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Nutritional Effects of Extrusion-Cooking*

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ABSTRACT

HTST extrusion-cooking, as a multi-step, multi-function thermal/mechanical process, has permitted a large number of food applications. Beneficial or detrimental changes in the bioavailability and in the content of nutrients may take place during extrusion and are of special interest in the case of bread or meat replacers and of infant or dietetic foods. The present paper reviews the mechanisms underlying these changes, as well as the influence of process conditions and of food mix composition. Special emphasis is placed on the physico-chemical and chemical modifications of protein, starch and dietary fibre.

INTRODUCTION

Extrusion-cooking has become a well established industrial technology, with a number of food and feed applications (Table 1). In addition to the usual benefits of heat processing, extrusion offers the possibility of modifying the functional properties of food ingredients and/or of texturizing them.

The extruder is viewed as a continuous chemical reactor processing biopolymers and food mixes at high temperatures (up to 250 °C) for relatively short residence times (usually 1–2 min), at high pressures (up to 25 mPa), under high shear forces, and, in most cases, at relatively low water contents (below 30 %), although recent applications with meat are carried out in twin-screw extruders at 40–80 % moisture.

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TABLE 1
Extrusion-Cooking Applications (With or Without Texturation)

Status	*Little nutritional concern*	*Avoid nutrient destruction; increase starch digestibility*	*Destroy anti-nutritional and/or toxic factors*	*Prepare nutritionally enriched or balanced foods*
Industrial	Bread crumbs Precooked starches Anhydrous decrystallization of sugars to make confectioneries (hard candies) Chocolate conching Pretreated malt and starch for brewing Stabilization of rice bran Gelatin gel confectioneries Caramel, liquorice, chewing gum	Corn and potato snacks Co-extruded snacks with internal filling Flat crispbread (bread substitute), toasted bread Biscuits, crackers, cookies Breakfast cereals and flakes Precooked flours, instant tortilla flour, instant rice pudding Cereal-based instant dry soup mixes or drink bases Transformation of casein into caseinate	Oilseed meals Precooked soy flours (including full fat soy flour) (for enrichment of bread, pasta, etc.)	Animal feeds (cattle, pet foods, fish food) Precooked instant weaning foods or gruels (cereal/legume blends such as CSM-WSB) Texturized vegetable proteins (meat replacers) Dietetic foods (gluten-free, bran-enriched, etc.)
Development	Degermination of spices Encapsulation or generation of flavouring agents Enzymatic liquefaction of starch for fermentation into ethanol	Quick-cooking pasta products Oilseed treatment for subsequent oil extraction Preparation of specific doughs (no retrogradation during cold or frozen storage)	Destruction of aflatoxins or gossypol in peanut or cottonseed meal Sterilization of blood meal	Gelation of vegetable proteins (high moisture) Restructuring of minced meat or MDM (high moisture) Prepare new sterile process cheeses (high moisture, high fat) Prepare sterile baby foods (high moisture)

Extrusion-cooking is not a single unit operation (Table 2). Its specificity and wide range of applications, as compared with other thermal or HTST processes, depend on (1) the number of mechanical and thermal processing steps that can take place along the screw(s) and barrel and (2) the high shear and pressure exerted on low moisture food mixes. Extruder geometry, process conditions and food mix composition interplay to bring about various physical, chemical and nutritional modifications of the food constituents (Harper, 1981; Linko *et al.*, 1981; Jowitt, 1984; Zeuthen *et al.*, 1984).

New long barrel extruders are equipped with several inlets for liquids and solids, and with successive modular screw segments permitting independent control of temperature, pressure, shear and residence time. Sequential transformations are therefore possible.

While nutritional changes are of little concern in some extruded foods, prevention or reduction of nutrient destruction, together with improvements in starch or protein digestibility, are clearly of importance in most other applications. Extrusion also permits the inactivation of several antinutritional or toxic factors, of oxidative (lipoxigenase, peroxidase) and other deterioration enzymes. The highest degree of nutritional concern is reached when extrusion is used specifically to produce foods that are nutritionally balanced or enriched (weaning foods, meat replacers, animal feeds, dietetic foods) (Table 1). Detailed surveys of the nutritional effects of extrusion-cooking have been recently published (Björck & Asp, 1983; Asp & Björck, 1984; de la Guérivière *et al.*, 1985). The present paper reports the beneficial and detrimental effects of extrusion on protein, starch and dietary fibre, emphasizing reaction mechanisms. Changes in lipids, vitamins and minerals have been studied to a lesser extent.

The following abbreviations are used: Tm = temperature of food mix just before the exit die. *Tb* = temperature of metal barrel. $\%H_2O$ = total water content of food mix during extrusion, in g per 100 g wet basis. RT = mean or median residence time. *RPM* = rotations of screw(s) per min. *F* = total mass feed rate.* Extruder geometry (screw profile, die

* Other abbreviations used are: HTST (high temperature–short time); PER (protein efficiency ratio); TVP (texturized vegetable protein); FDNB-reactive lysine (protein-bound lysine with its ε-amino group still free to react covalently with fluorodinitrobenzene following Carpenter's method); NPU (net protein utilization); CSM, WSB (corn–soy–milk, wheat–soy blend); MDM (mechanically deboned meat).

TABLE 2
Extrusion-Cooking as a Multi-Step, Multi-Functional Operation (By Chronological Order)

Successive extruder sections	*Unit operations and modifications of the food mix*
Transport zone(s) (initial screw elements, usually)	Transport (approximately at the speed of the screw(s))
Compression zone Reverse screw elements Kneading disks Space between end of screw(s) and die	Grinding, mixing, hydration, dough kneading, shearing, compression, degassing Thermal processing (cooking): partial melting, plastification, starch gelatinization and solubilization, protein denaturation and insolubilization, inactivation of enzymes, microorganisms and/or toxic factors. Browning, other chemical reactions Homogenizing, dispersion of residence times, compression, agglomeration, densification, pumping (centrifugal pump: single screw; volumetric pump: twin screw) Cooling (eventually), pressure release (eventually) Degassing (eventually), with or without vacuum pump (partial drying)
Low pressure sections	Introduction of liquids and/or solids: reagents, enzymes, flavours, gelling agents, thermolabile ingredients Sequential chemical reactions
Die	Texturation through the die: stream orientation and aligment of molecules and aggregates; agglomeration Forming, shaping, co-extrusion
Die outlet	Texturation: expansion by steam bubbles; formation of expanded, porous, eventually fibrous, structures; hardening upon cooling Partial drying; loss of flavours through flash evaporation Vacuum application (eventually) for increased expansion, porosity and instant properties
Post-extrusion equipment	Cutting, grinding, flattening, cooking, drying, etc.

dimensions) is important but not given here. Pressure, torque and energy consumption are usually not known. Process parameters are interrelated, making it difficult to relate chemical or nutrient change to any single factor.

PROTEIN

This often limiting nutrient is sensitive to heat and shear and can react with various food components or additives (Cheftel, 1979; Cheftel *et al.*, 1985).

Physico-chemical modifications: Improved protein digestibility due to protein denaturation

Most proteins undergo structural unfolding and/or aggregation when subjected to moist heat or shear. This often leads to insolubilization and to inactivation (when the native molecules possess a biological activity).

Soybeans and many legume- or oilseeds provide a good example of improved protein digestibility and bioavailability of (limiting) sulphur amino acids through (1) thermal unfolding of the major seed globulins and (2) thermal inactivation of trypsin inhibitors and other growth-retarding factors, such as lectins (Mustakas *et al.*, 1964, 1970; De Muelenaere & Buzzard, 1969; MacLean *et al.*, 1983; Molina *et al.*, 1983; Harper & Jansen, 1985).

When dehulled full fat soybeans, defatted soy flour or corn/soy blends (70/30 w/w; ~17% protein) are precooked in a single screw extruder ($Tb = 140$–$170\,°C$, $\%H_2O \geq 15$), the nitrogen solubility index decreases markedly (from 53 for raw soybean to 10 after extrusion), and the trypsin inhibitors are inactivated to an extent of 70–95%. Improved nutritional value of the protein is consistently obtained, as shown by PER determinations on rats (from 1 to 2·15 after extrusion of raw soybeans at 140°C and 8–20% moisture), growth of domestic animals, or nitrogen balance experiments with infants aged from 5 to 30 months.

The ground extrudates can be used for protein enrichment of bread or pasta, as instant weaning foods or gruels for children, or as animal feeds.

Similar beneficial effects are often obtained with blends of other cereals, oilseeds and legumes. Autoclaving can be used, but extrusion-cooking is more efficient from an industrial standpoint. Low-cost extruders are useful in developing countries for manufacturing nutritious precooked flours from local commodities (Harper & Jansen, 1985). While amino acid complementation between cereal and oilseed (or legume) usually results in high PER close to that of casein, it is sometimes desirable to supplement the extruded flours with free lysine or methionine (together with vitamins and minerals).

In the *texturation of vegetable proteins* by extrusion-cooking, advantage is taken of unfolding and aggregation reactions to promote the formation of insoluble dry expanded and fibrous structures that readily rehydrate into elastic and chewy 'meat extenders or analogs'. Defatted flours or protein concentrates from soy or other oilseeds or legumes (40–65 % protein) are texturized in single or twin-screw extruders under moderate process conditions (Tm = 160–170 °C, % H_2O = 15–30), with or without the addition of gluten, milk proteins, meat powders, alginates, etc. Specific extruder geometry, process conditions and rheological properties of the initial food mix are necessary to obtain satisfactory texturation. The exact texturation mechanisms are not known, although protein insolubilization clearly results from new hydrogen, hydrophobic and disulphide bonding. Other covalent crosslinks such as lysinoalanine and lanthionine are not formed in appreciable amounts (Jeunink & Cheftel, 1979). Glutamyl-lysine was not present in a sample of commercial extruded TVP (Jeunink & Cheftel, unpublished data). Small ($\leq$15 %) losses in cysteine/cystine and in FDNB-reactive lysine are observed.

The protein nutritional value of experimental and commercial extruded TVP has been assessed in human adolescents and adults, and with rats (Vemury *et al.*, 1976; Kinsella, 1978; Alid *et al.*, 1981; Elias *et al.*, 1984). In human adults, apparent protein digestibility and nitrogen balance (g N per subject and per day) averaged 66·3 % and −1·16 for TVP from defatted soy flour, and 63·4 % and −1·31 for TVP from soy protein concentrate, against 73·2 % and −0·42 for beef. In rats, PER of commercial soy TVP ranged from 1·8 to 2·4 (casein control = 2·5). The lowest values appear to result from the poor quality of the initial soy flours (low methionine content), rather than from excessive extrusion conditions. Nitrogen balance and PER can be improved by the addition of methionine or by blending with gluten or meat. The low quality TVP would markedly reduce the protein value of hamburgers, if introduced at a 30–40 % level.

Extrusion-cooking usually brings about complete *enzyme inactivation*, in spite of the HTST process conditions (Linko *et al.*, 1981). This contributes to the stability of extruded foods, and may help retard oxidation of ascorbic acid and of unsaturated fatty acids. The inactivation ratio of endogenous or added thermo-resistant enzymes can be used as a quantitative indicator of the severity of the heat process under different extrusion conditions or in different extruders (Mustakas *et al.*, 1970; Bounie & Cheftel, 1986).

The respective effects of thermal and mechanical factors on the extrusion denaturation of proteins deserve to be investigated, at different moisture contents.

Chemical changes: Decreased nutritional availability of lysine due to Maillard reactions

Extensive lysine loss and nutritional damage can take place when cereal flours or cereal/legume blends are extruded into biscuits, cookies, flat crispbread, breakfast cereals or instant flours under severe conditions of temperature (Tm $\geq$ 180 °C) or shear forces ($RPM > 100$) at low moisture ($\%H_2O \leq 15$), especially in the presence of reducing sugars ($\geq 3\%$ glucose, fructose, maltose, lactose) (Beaufrand *et al.*, 1978; Racicot *et al.*, 1981; Noguchi *et al.*, 1982; Björck *et al.*, 1983; Grébaut *et al.*, 1983; Björck *et al.*, 1984*b*; Pham & del Rosario, 1984). Decreases in total and FDNB-reactive lysine contents and in the bioavailability of lysine (measured as NPU in rats under lysine limitation) were respectively equal to 37%, 37% and 50% when a biscuit mix containing starch, protein (22%) and sucrose (20%) was extruded under excessive conditions (Creusot Loire BC 45 twin-screw extruder, Tm = 210 °C, $\%H_2O = 13$, $RPM = 80$, RT = 1 min, $F = 640$ g/min) (Noguchi *et al.*, 1982; Björck *et al.*, 1983). Overall decrease in protein digestibility was responsible for the difference between lysine availability and lysine content. This extruded sample was over-cooked, as judged by browning and taste, but smaller lysine loss can also take place without browning.

These damages depend on the well known Maillard condensation between ε-NH_2 groups of lysine residues and C=O groups of reducing sugars. When the mentioned biscuit mix was severely processed as indicated above, 10% of the initial sucrose molecules were hydrolyzed into glucose and fructose, thus permitting Maillard condensation (Noguchi *et al.*, 1982).

With food mixes of low initial dextrose equivalent (DE $\leq$ 1) containing

TABLE 3

Lysine Content and Protein Quality of Extruded Wheat Flour and Whole Grain Wheat Flour as a Function of Extrusion Conditions[a,b]

	Wheat flour					*Whole grain wheat flour*		
Tm (°C)	161	161	171	171	156	164	166	166
% H_2O	15	15	15	15	15	20	20	20
RPM	150	100	150	200	150	100	150	200
F (g/min)	350	200	200	200	200	200	200	200
Lysine retention (% of lysine in corresponding raw wheat flour)[c]	100	96	75***	63***	75***	106	94	91*
True digestibility[d] ± SD	96·3 ± 0·9	95·5 ± 0·7	93·9 ± 2·1	93·5 ± 3·0	95·5 ± 1·3	nd	nd	84·4 ± 1·7**
Biological value[d] ± SD	50·6 ± 1·7	48·7 ± 2·0	40·2 ± 2·3***	37·6 ± 5·1***	40·8 ± 3·0	nd	nd	49·7 ± 2·9**
Net protein utilization[d] ± SD	48·7 ± 1·7	46·5 ± 1·8	37·8 ± 2·6***	35·3 ± 5·8***	39·0 ± 3·2	nd	nd	41·9 ± 1·7***

[a] After Björck *et al.* (1984*b*).
[b] Creusot-Loire BC 45 twin-screw extruder; *Tb* = 150 °C.
[c] The lysine contents of raw wheat flour and raw whole grain wheat flour were 2·4 and 3·2 g per 16 g N, respectively.
[d] TD, BV and NPU were, respectively, 94·4, 50·7 and 47·8 for raw wheat flour and 89, 55·8 and 49·6 for raw whole grain wheat flour.
Significant differences from the corresponding raw flour: ***, $P < 0{\cdot}001$; **, $P < 0{\cdot}01$; *, $P < 0{\cdot}05$.
nd, None determined.

starch but no sucrose, no nutritional damage is observed under mild processing (whole grain wheat flour, Creusot Loire BC 45, Tm = 125–165 °C, $\% H_2O$ = 12–18, *RPM* = 80–150, *F* = 300 g per min) (Harmuth-Hoene & Seiler, 1984). Under slightly more severe conditions, however (wheat flour and whole grain wheat flour, same extruder, Tm = 156–171 °C, $\% H_2O$ = 15 or 20, *RPM* ≥ 150, *F* = 200 g per min), serious decreases in the lysine content and in the protein biological value were noted (Table 3) (Björck *et al.*, 1984*b*). An increase in *RPM* decreased lysine content and biological value, while an increase in feed rate had opposite effects. An increase in feed rate is known to reduce the dispersion of residence times (and the mean residence time) and also to reduce heat transfer to the food mix.

It is not fully understood whether the damaging effects at low water contents are due to local temperature increases through intense shear forces, to specific mechanical effects (splitting of the glycosidic bonds of starch or of oligosaccharides, decrease in the diffusion barrier existing at low water content), to an enhancing effect of low moisture on the Maillard condensation, or to a combination of these effects. Reducing sugars can be formed from starch or oligosaccharides under severe extrusion conditions (see Linko *et al.*, 1981, and below). Model studies in rheometers permitting high shear stress at low moistures are needed to determine reaction kinetics, activation energies, effect of mix composition (pH, nature and concentration of starch, protein, oligosaccharides) and comparison of various time–temperature conditions.

In order to keep lysine losses within the 10–15 % limit accepted in bread baking or in the drum-cooking and drying of instant flours, it is necessary: (1) to avoid extrusion above 180 °C at water contents below 15 % (even if a subsequent oven-drying step is then necessary) and (2) to avoid the presence of reducing sugars during extrusion.

Research needed on recent applications of extrusion to protein foods or ingredients

New applications include: (1) manufacture of gelatin gel confectionery; (2) transformation of acid casein into sodium caseinate, at 100 °C and 20 % moisture (Millauer *et al.*, 1984*b*); (3) destruction of aflatoxin in peanut meal with 2 % NH_3 (Gréhaigne *et al.*, 1983; Van de Velde *et al.*, 1984); (4) chemical modification of proteins such as covalent attachment of fatty acids, etc.; (5) improvement in the functional properties of protein through mild mechanical/thermal processing; (6) pasteurization or sterilization (baby foods, concentrated viscous dairy preparations, animal blood) (Bouveresse *et al.*, 1982; Van de Velde *et al.*, 1984); (7) moist solubilization of collagen or keratin; (8) acid/mechanical hydrolysis of vegetable protein or fish mince as an initial step in sauce preparation; (9) wet-state texturization. Continuous gelation of soy proteins (Kitabatake *et al.*, 1985), continuous restructuring of mechanically deboned meat (Mégard *et al.*, 1985) and continuous emulsification of dairy products into process cheese, can all be achieved in a twin-screw extruder. Wet-state extrusion (40–85% water) does not induce high pressure, intense shear or expansion. Severe chemical changes and nutritional damage are therefore unlikely.

STARCH

Extensive investigations have dealt with the specific effects of extrusion-cooking on starch, as compared with those of boiling in water, autoclaving in steam, oven-baking or drum-cooking and drying.

Moist thermal treatments of cereal grains, pulses and starchy tubers induce physico-chemical modifications in starch granules and constituents that lead to (1) rheological and textural changes and (2) increased digestibility and availability as a source of energy.

Physico-chemical and chemical modifications: Starch gelatinization and hydrolysis

Extrusion-cooking, depending on process conditions and food mix composition, causes swelling and rupture of starch granules, modification of crystalline spectra and DSC peaks, cold water-solubility and reduced viscosity of starch and partial, to complete, release of amylose and amylopectin. Although it is difficult to give precisely the various combinations of temperature, moisture, shear and residence time which bring equivalent degrees of starch gelatinization when applied to different food mixes, complete starch gelatinization is generally achieved at $Tm \geq 120\,°C$, $\%H_2O = 20–30$, or even at lower moisture levels (10–20%), provided high shear and temperatures are reached during extrusion (Linko *et al.*, 1981).

Viscosity and molecular weight determinations clearly indicate that amylose and amylopectin are partly hydrolyzed to maltodextrins as a result of high shear extrusion of wheat starch (Tm = 180 °C, $\%_0 H_2O = 11$, $RPM = 270$) but not of drum-cooking (Colonna *et al.*, 1984*a*,*b*; Davidson *et al.*, 1984). In potato starch, free of lipids, amylose readily hydrolyses into linear maltodextrins of MW 2000 during extrusion (Mercier, 1977).

Starch constituents in cereal or legume flours may be more readily hydrolyzed than in purified starches, probably because endogenous amylases are active during the initial extrusion steps. However, the dextrose equivalent rarely exceeds 3 after extrusion unless the initial flour contains endogenous or added di- or oligosaccharides and/or the pH is lowered (Nierle *et al.*, 1980; Grébaut *et al.*, 1983; see above). The α-galactosides known to cause flatulence upon ingestion of legume seeds do not appear to be hydrolyzed during extrusion (de la Guérivière *et al.*, 1985).

Because of starch gelatinization and partial hydrolysis, extrusion-cooking is used to produce flours and starches with a whole range of functional and rheological properties. Precooked flours of reduced viscosity and increased solubility permit the preparation of weaning foods or gruels of higher concentration and calorie density as consumed (Harper & Jansen, 1985).

Crystalline complexes are known to form between amylose and polar lipids (fatty acids, mono- or diacylglycerols) during the extrusion of cereal starches (Mercier, 1980). Such complexes may improve functional properties (lower stickiness of snacks and biscuits, modified viscosity profiles, etc.). The formation of anhydroglucose end-chains has also been observed in extruded starch (Theander & Westerlund, 1984).

Increased *in vitro* enzymatic digestibility of starch

Björck *et al.* (1984*a*) indicate that mildly or severely extruded wheat flours (Creusot-Loire BC45, Tm = 161–171 °C, $\%_0 H_2O = 15$ or 20, $RPM = 100$–200, $F = 200$–350 g per min) are as available *in vitro* to α-amylase as autoclaved (125 °C, 20 min) controls, and more available than boiled (20 min)—and especially raw—controls. Extrusion probably increased the enzymatic availability of starch by way of gelatinization, inactivation of endogenous α-amylase inhibitor, disruption of cellular structure, size reduction and increased starch surface, partial separation from bran and protein.

The same extruded flours, when suspended in water and used for mouth rinse, were readily fermented to organic acids by microorganisms in the dental plaque, with resulting decreases in pH. Judging from this pH drop, extruded flours must be considered as more cariogenic than boiled or drum-cooked flours (especially if they are retained in the mouth because of their stickiness).

Increased *in vivo* digestibility of starch

Rat balance experiments showed that both raw wheat starch and extruded wheat starch (or starch from extruded wheat flours) were completely digested *in vivo*. However, these experiments do not allow us to distinguish between digestion plus absorption and bacterial fermentation in the colon (Björck *et al.*, 1984*a*).

The wheat flours that had been subjected to *in vitro* α-amylolysis were also investigated for *in vivo* starch absorption, as judged by plasma glucose and insulin levels within a 2-h period after gastric intubation of young rats. The plasma glucose responses varied in the following order of intensity: severe extrusion (Tm = 170 °C, $\% H_2O = 15$, $RPM = 200$) > mild extrusion (flat crispbread type) = boiling = soft bread baking > regular mild drum-cooking and drying (Asp & Björck, 1984; Björck *et al.*, 1984*a*).

Since slowly absorbed carbohydrates are considered as beneficial in relation to diabetes and obesity on account of a lower insulin need and a longer duration of satiety, it is of nutritional interest that extrusion conditions can influence the rate of starch absorption and the glycemic response to starch.

Amylose–polar lipid complexes resist α-amylase *in vitro* but were found to be completely (although slowly) digested and absorbed by rats (Holm *et al.*, 1983).

DIETARY FIBRE

Partial solubilization and increased fermentability

Cereals are an important source of dietary fibre. The behaviour of fibre components is therefore of interest when whole or extracted cereal flours are extruded into dietetic (e.g. bran-enriched) or regular flat bread, breakfast cereals, etc.

Modifications in particle size, solubility and chemical structure of the various fibre components could occur and cause changes in bacterial degradation in the intestine and in physiological properties.

Severe extrusion-cooking of wheat flours causes an apparent increase in dietary fibre due to the formation of amylase-resistant starch fractions. In order to avoid such artefacts, it is necessary to carry out extensive digestion with bacterial α-amylase (at high temperature), and with glucoamylase, before the gravimetric determination of fibre (Holm *et al.*, 1983; Björck *et al.*, 1984*c*). Under these analytical conditions, the total fibre content of whole grain wheat flour and of white wheat flour were 13 and 4% (w/w db), respectively.

Extrusion-cooking of white wheat flour (Tm = 161–171 °C, $\% H_2O = 15$, $RPM = 100$–200, $F = 200$ g per min) was found to cause a redistribution of insoluble to soluble dietary fibre (Björck *et al.*, 1984*c*). Thus 50–75% of total fibre were soluble in the extruded flour, depending on process conditions, versus 40% in the raw flour. Relative fibre solubilization was smaller in the case of extruded whole grain wheat flour.

Rat balance experiments showed that dietary fibre in raw white wheat flour was highly available to bacterial degradation since the fecal recovery of arabinose, xylose and glucose averaged a low 22%. After mild extrusion, the fecal recovery further decreased to 12%. The higher solubility is probably responsible for this increased fermentability. The fecal recovery of fibre constituents from raw whole grain wheat flour was higher (~42%) and remained unchanged after extrusion. Some chemical structures are therefore resistant to bacterial degradation *in vivo*, in spite of the intense shear treatment during extrusion.

The effects of extrusion and of other cooking processes on the physiological properties of dietary fibre (fecal bulking effect, accelerated transit time, improved glucose tolerance, lowered plasma lipids, chelating effects) deserve further investigation.

LIPIDS

Most extruded cereal foods contain less than 6–7% lipids immediately after extrusion, because high lipid levels prevent expansion. In contrast, small lipid levels (~5%) facilitate steady extrusion and improve the texture. Expanded extrudates can thus be considered as low calorie foods.

The nutritional value of lipids could be affected during extrusion as a result of oxidation, hydrogenation, isomerization or polymerization. According to Maga (1978), the extent of hydrogenation and *cis* → *trans* isomerization of fatty acids that takes place during extrusion is too small to be nutritionally significant.

Extrusion–inactivation of lipase and lipoxidase helps protect against oxidation during storage, but the porosity of expanded foods is detrimental with respect to rancidity.

Like bread-baking (kneading + baking), extrusion reduces the extractability of lipids. The recovery of lipid in extruded whole grain wheat flour (Creusot-Loire BC 45, Tm ~ 165 °C, $\% H_2O = 20$, $RPM = 100$–200, $F = 200$ g per min) ranged from 35 % to 43 % with chloroform/methanol. Amylose–polar lipid complexes may be partly responsible for this low extractibility. When acid hydrolysis was performed before extraction with organic solvents, the lipid content was the same before and after extrusion (Asp & Björck, 1984).

VITAMINS

Cereals constitute an important source of B-vitamins. The retention of these vitamins has been investigated during crispbread production in two Werner-Pfleiderer extruders: a Continua 58 (Tm = 178 °C, $\% H_2O =$ 16–24, $RT = 0{\cdot}5$–1 min, $F = 100$ kg/h) and a Continua 120 ($F = 500$ kg/h) and is reported in Table 4 (Millauer *et al.*, 1984). Two per cent of a vitamin

TABLE 4
Retention of Vitamins B after Extrusion of Crispbread[a]

Vitamin	*Initial vitamin content of food mix (mg per 100 g dry weight)*	*Retention (%)*	
		Continua 58	*Continua 120*
Folic acid	0·92	35–45	56
B_1	3·7	38–65	62
B_{12}	$11{\cdot}5 \times 10^{-3}$	65–96	99
B_6	4·2	71–83	90
Biotin	ni[b]	nd[c]	74
Niacinamide	ni	80	nd
B_2	ni	85	nd
Calcium pantothenate	ni	nd	91

[a] After Millauer *et al.* (1984*a*).
[b] ni, none indicated.
[c] nd, none determined.

mix were added to the crispbread formulation before extrusion. A linear relationship has been established between the per cent destruction of the most thermolabile B-vitamins (folic acid, B_1, B_{12} and B_6) and the energy input, which ranged from 0·09 to 0·13 kWh per kilogram of food mix. Both the energy input and the per cent destruction of a given vitamin (added to a food mix) could serve as quantitative indicators of the severity of extrusion processing and facilitate size extrapolation of extruders.

It is of interest that the final post-extrusion drying of the same crispbread did not cause more than 10% additional vitamin destruction.

Interesting data on the stability of carotenoid pigments (which are also vitamin A precursors) were obtained during extrusion and subsequent storage of corn starch (Creusot-Loire BC 45, Tm = 170–185 °C) (Berset *et al.*, 1984). Fifty to eighty milligrams of pigments were introduced per kilogram of corn starch before extrusion. Pigment retention was determined by spectrophotometric absorption after extraction (Table 5). Carotenoids resisted extrusion fairly well but some were further oxidized during storage, depending on their chemical structure. All *trans* β carotene was partly converted to 15-*cis* and 9-*cis* carotene as a result of extrusion, all three forms then decreasing during storage. The porosity of expanded extrudates probably increased oxidative sensitivity, as did

TABLE 5
Retention of Vitamin A Precursors after Extrusion of Corn Starch and Storage of Extrudates[a,b]

Vitamin precursor and/or pigment	*Retention (%)*		
	Immediately after extrusion	*After extrusion plus 3 weeks' storage*	*After extrusion plus 7 weeks' storage*
β carotene (commercial preparation No. 1)[c]	87	12	4
β carotene (commercial preparation No. 2)[d]	94	90	85
β apo 8′ carotenal	88	85	84
Canthaxanthine (not a vitamin A precusor)	82	70	50

[a] After Berset *et al.* (1984).
[b] Storage at room temperature, in the presence of air and absence of light.
[c] This preparation initially contained 90% of all *trans* β carotene.
[d] This preparation also contained 15-*cis* and 9-*cis* carotenes.

exposure to light. From the standpoint of colour and provitamin activity, β-apo 8′ carotenal appeared as the most useful derivative.

Protective measures, such as storage under vacuum or in nitrogen, and addition of anti-oxidants, may be necessary. Air exclusion or nitrogen flushing during extrusion are less feasible.

Twenty to forty per cent losses of vitamin C are consistently observed during extrusion, probably as a result of enhanced oxidation at high temperature. The iron content of the food mix may have a catalytic effect (Maga & Sizer, 1978). Process conditions influence the destruction of vitamin C.

The use of model systems and of rheometers is recommended to study the combined effects of temperature, shear, moisture and time on vitamin destruction in food mixes of different composition and low moisture levels. In extruders, an increase in screw speed may, for example, increase vitamin destruction at low moisture (because of shear-induced local temperature increases) but may decrease destruction at higher moisture (because the decrease in residence time then exerts a predominant effect). The benefits of HTST extrusion-cooking with respect to other processing methods are not clearly demonstrated for vitamin retention, perhaps because of inadequate analytical methods, multiple chemical forms of a given vitamin, variable initial level of endogenous or added vitamin, binding of vitamins to food constituents, or other difficulties. In addition, the change in nutritional availability of some B vitamins as a result of extrusion may not parallel the change in vitamin content.

Although extruders are used successfully for the industrial production of nutritionally balanced feeds and pet foods, it is advisable to carry out vitamin fortification after extrusion, whenever possible.

MINERALS

The digestibility and bioavailability of Fe, Cu, Zn and Mg is usually low in cereals and in leguminous seeds since these elements may be present as insoluble complexes with dietary fibres, phytate or proteins. When vegetable meat or bread substitutes are manufactured, it is desirable to ensure that the extrusion process does not reduce the solubility and bioavailability of endogenous or added minerals.

Data concerning minerals in extruded foods are scarce and partly contradictory and additional research is needed. A 13–35% reduction in phytate content was observed after extrusion of a wheat bran–starch–gluten mix (Andersson *et al.*, 1981). Phytate destruction takes place also during bread baking. The apparent availability of Zn, Cu and Mg was found to decrease in patients with ileostomy, after extrusion of wheat flour into crispbread (see Asp & Björck, 1984).

Minerals added for fortification should possess high bioavailability, mix homogeneously with the food ingredients and remain compatible with processing (calcium salts reduce expansion) and post-extrusion storage. Thus, ferrous sulphate has high solubility and bioavailability but catalyses lipid oxidation. Micronized elemental iron (particle size below 15 μm) is preferable.

Whether screw and barrel wear may cause significant iron or chromium levels in foods should be established during industrial production through weight determination of screw elements and frequency of replacement or resurfacing.

CONCLUSIONS

As a versatile and efficient industrial technology, extrusion-cooking is now used to process, mix, functionally improve, detoxify, sterilize and texturize an increasing variety of commodities and food ingredients over a wide range of moisture, shear, pressure, time and temperature conditions. Extrusion also permits the utilization and co-processing 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.

Severe extrusion conditions (temperature above 180 °C associated with moisture below 15%, high screw speed and low feed rate) or improper formulation (e.g. presence of reducing sugars) can indeed cause nutritional damage, given the usual residence time of 0·5–1 min in the hot screw segments. Recent investigations have highlighted many of the chemical mechanisms and processing conditions responsible for such damage. This knowledge, together with improved extruders and process control, will help in optimizing both organoleptic and nutritional quality.

It can be questioned whether an increased availability of extruded foods may significantly change dietary pattern and nutrient intake. Expanded snacks have been criticized for their ‘empty calories’, but they may be improved and they may also displace sugar confectionery in the diet of children. It is probably too early to say how extruded crispbread and TVP have modified the consumption of regular bread and of comminuted meat products.

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