture content (15–25%) significantly improves lysine retention (Noguchi *et al.*, 1982; Bjorck & Asp, 1983; Asp & Bjorck, 1989). It was found that, at a given process temperature during extrusion cooking of cow-pea and mung bean, the available lysine decreased with increasing feed moisture content at 93–167 °C barrel temperature, 30–45% feed moisture and 100 to 200-r.p.m. screw speed (Pham & Del Rosario, 1984). Owing to the complex nature of interactions between extruder conditions, these changes might not be related to a single factor. Hence, the role of feed moisture content and the interactions of other parameters on the protein nutritional value is a point that obviously needs further investigation.

Maillard reaction

Nutritional availability of lysine

Maillard reaction is a chemical reaction involving amino groups and carbonyl groups, which are common in foodstuffs, and leads to browning and flavour production. The nutritional significance of Maillard reaction is most important for animal feeds and foods intended for special nutritional needs, such as weaning, or intended as the sole item in a diet (Fukui *et al.*, 1993). Maillard reaction occurs between free amino groups of protein and carbonyl groups of reducing sugars, and lead to a decrease in the availability of amino acids involved and in protein digestibility. Pentoses are most reactive, followed by hexoses and disaccharides. For hexoses, the order of reactivity is D-galactose > D-mannose > D-glucose. Reducing disaccharides are considerably less reactive than their corresponding monomers. Basic amino acids are more reactive than natural or acid amino acids (Kroh & Westphal, 1989).

Lysine appears to be the most reactive amino acid, owing to the fact that it has two available amino groups (O'Brien & Morrissey, 1989). Furthermore, lysine is limiting in cereals, and loss in availability would

immediately result in a decrease in protein nutritional value. Lysine may thus serve as an indicator of protein damage during processing. However, arginine, tryptophan, cysteine and histidine might also be affected (Iwe *et al.*, 2001).

The process conditions used in extrusion cooking – high barrel temperatures and low feed moistures are known to favour the Maillard reaction. In the extrusion cooking of a cereal mixture, the loss of available lysine ranged from 32% to 80% at 170 °C mass temperature, 10–14% feed moisture and 60-r.p.m. screw speed (Beaufrand *et al.*, 1978). There was a substantial loss (32%) of available lysine without addition of sugars in the cereal mixture, which might be the result of hydrolysis of starch. Free sugars might be produced from starch hydrolysis during extrusion to react with lysine and other amino acids with free terminal amines. Starch and dietary fibre fragments, along with sucrose hydrolysis products, are available for Maillard reaction. Lower pH favoured Maillard reactions, as measured by increased colour in the model system, consisting of wheat starch, glucose and lysine (Bates *et al.*, 1994). Sucrose, maltose and fructose were found to be much less reactive than glucose under similar extrusion conditions. There was selective damage to lysine at low hexose contents (1–5%). At a high-energy input to the extruder, glucose caused losses of available lysine and arginine of 61% and 15%, respectively. In contrast, with xylose, the losses were greater, being 70% and 32%, respectively (Asp & Bjorck, 1989).

It was found that the retention of available lysine during processing of a cereal/soy-based mixture containing 20% sucrose ranged from 0% to 40% at 170 °C mass temperature, 10–14% feed moisture and 60-r.p.m. screw speed (Noguchi *et al.*, 1982). The loss depends on extrusion conditions, increasing with temperature and decreasing with moisture content of the feed.

In order to keep lysine losses within an acceptable range, it is necessary to avoid extrusion cooking above 180 °C at water contents below 15%, and/or avoid the presence of higher amount of reducing sugars during the extrusion process.

Apart from lysine, limited data is available about the effects of the Maillard reaction on other essential amino acids during the extrusion process. It is known that the loss of amino acids, owing to the Maillard reaction, is affected by the degree of reactivity of different sugars. The usage of less reactive sugar to prevent Maillard reaction eventually minimizes the loss of amino acids. Further research is needed in this area both for lysine and for all essential amino acids.

Apart from affect on lysine availability, recent studies have confirmed that Maillard reaction is an important reaction route for acrylamide formation in potato, rice and cereals products (Becalski *et al.*, 2004; Kim *et al.*, 2005).

Acrylamide formation

Acrylamide, classified as a Group 2A carcinogen, has been found in common foods, such as potato chips, French fries, cookies, cereals and bread, which are prepared at a temperature of over 120 °C (Ono *et al.*, 2003; Granda *et al.*, 2004; Kim *et al.*, 2005). The main amino acid contributing to the acrylamide formation is asparagine, especially in the presence of reducing sugars, such as glucose, whereas cysteine, glutamine, arginine and aspartic acid produce only trace quantities of acrylamide (Mottram *et al.*, 2002; Stadler *et al.*, 2002; Becalski *et al.*, 2003; Yaylayan *et al.*, 2003; Becalski *et al.*, 2004; Kim *et al.*, 2005).

As extrusion cooking involves high temperature, acrylamide might be formed during the process. In cereal-based products, acrylamide formation might have occurred as a result of extrusion, baking and roasting process (Studer *et al.*, 2004). Cereals have differing potential for the formation of acrylamide, depending on their type and varying content of free asparagine. Raw materials with low asparagine contents cause the extrusion process to form end products with low acrylamide values. Rye has higher asparagine content in comparison with rice, maize and wheat. The extruded products from rye are found to contain higher acrylamide content. By the addition of monosaccharides, disaccharides and oligosaccharides, along with skim-milk powder and malt flour, the acrylamide content can be increased significantly (Kretschmer, 2004).

During extrusion, feed and product moisture contents, process temperature and resultant energy input are relevant parameters for the acrylamide formation. Accordingly, the use of twin-screw extruders with high thermal and mechanical energy inputs leads to a high acrylamide content in the end product. This can be perceptibly reduced if the extrusion temperature is reduced by 1%, and the extrusion moisture content increased accordingly (Kretschmer, 2004).

The presence of glycine, cysteine and lysine has significant effects on the decrease in acrylamide in the fired products. Glycine at 0.1% and 0.5% reduced the acrylamide concentration by 43% and 69%, respectively (Kim *et al.*, 2005). This may be attributed to competitive consumption of acrylamide precursors and/or increased elimination of acrylamide by nucleophilic components in the amino acids. Addition of free amino acids or a protein-rich food component strongly reduces the acrylamide content, probably by promoting competing reactions and/or covalently binding the acrylamide formed.

These findings can be applied to reduce acrylamide levels in extruded products, but currently, very limited information is available on the mechanism of acrylamide formation and the techniques that can reduce or prevent the formation of acrylamide in extruded foods.

Thus, further research is needed specifically in the extrusion area.

Effects on other amino acids

Apart from lysine, a few other amino acids have been affected by a decrease in moisture content during extrusion. Cysteine decreases below 14.5% moisture content during the extrusion (181–187 °C mass temperature, 12–25% feed moisture, 35 to 79-Nm torque) of maize grits (Iwe *et al.*, 2001). Biological evaluation also revealed a decrease in the availability of aspartic acid, tyrosine and arginine with decreasing moisture content. With increasing energy input to the extruder, a significant reduction in the availability of several amino acids was found. The loss of available arginine (21%), histidine (15%), aspartic acid (14%) and serine (13%) was significant at 135–160 °C mass temperature and 150 or 200-r.p.m. screw speed (Iwe *et al.*, 2001). Extrusion cooking of a cereal blend resulted in a considerable loss of arginine, and to a lesser extent also of histidine (170 °C mass temperature, 10% feed moisture and 40-r.p.m. screw speed). Lysine and methionine availability was not affected below 149 °C during extrusion cooking of soybeans (127–154 °C mass temperature, 14% feed moisture and 20-s residence time). At the highest temperature, lysine showed the greatest loss (31%), although a 13% decrease in methionine was noted (Bjorck & Asp, 1983).

Free amino acids are much more sensitive to damage during extrusion cooking than those in proteins. Phenylalanine, tyrosine, serine, isoleucine and lysine decreased considerably during potato flake extrusion at 70–160 °C barrel temperature, 48% feed moisture, 100–r.p.m. screw speed (Maga & Sizer, 1978). At 160 °C, the total loss of amino acids was 89%. Potato flakes extruded at 100 and 130 °C contained higher levels of free amino acids than the product processed at 70 °C. This is probably the result of some hydrolysis of protein at elevated temperatures (Maga & Sizer, 1978).

Carbohydrates

Carbohydrates range from simple sugars to more complex molecules, like starch and fibre. The effects of extrusion on each of these components will be discussed.

Sugar

Sugars, such as fructose, sucrose and lactose, are a great source of quick energy. They provide sweetness and are involved in numerous chemical reactions during extrusion. Control of sugars during extrusion is critical for nutritional and sensory quality of the products. Extrusion conditions and feed materials must be selected carefully to produce desired results. For example, a weaning food should be highly digestible, yet a snack for

obese adults should contain little digestible material (Camire, 2001).

Several researchers have reported sugar losses in extrusion. In the preparation of protein-enriched biscuits, 2–20% of the sucrose was lost during extrusion at 170–210 °C mass temperature and 13% feed moisture (Noguchi *et al.*, 1982; Camire *et al.*, 1990). It may be explained based on the conversion of sucrose into glucose and fructose (reducing sugars), and loss of these reducing sugars during Maillard reactions with proteins. Involvement of sugars in Maillard reactions has been discussed under lysine retention.

Oligosaccharides (raffinose and stachyose) can induce flatulence and therefore, impair the nutritional utilisation of grain legumes (Omueti & Morton, 1996). Raffinose and stachyose decreased significantly in extruded high-starch fractions of pinto beans (Borejszo & Khan, 1992). Extruded snacks, based on corn and soy contained lower levels of both stachyose and raffinose compared with unextruded soy grits and flour, but values were not corrected for the 50–60% corn present (Omueti & Morton, 1996). The destruction of these flatulence-causing oligosaccharides might improve the nutritional quality of extruded legume products.

Starch

Starch is a polysaccharide made up of glucose units linked together to form long chains. There are two types of starch molecules, amylose and amylopectin. Amylose (linear) averages 20–30% of the total amount of starch in most native starches. There are some starches, such as waxy cornstarch, which contain only amylopectin (branched); others may only contain amylose. These different proportions of the two types of starch within the starch grains of the plant give each starch its characteristic properties in cooking and gel formation. In extrusion, amylose and amylopectin molecules contribute to gel formation and viscosity to the cooked paste, respectively.

Starch is the storage form of energy for plants. Rice, wheat and corn are major sources of starch in the human diet and the main raw materials for extruded products. Starchy cereals and tubers provide the bulk of calories consumed by most people, particularly those living in less-developed nations. Thus studies of extrusion effects on starch are significant. Humans and other monogastric species cannot easily digest ungelatinised starch. Extrusion cooking is somewhat unique because gelatinisation occurs at much lower moisture levels (12–22%) than is necessary in other forms of food processes (Qu & Wang, 1994).

Third-generation snack pellets, sometimes referred to as semi or half products, having a stable moisture content, are formed and partially cooked by extrusion, then puffed by frying or baking. A critical temperature of 70–80 °C was required to gelatinise cassava-based

shrimp pellets (Seibel & Hu, 1994). Extrusion greatly increased wheat bran and whole flour starch susceptibility to enzymes, but no samples were fully gelatinised under the extrusion conditions employed in the study (Wang & Klopfenstein, 1993). Addition of sucrose, salt or fibre to starchy foods, such as cornmeal may affect gelatinisation, and thus, expansion (Jin *et al.*, 1994). Sugars and other nonionic species may depress gelatinisation by increasing the temperature needed for initiation and depressing the enthalpy of gelatinisation.

The branched structure of amylopectin makes it susceptible to shear. Both amylose and amylopectin molecules might decrease in molecular weight. Larger amylopectin molecules in corn flour had the greatest molecular weight reductions (Politz *et al.*, 1994a). Low die temperature (160 vs. 185 °C) and feed moisture (16 vs. 20%) significantly reduced the average starch molecular weight in wheat flour, but protein content of flour was not an important factor (Politz *et al.*, 1994b). Screw configuration can be designed to minimise or maximise starch breakdown (Gautam & Choudhoury, 1999).

Rapid molecular degradation/starch digestion may be exploited to produce dextrin and/or free glucose for syrups or subsequent fermentation processes. High shear conditions are necessary to maximise the conversion of starch to glucose. Use of thermostable amylase considerably accelerates the process. Glucose production from starch has been studied in barley (Linko *et al.*, 1983), cassava (Grossman *et al.*, 1988), corn (van Zuilichem *et al.*, 1990; Roussel *et al.*, 1991) and potato waste (Camire & Camire, 1994). High amylose rice extruded into noodles had lower starch digestibility and reduced glycemic index in human volunteers (Panlasigui *et al.*, 1992), which is advantageous. The rise in blood glucose after eating is often measured as the glycemic index, with glucose or white bread used as an arbitrary control with a value of 100.

During extrusion, the formation of amylose–lipid complex is evident. The extent of amylose–lipid complex formation is dependent upon both starch and lipid type present in a food. Monoglycerides and free fatty acids are more likely to form complexes than are triglycerides, when added to high-amylose starch (Bhatnagar & Hanna, 1994). Low feed moisture (19%) and barrel temperature (110–140 °C) induced the greatest amount of complex formation between stearic acid and normal cornstarch, with 25% amylose (Bhatnagar & Hanna, 1994). High viscosity and longer residence time may favour complex formation.

Dietary fibre

Fibre is a term used to describe many food components. The American Association of Cereal Chemists (2001) coined the following description of dietary fibre:

“Dietary fibre is the edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine. Dietary fibre includes polysaccharides, oligosaccharides, lignin, and associated plant substances. Dietary fibres promote beneficial physiological effects including laxation, and/or blood cholesterol attenuation, and/or blood glucose attenuation.”

A major difficulty in interpreting research involving fibre and extrusion is the variety of analytical methods used to quantitate and characterize different fibre components. For example, the Association of Official Analytical Chemists (AOAC) total dietary fibre method measures all compounds not digested by amylase and protease and insoluble in 80% aqueous ethanol. While cellulose, pectin, hemicelluloses, gums and lignin do meet these criteria, extrusion-modified starches and proteins could also be measured as fibre (Camire, 2001).

The measurement of total dietary fibre may meet food-labelling requirements, but this assay also does not discriminate changes in fibre solubility induced by extrusion. An enzymatic-chemical method found differences among foods for lignin and nonstarch polysaccharides, but uronic acids were unaffected by extrusion (Camire & Flint, 1991). The ratio of soluble to insoluble nonstarch polysaccharides increased for oatmeal and potato peels, but not for corn meal under the same conditions. Extrusion most likely solubilises large molecules in a manner similar to that reported for starch.

Extrusion reduces the molecular weight of pectin and hemicellulose molecules, resulting in increased water solubility of sugar beet pulp fibre (Ralet *et al.*, 1991). Ferulic acid, a phenolic acid normally associated with plant cell walls, was also recovered from the soluble sugar beet fraction. Smaller fragments may be soluble in aqueous ethanol, which is used for extraction steps in enzymatic-gravimetric and enzymatic-chemical methods of fibre analysis.

Many factors influence fibre solubility. Acid and alkaline treatment, prior to extrusion, increased the soluble fibre slightly in corn bran (Ning *et al.*, 1991). Grinding doubled the soluble fibre of pea hulls to 8% (dry basis), but all the extruded hulls contained over 10% soluble fibre (Ralet *et al.*, 1993).

Conflicting findings have been reported about the effect of extrusion on dietary fibre and, are summarized in Table 3. The viscosity of aqueous suspensions of extruded wheat, oats and barley were higher than unprocessed grains (Wang & Klopfenstein, 1993). Viscous gums and other soluble fibres may reduce cholesterol levels by trapping bile acids; increased excretion of bile eventually depletes body stores of cholesterol, which are tapped to synthesise new bile acids.

Insignificant changes in dietary fibre content were reported in both untreated and twin-screw extruded wheat flour and whole-wheat meal at 161–180 °C mass temperature, 15% feed moisture and 150–200-r.p.m. screw speed (Varo *et al.*, 1983). No significant change was found in dietary fibre content when wheat was extruded under milder conditions, but the fibre present became slightly more soluble (Siljestrom *et al.*, 1986). On the other hand, an increase in dietary fibre content of wheat flours with increasing product temperature (150–200 °C) was reported. The increase may be the result of the glucans, present both in the soluble and insoluble dietary fibre fractions, indicating starch alterations.

Extrusion cooking increased the total dietary fibre of barley flours. The total dietary fibre increase in waxy barley was the result of an increase in soluble dietary fibre. For regular barley flour, the increase in both insoluble dietary fibre and soluble dietary fibre contributed to the increased total dietary fibre content (Vasanthan *et al.*, 2002). The change in dietary fibre profile during extrusion of barley flour may be attributed, primarily, to a shift from insoluble dietary fibre to

Table 3 Nutritional effects of dietary fibre during extrusion

Food Source	Dietary fibre change	Nutrition assay	Health effect	References
Extruded wheat, barley with husks, or oats with husks	↑ soluble dietary fibre	6-week rat feeding study	↓ cholesterol in rats fed extruded grains vs. raw grains or casein control	Wang & Klopfenstein (1993)
Potato peels	↓ soluble dietary fibre at lower barrel temperature	<i>In vitro</i> bile acid binding	↓ binding could lower serum cholesterol	Camire <i>et al.</i> (1993)
Wheat cereal with added guar gum		Human glucose tolerance test	↓ serum glucose postprandial compared with low-fibre cereal	Fairchild <i>et al.</i> (1996)
Extruded rice, oat, corn and wheat bran	No change	Hamster feeding study	Extrusion did not affect cholesterol – lowering properties	Kahlon <i>et al.</i> (1998)

↑, increase; ↓, decrease.

Source: Adapted from Camire (2001).

soluble dietary fibre, and the formation of resistant starch and enzyme-resistant indigestible glucans formed by transglycosidation.

In summary, at mild or moderate conditions, extrusion cooking does not significantly change dietary fibre content but it solubilises some fibre components. At more severe conditions, the dietary fibre content tends to increase, mainly owing to the increases in soluble dietary fibre and enzyme-resistant starch fractions.

Lipids

The class of chemical compounds known as lipids is a heterogeneous group of nonpolar materials, including glycerides, phospholipids, sterols and waxes. Although many types of lipids occur in foods, the triglycerides are the most common. A triglyceride consists of three fatty acid molecules esterified to one glycerol molecule. Although lipids serve as a concentrated form of energy, excess dietary lipid consumption is associated with chronic illnesses, such as heart disease, cancer and obesity (Camire, 2001).

During the extrusion of foods, native lipids might be present within the raw materials or added to the ingredients. Cereals, such as wheat and corn are typically low (2%) in oils, although oats may contain up to 10% oil. The oil is concentrated in the bran and germ portions of the seed kernel, and is removed during milling to improve storage stability. Oilseeds, such as soybeans and cottonseed may contain up to 50% by total seed weight as oil. Oilseed flours used in extrusion may be full fat or partially or wholly defatted.

Extrusion of high-fat materials is generally not advisable, especially in the case of expanded products, as lipid levels over 5–6% impair extruder performance (Camire, 2000a). Torque is decreased because the lipid reduces slip within the barrel, and often product expansion is poor because insufficient pressure is developed during extrusion. Lipid is released from cells owing to the high temperature and physical disruption of plant cell walls. At the same time, small lipid levels (<5%) facilitate steady extrusion and improve the texture. A decrease in extractable fat after extrusion cooking has been found with an average of 40% of the original recovered in extruded maize, by using different solvents (Nierle *et al.*, 1980). Some lipid might be lost at the die as free oil, but this situation only occurs with high-fat materials, such as whole soy. Another explanation for the lower lipid level is the formation of complexes with amylose or protein (Camire, 2000a). When extrudates are digested with acid or amylase and then extracted with solvent, lipid recovery is higher. Although only 50% of the extractable lipids in extruded whole wheat were recovered, acid hydrolysis indicated that total fat was not significantly changed owing to extrusion (Wang & Klopfenstein, 1993).

High levels of free fatty acids in foods create a number of problems. Increased levels of free fatty acid produce off flavours and affect the storage quality of foods (Camire *et al.*, 1990). Free fatty acids are produced in foods from hydrolysis of triglycerides, mainly because of lipase enzymes and high temperatures. The extrusion process can prevent free fatty acid release by denaturing hydrolytic enzymes (Camire *et al.*, 1990). Lipid oxidation has negative impact on sensory and nutritional qualities of foods and feeds. It probably does not take place during extrusion owing to the very short residence time. However, rancidity is a concern for extruded products during storage. Screw wear is a concern as metals can act as pro-oxidants. Iron content and peroxide values were higher in extruded rice and dhal compared with similar products processed by drying methods (Semwal *et al.*, 1994). The larger surface area created by the air cells throughout highly expanded extrudates, favours oxidation. On the other hand, extrusion denatures enzymes that can promote oxidation, and lipids held within starch are less susceptible to oxidation. Compounds produced by Maillard reactions can also act as antioxidants. Oatmeal cookies with added potato peels had lower peroxide values than control samples, and higher antioxidant activity was observed for extruded peels compared with unextruded peels (Arora & Camire, 1994).

In summary, feed with low fat level is favourable for extrusion cooking. The extrusion process minimises lipid oxidation, thus increasing the nutritional and sensory quality of foods and feeds.

Vitamins

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

As vitamins differ greatly in chemical structure and composition, their stability during extrusion is also variable. The extent of degradation depends on various parameters during food processing and storage, e.g. moisture, temperature, light, oxygen, time and pH. This subject is addressed in reviews on nutritional changes during extrusion (Bjorek & Asp, 1983; Camire *et al.*, 1990; Camire, 1998) and in a review of vitamin retention by Killeit (1994). Minimising temperature and shear within the extruder protects most vitamins.

Among the lipid-soluble vitamins, vitamins D and K are fairly stable. Vitamins A and E and their related compounds – carotenoids and tocopherols, respectively,

are not stable in the presence of oxygen and heat (Killeit, 1994). Thermal degradation appears to be the major factor contributing to β -carotene losses during extrusion. Higher barrel temperatures (200 °C compared with 125 °C) reduce all trans- β -carotene in wheat flour by over 50% (Guzman-Tello & Cheftel, 1990).

Pham & Del Rosario (1986) and Guzman-Tello & Cheftel (1987) began to assess the effects of high-temperature, short-time extrusion cooking on vitamin stability using mathematical models. Thiamine has been investigated most frequently, followed by riboflavin, ascorbic acid and vitamin A. Very few studies dealt with other B-complex vitamins or vitamin E. A synopsis of the most relevant studies is shown in Table 4.

Ascorbic acid (vitamin C) is also sensitive to heat and oxidation. This vitamin decreased in wheat flour when extruded at a higher barrel temperature at fairly low (10%) moisture (Andersson & Hedlund, 1990). Blueberry concentrate appeared to protect 1% added vitamin C in an extruded breakfast cereal compared with a product containing just corn, sucrose and ascorbic acid (Chaovanalikit, 1999). When ascorbic acid was added to cassava starch to increase starch conversion, retention of over 50% occurred at levels of 0.4–1.0% addition (Sriburi & Hill, 2000).

In summary, the retention of vitamins in extrusion cooking decreases with increasing temperature, screw speed and specific energy input. It also decreases with

Table 4 Effects of extrusion cooking on B vitamins

Parameter	Type of vitamin B	Retention (%)	Remarks	References
T_b : 149/193 °C W : 13/16% r.p.m.: 75/125	Thiamine (B ₁) Riboflavin	19–90 54–125	$\uparrow T$: B ₁ ↓; B ₂ → \uparrow r.p.m.: B ₁ ↓; B ₂ ↓	Beetner (1974)
T_b : 177–232 °C W : 15–25%	Thiamine Riboflavin	0–76 35–90	$\uparrow T$: B ₁ ↓; B ₂ → $\uparrow W$: not significant	Beetner (1976)
T_b : 70–160 °C W : 25–59% r.p.m.: 40–200	Thiamine	>85	$\uparrow W$: B ₁ ↑	Maga & Sizer (1978)
T_b : 175–185 °C T_m : 115–130 °C W : 16–24 % P : 50–60	Thiamine	27–70		Appelt (1986)
T_b : 150 °C r.p.m.: 300 W : 16–24% F : 63–105	Thiamine Pyridoxine (B ₆) Cyanocobalamin (B ₁₂) Folate	38–65 71–83 65–96 35–45	B ₁ , B ₆ , B ₁₂ , folate: $\uparrow F$: all ↑ $\uparrow W$: all ↑	Killeit & Wiedmann (1984)
T_m : 93–132 °C W : 30–45% r.p.m.: 100–200 pH: 6.2–7.4	Thiamine	12–42	$\uparrow T$: B ₁ ↓ $\uparrow W$: B ₁ ↑ \uparrow r.p.m.: B ₁ ↓ \uparrow pH: B ₁ ↓	Pham & Del Rosario (1986)
T_b : 125–200 °C W : 18.6% r.p.m.: 150 W : 14–24%	β -carotene	27–62	$\uparrow T$: carotene ↓ No effect of type of twin-screw extruder	Guzman-Tello & Cheftel (1990)
T_b : 171 °C	Thiamine Riboflavin Pyridoxine Folic Acid	90	Extrusion of corn-soy blends	Lorenz & Jansen (1980)
0% water added	Thiamine Riboflavin Niacin	Very less Not affected Not affected		Andersson & Hedlund (1990)

T_m , temperature of material; T_b , temperature of barrel; W , water content; r.p.m., rotations/min; P , pressure (bar); F , feed rate (kg/h); \uparrow , increase; \downarrow , decrease; \rightarrow , no change.

Source: Adapted from Andersson & Hedlund (1990); Killeit (1994); Camire (2001).

decreasing moisture, feed rate and die diameter. Depending on the vitamin concerned, considerable degradation can occur, especially in products with high sensory appeal. The following options for the nutritional enrichment of extruded products with vitamins are possible.

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

Minerals

Although mineral elements represent a minor portion of the composition of foods, they play major roles in food chemistry and nutrition. Minerals are solid, crystalline, chemical elements that cannot be decomposed or synthesised by ordinary chemical reactions. Minerals are classified as macro- and microminerals. Macrominerals include calcium, phosphorus, sodium, potassium and chloride. Of these, calcium and phosphorus are needed in large amounts, while the rest are needed in smaller amounts. Microminerals include magnesium, manganese, zinc, iron, copper, molybdenum, selenium, iodine, cobalt and chromium, which are needed in minute amounts.

The distribution of minerals is widespread in foods. Phosphorus, in the form of phosphates, is commonly added during food processing; however, iron and calcium are the mineral elements typically added to foods for improving nutritional value (Camire *et al.*, 1990). Metals, particularly iron (Fe), copper (Cu), magnesium (Mg), and calcium (Ca), act as catalysts for enzymes. Iron is essential for the prevention of anaemia, and calcium is necessary for bone health (Camire *et al.*, 1990). Depending upon the product and the population for which it is intended, other minerals may be added at fortification or enrichment levels.

Extrusion cooking generally affects macromolecules. Smaller molecules may be impacted upon by either the extrusion process itself or by changes in larger molecules, which in turn affect other compounds present in the food. Despite the importance of minerals for health, relatively few studies have examined mineral stability during extrusion because they are stable in other food processes (Camire *et al.*, 1990). Minerals are heat stable and unlikely to become lost in the steam distillate at the die.

Extrusion can improve the absorption of minerals by reducing other factors that inhibit absorption. Phytate may form insoluble complexes with minerals and eventually affect mineral absorption adversely (Alonso *et al.*, 2001). Extrusion hydrolyses phytate to release phosphate molecules. Extrusion of peas and kidney

beans resulted in phytate hydrolysis, which explains the higher availability of minerals after processing (high temperature extrusion) (Alonso *et al.*, 2001).

A 13–35% reduction in phytate content was observed after extrusion of a wheat bran-starch-gluten mix (Andersson *et al.*, 1981). Extrusion reduces phytate levels in wheat flour (Fairweather-Tait *et al.*, 1989), but not in legumes, at low extrusion temperature (Lombardi-Boccia *et al.*, 1991). Boiled legumes and ones extruded under high-shear conditions had less dialysable iron than samples extruded under low-shear conditions (Ummadi *et al.*, 1995); although phytic acid was lower under all processing conditions, total phytate was not affected. Thus, processing conditions play an important role in the reduction of phytate in legumes.

The presence of natural polyphenols might be an inhibitory factor in mineral absorption, although tannin content is substantially low. Tannins might form insoluble complexes with divalent ions in the gastrointestinal tract, lowering their bioavailability. The increase in mineral absorption, observed after extrusion, could be partly attributed to the destruction of polyphenols during heat treatment. Changes in the polyphenol content after thermal treatment might result in the binding of phenolics with other organic materials present (Alonso *et al.*, 2001).

Mineral absorption could be altered by fibre components. Cellulose, lignin and some hemicelluloses affect the mobility of the gastrointestinal tract and interfere with the absorption of minerals. Extrusion processing (high temperature) might have reorganised dietary fibre components, changing their chelating properties. Moreover, it must be taken into consideration that complex agents, present in foodstuffs, such as phytate may interact with fibre, modifying the mineral availability (Alonso *et al.*, 2000a,b).

Extrusion does not significantly affect mineral composition of pea and kidney bean seeds, except for iron. Iron content of the flours is increased after processing and it is most likely to the result of the wear of metallic pieces, mainly screws, of the extruder (Alonso *et al.*, 2001). The incorporation of wheat bran in broken rice flour in extrusion (300-r.p.m. screw speed, 27-kg h⁻¹ feed rate, 5/32 inches die size, 93–97 °C outlet temperature) increases the content of calcium, phosphorus, iron and copper, which might be attributed to the addition of these minerals through water used during extrusion and also from the extruder barrel (Singh *et al.*, 2000).

Fortification of foods with minerals prior to extrusion poses other problems. Iron forms complexes with phenolic compounds that are dark in colour and detract from the appearance of foods. Ferrous sulphate heptahydrate was found to be a suitable source of iron in a simulated rice product, because it did not discolour (Kapanidis & Lee, 1996). Added calcium hydroxide

(0.15–0.35%) decreased expansion and increased lightness in the colour of cornmeal extrudates (Martinez-Bustos *et al.*, 1998).

In conclusion, extrusion cooking enhances apparent absorption of most minerals studied in either pea- or kidney bean-based diets. This increased absorption can be explained by the positive effect of extrusion in the reduction of antinutritional factors (phytates, condensed tannins). Chemical alteration, induced by heat in other compounds of legume flours, such as fibre, can also be responsible for the higher mineral absorption observed in processed seeds. Extrusion cooking increases the amount of iron available for absorption, almost in all cases. However, the effects of extrusion on iodine and other essential elements have not been studied in detail. Further research in this area is necessary, particularly if extruded foods are produced as vehicles for mineral fortification.

Non-nutrient healthful components of foods

Apart from nutritional contribution, many foods have been reported to contain components with potential health benefits. These biologically active phytochemicals are found to be beneficial in reducing risk of many diseases. Cereal grains contribute significant quantities of non-nutrients, such as phenolic compounds (phenolic acids, lignans) and phytic acid to the human diet. Extrusion research is at the moment providing clues as to the fate of non-nutrients during extrusion. As nutrition science begins to unravel the importance of non-nutrient chemicals in foods, it is clear that extrusion effects on these compounds must be studied.

Phenolic compounds

Phenolic compounds, such as genistein and phytoestrogens in soy may help prevent breast cancer, yet extrusion texturisation of soy to produce more palatable soy foods might significantly reduce these compounds (Camire, 1998). Extrusion of soy protein concentrate and a mixture of cornmeal and soy protein concentrate (80:20) did not result in changes in total isoflavone content (Mahungu *et al.*, 1999). The aglycones and malonyl forms tended to decrease with extrusion, while acetyl derivatives increased.

Phenolic compounds in plants protect against oxidation, disease and predation. These compounds, including the large flavonoid family, are the focus of numerous studies to elucidate their role in human health. Total free phenolics, primarily chlorogenic acid, decreased significantly, owing to extrusion in potato peels produced by steam peeling (Camire, 1998). More phenolics were retained with higher barrel temperature and feed moisture. It might be possible that lost phenolics reacted with themselves or with other compounds to form larger insoluble materials. The effect of

screw speed (220–340 r.p.m.), feed moisture content (11–15%) and feed rate (22–26 kg h⁻¹) on the total antioxidant activity and total phenolic content in a snack product has been reported (Ozer *et al.*, 2006). The total antioxidant activity value of samples decreased with an increase in screw speed and decrease in moisture content, while total phenolic values had insignificant (95% confidence interval) changes after extrusion. In a model breakfast cereal, containing cornmeal and sucrose, anthocyanin pigments were degraded at higher levels of added ascorbic acid, and total anthocyanins significantly decreased by extrusion (Camire, 2000b).

The red and blue anthocyanin pigments provide attractive colours and are believed to serve as antioxidants that protect vision and cardiovascular health (Camire, 2000b). Blueberry anthocyanins are significantly reduced by extrusion and by ascorbic acid in breakfast cereals containing cornmeal and sucrose (Chaovanalikit, 1999). Polymerisation and browning might also have contributed to anthocyanin losses.

Glucosinolates

Glucosinolates are found in many commercially important *Brassica* species, and may have a role in cancer prevention (van Poppel *et al.*, 1999). Extrusion alone is likely to have little effect on retention of glucosinolates (Fenwick *et al.*, 1986). Total glucosinolates in canola meal were reduced by added ammonia during extrusion (Darroch *et al.*, 1990). Although extrusion with ammonium carbonate did not completely destroy glucosinolates in rapeseed meal, the process did improve nutritional parameters in rats fed with the extruded vs. unprocessed rapeseed meal (Barrett *et al.*, 1997).

Isoflavones

Soy isoflavones have estrogenic activity, and thus may protect postmenopausal women from osteoporosis and heart disease, while men may receive protection against prostate and other testosterone-dependent cancers. Okara, a by-product of tofu manufacture, was mixed with wheat flour and evaluated for the retention of isoflavones (Rinaldi *et al.*, 2000). The aglycone genistein significantly decreased under all extrusion conditions, and glucosides of daidzin and genistin increased, presumably at the expense of acetyl and malonyl forms. Total isoflavone values were significantly lower in 40% okara samples extruded at high temperature. In blends of 20% soy-protein concentrate with cornmeal, increasing barrel temperature caused decarboxylation of isoflavones, leading to increased proportions of acetyl derivatives (Mahungu *et al.*, 1999). Total isoflavones also decreased in the soy–corn blends. In a related study, although the content of the biologically active aglycones did not change with extrusion, extruded corn–soy blends were less effective in preventing proliferation of breast cancer cells *in vitro* (Singletary *et al.*, 2000). The

optimisation of extrusion conditions to retain health benefits of soy products is clearly needed.

Conclusion

Extrusion cooking is an ideal method for manufacturing a number of food products from snacks and breakfast cereals to baby foods. Extrusion also permits the utilisation and coprocessing of various by-products. Beneficial nutritional effects range from increased protein and starch digestibility to the preparation of low-cost, protein-enriched or nutritionally balanced foods and feeds.

As a complex multivariate process, extrusion requires careful control if product quality is to be maintained. Mild extrusion conditions (high moisture content, low residence time, low temperature) favour higher retention of amino acids, high protein and starch digestibility, increased soluble dietary fibre, decreased lipid oxidation, higher retention of vitamins and higher absorption of minerals. Severe extrusion conditions and/or improper formulation (e.g. presence of reducing sugars) can cause nutritional destruction, given the usual residence time of 0.5–1 min in the hot-screw segments. Generally, high extrusion temperature (≥ 200 °C) and low moisture content ($\leq 15\%$) should be avoided to maintain nutritional quality.

There are many areas that require further research regarding extrusion and nutrition. Very little has been published on the effects of extrusion on phytochemicals and other healthful food components. Future research may be focussed on the relationships between compositional changes on product quality – both nutritional and sensory aspects, and the effects of interactions between complex extruder conditions on nutrient retention. High-moisture extrusion and use of less reactive sugars may create a new line of research objectives.

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