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Source / Izvornik: **Journal of food and nutrition research, 2014, 53, 189 - 206**

Journal article, Published version
Rad u časopisu, Objavljena verzija rada (izdavačev PDF)

REVIEW

Improvement of nutritional and functional properties of extruded food products

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Summary

For the production of "snack" foods, maize, wheat, rye and rice are used as basic ingredients. With the development of extrusion technology, special attention is focused on the enrichment of extruded products with different ingredients like proteins, dietary fibre or bioactive compounds. Physical and sensory properties of the extrudates are strongly affected by adding ingredients rich in proteins or fibre. Extrusion parameters like temperature, screw speed and water content are crucial for obtaining an acceptable product. In this paper, review of the newest research and achievements in incorporating various raw materials that improve nutritional value of the extruded food products is presented.

Keywords

extrusion; extrudate; protein; dietary fibre; anthocyanin; carotenoid

Extrusion is predominantly a thermomechanical processing operation that combines several unit operations, including mixing, kneading, shearing, conveying, heating, cooling, forming, partial drying or puffing, depending on the material and equipment used [1]. Food extruders belong to the family of HTST-equipment (high temperature short time), capable of performing cooking tasks under high pressure. This is advantageous for vulnerable food as exposure to high temperatures for only a short time will restrict the unwanted denaturation effects on proteins, amino acids, vitamins, starch and enzymes [2]. The most used raw materials in the extrusion process are starch- and protein-based materials, which form the structure of the extruded products. Most products, such as breakfast cereals, snacks and biscuits, are formed from starch, while protein is used to produce products that have meat-like characteristics and that are used either as full or partial replacements for meat in ready meals and dried foods [3]. Extruded foods are composed mainly of cereals, starches and/or vegetable proteins. The major role of these ingredients is to give structure, texture, mouth feel, bulk and many other characteristics desired for the specific finished products. While maize starch provides all the features for production of highly acceptable extruded snack foods, its nutritional value is far from satisfying the needs of health-conscious consumers [4].

Functional food is any fresh or processed food that is claimed to have a health-promoting and/or disease-preventing property beyond the basic nutritional function of supplying nutrients. These foods may help prevent disease, reduce the risk of developing disease, or enhance health [5]. Functional foods can also be useful in making nutrients more available by providing particular dietary components in foods that will increase their availability and palatability beyond that which might normally be consumed [6]. Functional foods represent one of the most interesting areas of research and innovation in the food industry. In Europe, functional foods sales have increased significantly, although demand for functional foods within European Union varies considerably from country to country mainly due to food traditions and cultural heritage [7]. Extrusion is flexible in

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the production of new products, such as cereal baby foods, breakfast cereals, snack foods, bakery products or pasta. In order to combine the need of ready-to-eat products with the need for the consumption of high-value products, beneficial ingredients are added to the extruded mixtures [8].

A relevant issue is whether the consumers are willing to accept functional foods that taste worse than the corresponding conventional foods, and if so, what is their profile and what are the determinants of their willingness to compromise on taste [9]. Addition of high-fibre, high-protein alternate ingredients to starch was demonstrated to significantly affect the texture, expansion and overall acceptability of extruded snacks [4]. A scheme for the development of the extruded functional food was published by Guy [10]: Extruded products can promote weight loss by adding dietary fibre and resistant starch to the products, or can impact heart health by adding antioxidants and minimizing fat, or can promote immune protection by adding inulin and dairy protein.

Reviews of various chemical changes during extrusion were published by Cheftel [11], Camire et al. [12], Areas [13], Singh et al. [14], Brennan et al. [15] and Robin et al. [16]. These studies explain the nutritional changes of certain compounds. The aim of this paper is to review the research that cover different aspects of the extrudates fortification, with the accent not only on nutritional improvement, but also on physical and sensory properties of the extrudates, which are crucial for the actual acceptance. This paper contains an attempt to improve different nutritional characteristics: protein, fibre and bioactive compounds content.

IMPROVEMENT OF THE PROTEIN CONTENT OF THE EXTRUDATES

Raw ingredients usually used for extrusion contain considerable protein amounts, which vary from 6.0% to 10.3% in various types of flours such as barley, maize, rice, rye and wheat flour [17]. Soya and whey proteins are used for protein fortification of extrudates.

Protein nutritional value is dependent on the quantity, digestibility and availability of essential amino acids. Digestibility is considered as the most important determinant of protein quality in adults. The nutritional value in vegetable proteins is usually enhanced by mild extrusion cooking conditions, owing to an increase in digestibility. 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 [14]. Disulfide bonds are involved in stabilizing the native tertiary configurations of most proteins. Their disruption during extrusion aids in protein unfolding and thus digestibility [1]. Disulfide bonds break and reform, while new electrostatic and hydrophobic interactions promote aggregate formation [18]. The aggregation of soya protein subunits in extruded samples showed that hydrophobic interactions, hydrogen bonds, disulfide bonds and their interactions collectively hold the structure of extrudate; and the importance of non-covalent bonds outweighs covalent bonds. Increasing the food moisture content could increase the interactions between disulfide bonds and hydrogen bonds, and between disulfide bonds and hydrophobic interactions, reduce the degree of aggregation and the difference in protein-protein interactions and protein subunits among different zones within the extruder [19]. Increasing specific mechanical energy can enhance the extent of breakdown of soya protein aggregates and increase the proportion of the smaller fraction, which indicates that protein was disassociated/depolymerized by mechanical shear in extrusion cooking [20].

One major constraint in the utilization of protein-rich crops is the presence of a number of antinutritional compounds, in particular the trypsin inhibitor, phytic acid and tannins. Extrusion cooking is one effective method of inactivating the trypsin inhibitor and other antinutrients in food [21, 22].

Addition of soya protein and proteins of other legumes

A reappraisal effect of legume seed dietary intake is currently taking place. Soya proteins have been widely used as a functional ingredient in many processed foods because of their ability to form gels with high nutritional, sensory and physiological qualities [23]. The use of plant proteins, such as soya protein, instead of animal proteins is a cheaper and more viable intervention strategy to reduce the risk of coronary heart disease [24]. Animal and human studies have indicated that the presence of soya in the diet improves cardiovascular health and has particularly beneficial effects for those with elevated low density lipoproteins and hyperlipidemia [25, 26]. In recognition of the health-promoting properties of soya foods, the Food and Drug administration (FDA) allowed in 1999 food companies to use health claims on soya-derived foods containing at least 6.25 g of soy protein per serving [27]. Since FDA approval linking soya protein consumption to reductions in cholesterol level, there has been increased production, marketing and consumption of soybean and its products [24, 28]. It should be pointed out that European Food Safety Authority did not approve this health-claim [24].

Soybeans contain approximately 42% proteins, 20% lipids, 33% saccharides and 5% ash on dry basis [29]. The important issue is whether the addition of soya proteins makes the physical and sensory properties of the extrudates acceptable for consuming. Fortification of cereal-based snacks with soybean naturally has a positive effect on chemical properties. On the other hand, there is a negative effect on the physical and consequently sensory characteristics. Some examples are shown in Tab. 1. Addition of soybean to the extrusion mix led to poor product texture and, as a result, lowered the consumer acceptance. However, some conflicting findings have also been reported. The porous texture and crispness of the samples were improved by soya flour. Thus, the consumer panel showed better purchasing intent of the samples made from a mixture fortified with soybean.

Soya protein concentrate forms small uniform pores in the extruded products after being squeezed out of the die, as soya protein concentrate can work as high-quality emulsifier between hydrophilic and hydrophobic materials by exposing the hydrophilic and hydrophobic groups to their respective phases. The thickness of the wall of the pores becomes thinner when the amount of soya protein concentrate increases and the soya protein concentrate absorbs high amounts of water. Thus, it is logical to expect an increasing bulk density of the extrudates with increasing the protein and moisture contents. High density product naturally offers high breaking stress because air cell membrane of the extrudates becomes harder due to the high soya protein concentrate content [34].

The role of starch and proteins in compounded formulations for expanded snacks should also be considered [35]. Starch gelatinization during extrusion processing has a big influence on bulk density of extrudates. The low processing temperature decreases the extent of gelatinization, which leads to low swelling, low volume and high bulk density [34]. Starch-protein interactions also probably play an important role in affecting the expansion either indirectly through specific mechanical energy (*SME*), or directly by disrupting the continuous starch matrix and thus reducing the extensibility of cell walls. Water absorption index (*WAI*) and water solubility index (*WSI*) are related to the degree of starch fragmentation. Higher *WAI* indicates the presence of larger starch fragments, while higher *WSI* implies that starch has been dextrinized. In general, *WAI* decreases with increasing the soya protein concentrate level, mainly because of a reduction in the starch content. *WSI* appeared to increase with increasing soya protein content, which was confirmed by gel permeation chromatography. The addition of soya protein concentrate also depressed the *SME*, in particular at levels up to 10%. At that level, a drop in melt viscosity due to the lipid and fibre contents of the soya protein concentrate caused a reduction in *SME*. Beyond 10% soya protein concentrate, protein interaction effects had an increased contribution, counteracting the effects of lipids and fibre [35].

Mixing different ingredients to make a puffed ready-to-eat product using the extrusion process is difficult. Oat bran, for example, has a high level of lipids and soluble gum. Combination of oat bran, soya flour and maize starch is good for obtaining high-fibre, high-protein extrudate, but reduces the starch level in the mixture, which is undesirable due to the resulting increase in hardness. The addition of inulin showed a positive effect on the extrusion of the mixture. Inulin has low degree of polymerization and can provide a lubricating effect, which is essential to impart flow to mixtures during extrusion [36].

Lysine is the limiting essential amino acid in cereals [10]. Extrusion of a soya-sweet potato system might favour Maillard reaction and of course lysine loss due to the presence of both reducing saccharides and the epsilon-amino group of lysine. Losses were more pronounced at increasing levels of soya addition, as it has a higher lysine content than sweet potato. Increase in screw speed increased the lysine retention owing possibly to reduced residence time of the mixture in the extruder [37]. During extrusion of rice-based snack fortified with protein, increasing the raw material moisture and reducing the barrel temperature enhanced lysine retention, but the best expansion was at low moisture and high barrel temperatures. Interestingly, the protein and moisture contents of raw material and barrel temperature had no significant influence on cysteine and methionine contents [31].

High barrel temperatures and low moisture promote Maillard reactions during extrusion. Reducing saccharides, including those formed during shear of starch and saccharose, can react with lysine, thereby lowering the protein nutritional value [10].

Incorporation of disaccharides into soya-based formulations for extrusion resulted in a decrease of *SME* values, and the colour of the product changed depending on the employed disaccharide.

Tab. 1. Examples showing the effect of protein content and extrusion conditions on physical properties of the extrudates.

Raw materials	Process conditions	Critical factors	Physical properties		Reference
			Increase	Decrease	
White maize Partially defatted soybean (10–30%)	Feed moisture 20% Screw speed 31.4 $rad \cdot s^{-1}$ Temperature 200 °C	Increase of soybean content	Density Breaking strength Hardness	Expansion ratio	[30]
Rice flour Wheat gluten Toasted soya grits	Feed moisture 200–300 $g \cdot kg^{-1}$ Screw speed 41.9 $rad \cdot s^{-1}$ Temperature 150–180 °C	Increase of protein content		Expansion	[31]
		Increase of temperature	Expansion	Breaking strength	
		Increase of moisture content	Breaking strength		
Yellow maize flour Soybean flour (10–40%)	Moisture content 21–23% Screw speed 20.9–36.6 $rad \cdot s^{-1}$ Temperature 24 °C, 110 °C, 127 °C, 150 °C	Increase of soya flour content	Specific volume	Hardness	[32]
		Increase of moisture content	Hardness	Specific volume	
		Increase of screw speed	Specific volume	Hardness	
Maize flour Powder lycopene Soya protein concentrate (0–30%)	Moisture content 20–30% Temperature 100–150 °C	Increase of soya protein content		Hardness	[33]
		Increase of moisture content	Hardness	Expansion index	
		Increase of temperature	Hardness		
Maize flour Soya protein concentrate (322–666 $g \cdot kg^{-1}$)	Feed moisture 316–484 $g \cdot kg^{-1}$ Temperature 126.4–193.6 °C	Increase of soya protein content	Bulk density Breaking stress	Expansion ratio	[34]
		Increase of moisture content	Bulk density Breaking stress Expansion ratio (then decrease)	Expansion ratio (at first increase)	
		Increase of temperature	Expansion ratio (then decrease)	Bulk density Expansion ratio (at first increase)	
Maize starch Soya protein concentrate (0–20%)	Screw speed 24.1–34.6 $rad \cdot s^{-1}$	Increase of soya protein concentrate level	Bulk density	Expansion ratio	[35]
Maize starch Soya flour Oat bran	Temperature 130–160 °C Screw speed 7.33 $rad \cdot s^{-1}$	Increase of starch content	Expansion ratio	Hardness	[36]
		Increase of temperature	Expansion ratio	Hardness	
Maize : „hard to cook“ bean (60 : 40)	Moisture content 15.5–19.5 $g \cdot kg^{-1}$ Temperature 155–185 °C Screw speed 13.6 $rad \cdot s^{-1}$	Increase of temperature	Density	Expansion index	[41]
		Increase of moisture content	Density	Expansion index	
Brown rice Whole maize Lathyrus seeds (15%)	Moisture content 14% Screw speed 15.7 $rad \cdot s^{-1}$ Temperature 175 °C	The addition of *Lathyrus* seeds	Density	Expansion	[42]

The degree of Maillard reaction was higher for materials with lactose than for those with saccharose, due to the presence of free hydroxyl group in the anomeric carbon of lactose. In the early stage of the reaction, the formation of protein-saccharide conjugates leads to highly coloured and insoluble polymeric compounds [38].

Little is known of the effects that soya protein concentrate and acid-hydrolysed vegetable proteins, as ingredients, have on the odour of extruded cereal-based foods. The retention of compounds responsible for these ingredient odours could influence the acceptability of the final product. Furthermore, the interaction of the cereal base with non-volatile components, such as amino acids and fatty acids, during extrusion could lead to the production of additional odours. SOLINA et al. [39] demonstrated how combinations of ingredients, such as soya protein concentrate, and acid-hydrolysed vegetable protein (aHVP), at 1% level affect the odour of starch-based extrudates. For example, 39 compounds were identified in the starch/soya protein isolate/aHVP feedstock, with lipid-derived compounds dominating the volatile profile. Thirty-eight compounds were identified in the extrudate obtained at 150 °C, and 51 were found in that obtained at 180 °C. Lipid-derived compounds qualitatively dominated the volatile profile of both extrudates, followed by the Strecker aldehydes. Additionally, eight Maillard reaction products were identified in the extrudate obtained under extreme conditions. Qualitative sensory assessment of the extrudates showed that those obtained at 180 °C had relatively "stronger" odours.

Legumes are a cheap and valuable potential source of good quality protein. The nutritive value of legume proteins is low in comparison to animal proteins. This has been attributed to poor digestibility, deficiency of sulphur amino acids and the presence of antinutritional compounds. Legume extrusion cooking allows reduction of antinutritional factors and therefore improves the nutritional quality at a cost lower than other heating systems, due to a more efficient use of energy. Extrusion cooking of legumes such as fava bean, pea, chickpea and kidney bean was shown to improve the in vitro protein digestibility, enhance phosphorus availability, reduce tannins and polyphenols, and eliminate trypsin and α-amylase inhibitors. Treating soaked legumes by extrusion at 140 °C or 180 °C at 22% moisture improved the nutritive value of the studied legumes [40]. Extrusion cooking is of special interest for incorporating "hard-to-cook" beans into cereals. A blend of quality protein maize and "hard-to-cook" bean (60:40, w/w) was extruded at 155 °C, 170 °C and 185 °C and moisture content 155 $g \cdot kg^{-1}$, 175 $g \cdot kg^{-1}$ and 195 $g \cdot kg^{-1}$. This combination provided the blend with almost 15% protein, producing extrudates with good nutritional quality. Increased protein digestibility was observed at both temperatures tested (155 °C and 170 °C). Available lysine content decreased by 17.3% at 155 °C and by 26.9% at 170 °C [41]. Chemical composition of cereal-legume blends depends upon the cereal type as well. For example, changes in leucine and valine contents depend on the type of cereal: maize samples had a higher content of leucine than the rice samples, but the addition of wild legumes did not significantly affect the value. On the other hand, changes in lysine content depend both on the type of cereal and the type of legume. Rice samples showed higher lysine values than maize samples, and the addition of legume significantly increased lysine content [42].

Addition of whey protein to extrudates

Whey proteins are globular molecules with a substantial content of α-helix motifs, in which the acidic/basic and hydrophobic/hydrophilic amino acids are distributed in a fairly balanced way along their polypeptide chains [43]. The various proteins in whey in the order of abundance are β-lactoglobulin, α-lactalbumin, proteose, peptone, immunoglobulins, bovine serum albumin, lactoferrin and lactoperoxidase [44]. β-Lactoglobulin is more sensitive to extrusion treatment than α-lactalbumin, especially with increasing moisture content [45]. These proteins have many biological activities: cancer prevention, tumour cell vulnerability increase, antimicrobial activities and immunomodulation [43]. Whey proteins and amino acid supplements have a strong position in the sports nutrition market based on the purported quality of proteins and amino acids they provide. Several studies support the notion that only indispensable or essential amino acids are necessary to stimulate muscle protein synthesis and suggest that proteins, which provides a high portion of these amino acids, will be efficient in promoting muscle growth [46]. Not only is whey protein a good source of amino acids, but it is also a rich source of bioactive peptides generated during its digestion. Peptides shorter than four residues can cross intercellular junctions and reach the bloodstream, whereas larger peptides can be transported via peptide transporter-mediated transport system [44].

The high-protein, low-saccharide diet trend may be contributing to increased utilization of whey protein. Extruded whey protein has unique properties as a food ingredient. Compared to spray-dried whey protein, it is more amenable to introduction into food products [47].

Research of extrudates containing whey proteins mostly focuses on physical properties, since they directly influence the acceptance of the product. Twin-screw extrusion is preferred for starch-protein blends [48]. ONWULATA et al. [49] showed that the addition of whey proteins reduces expansion and consequently increases breaking strength. This has been ascribed to protein-protein interactions at higher levels of protein content. The protein fractions reinforce the product cell wall and increase breaking strength. Incorporation of whey products, whey protein concentrate (WPC) and sweet whey solids (SWS) at 25% or 50% in maize meal at high and low shear extrusion conditions was studied. Higher shear resulted in higher moisture loss, and in an increase in melt temperature from 120 °C to 128 °C. SWS reduced post extrusion product moisture. On the other hand, incorporation of the same whey products in potato flour gave different results. The product containing SWS and WPC at 50% bound considerably more water at higher shear.

Moisture content of the maize-whey protein concentrate blends also affects expansion. Especially hard extrudates were obtained at water intake 14.3 $l \cdot h^{-1}$ when the levels of whey protein concentrate were 15% and 22.5%. These samples showed uneven distribution of water and proteins after extrusion since the regular structure of maize flour, water and proteins could not be formed [50]. The effect of extrusion processing on extrudate expansion depends to a large extent on the flour, and the extrudate properties are generally unpredictable when milk proteins are incorporated in flours. ONWULATA et al. [51] showed that substituting WPC (250 $g \cdot kg^{-1}$ and 500 $g \cdot kg^{-1}$) for maize, potato or rice flours reduces the expansion, but some earlier works reported that substitution of WPC (200 $g \cdot kg^{-1}$) for rice flour increased the extrudate expansion. The same author showed that, by reducing the moisture and adding reverse screw elements, specific mechanical energy was increased, which increased the product expansion. The negative textural indicators associated with the inclusion of whey products can be improved significantly by adding wheat bran fibre at 125 $g \cdot kg^{-1}$. Addition of fibre improved *SME* along with the improvement of quality characteristics of the product [52].

Particle size also affects the extrusion of whey protein blends. The use of maize meal fractions that approximated the particle size of added whey protein concentrate resulted in viscosity increase in the extruder, which enhanced the expansion ratio and the porosity of the puffed product. The hardness of the expanded extrudates decreased, making the snack more easily broken. Under temperatures of 105–130 °C, screw speed 31.4 $rad \cdot s^{-1}$ and moisture 8.5%, the expansion of the smallest fraction ($< 250\ \mu m$) was equivalent to, or greater than, the extrudate made from maize meal alone [53].

The overall colour of the extrudates tended towards brownish with increasing the whey protein content. It is known that the main reason for the colour difference is the Maillard reaction between the reducing saccharides (lactose, dextrinized starch) and the whey proteins [48]. Addition of whey products at 25% to maize, potato and rice flour tended to increase total colour difference; addition of whey products at 50% lightened the colour [49].

IMPROVEMENT OF DIETARY FIBRE CONTENT OF EXTRUDATES

A problem in defining dietary fibre arises due to the lack of a universally accepted method to quantify all components of dietary fibre. American Association of Cereal Chemists defined dietary fibre as the edible parts of plants or analogous saccharides that are resistant to digestion and absorption in human small intestine, with complete or partial fermentation in large intestine [54]. The types of plant materials that are included within the definition may be divided into two forms based on their solubility: insoluble dietary fibres, which include cellulose, hemicelluloses and lignin, and soluble dietary fibres, which include β-glucans, pectin, gums, mucilages and some hemicelluloses. This definition includes only non-starch polysaccharides, but resistant starch also may be considered as a component of dietary fibre because it is determined within the total dietary fibre when measured by the approved AOAC method [54].

Dietary fibre decreases the risk for type 2 diabetes, cardiovascular disease and colon cancer by reducing the digestion and absorption of macronutrients and decreasing the contact time of carcinogens within the intestinal lumen [55]. Supplementation with dietary fibre can result in fitness-promoting foods, low in energy cholesterol and lipids. According to current recommendations, the average daily requirement of dietary fibre is 21–25 g per day for women and 30–38 g per day for men [56]. Dietary fibre has also important health benefits in childhood, especially in promoting normal laxation. Studies also suggest that dietary fibre in childhood may be useful in preventing and treating obesity, and also at lowering blood cholesterol level, both of which may help reduce the risk of future cardiovascular disease [57].

In general, refined cereal flours contain a low amount of fibre (between 2% and 5%). Whole grain flours contain a higher amount of fibre (between 10% and 15%). The highest quantity of fibre is found in the bran part of cereals (20–90%). In cereals, dietary fibre is mostly insoluble except for oat, in which about 50% of the fibre is soluble [58]. Cereal, fruit and vegetable by-products can be recovered and used as value-added products [56, 59].

Addition of dietary fibre from cereals

Barley plays a minor role in human nutrition, but products with new functional and nutritional properties are a precondition for higher acceptance of barley. β-Glucan is an important nutritional component of this cereal [60]. It was shown that β-glucan from barley is hypocholesterolemic, and this property may be a result of its ability to increase viscosity of the intestinal content. It is also a potent inductor of humoral and cell-mediated immunity [61].

Depolymerization of polysaccharides during extrusion is affected by increased shear stress. The molecular weight of β-glucan extracted from barley meal is 160 000. β-Glucan extracted from extruded barley preparations prepared at 22.5% moisture showed, depending on the extrusion temperature, the following molecular weights: 110 000 (130 °C), 125 000 (150 °C) and 80 000 (170 °C). Binding and immobilization of water is an important function of soluble dietary fibre. Due to their cellulose-like structure, β-glucans are only partly soluble. Conditions during extrusion increase water retention with the increase in the extrusion temperature. Extrusion also leads to a higher solubility of the barley material. In order to obtain good textural properties of the barley extrudate, moisture of 20.0–22.5% is preferable [60].

The formation of resistant starch during barley extrusion cannot be generalized. Faraj et al. [62] showed that extrusion at 100 °C increased the resistant starch content but, at lower temperatures (60 °C and 80 °C), resistant starch content decreased. This suggests that starch fragmentation readily occurs at 100 °C, leading to formation of amylose chains that could be incorporated into the crystalline structure of resistant starch type 3. Resistant starch type 3 is defined as retrograded starch fraction formed after cooking and storage [63]. Vasanthan et al. [64] reported the formation of this type of starch in extruded high-amylose barley flour, but did not observe any resistant starch type 3 in the extruded low-amylose barley flour. Huth et al. [60] reported that generation of resistant starch during extrusion was distinctly influenced by technical parameters. Highest contents of resistant starch were obtained by using a mass temperature of approximately 150 °C, and moisture of approximately 20%. Different results obtained in different studies can be explained in several ways:

- After relaxation of the cereal-based material when leaving die, retrogradation and re-crystallization occurred, which are a precondition for the formation of enzyme-resistant starch type 3 [60].
- The extrusion conditions, especially the shearing action of the extruder screw, may have caused degradation of the amylose into molecules of a smaller polymerization degree that could not be incorporated into a crystalline structure of resistant starch type 3.
- Flour is a complex system and other components such as proteins, β-glucans and/or pentosans may interfere with the formation of resistant starch type 3 [62].

Extrusion of barley flour may be, in a certain way, unacceptable for consumers because extrudates may have “bran” flavour. Mixing of barley with tomato pomace gave extrudates with a high preference level, especially with tomato pomace at a level of 10%. High extrusion temperature (160 °C) was preferable because a decrease in die temperature increased the product hardness [65].

For economic reasons, it may be particularly interesting to utilize by-products from other branches of the food industry, which are sources of components of high nutritional value. Brewers spent grain is an example of such a material, which contains around 52% of insoluble dietary fibre and 2.5% of soluble dietary fibre. An addition of brewers spent grain to maze grits at a level of 5–20% significantly increased the contents of all dietary fibre fractions. Addition of 10% increased almost three times the contents of all fractions of dietary fibre. The highest proportions were recorded for fractions of hemicellulose and cellulose [66]. Higher content of dietary fibre after extrusion in comparison to their theoretical contents was observed [64, 66, 67]. This could be explained by the formation of resistant starch and interactions of partly degraded substances, leading to formation of new complexes resistant to digestion [66].

Fibre increases the hardness of the extruded products, and decreases the expansion [51, 68, 69], as a result of its effect on cell wall thickness [70]. Thickening of cell walls results in a decreased air cell size in the microstructure of the extrudate. Another explanation could be that the breakdown of components into smaller particles, which might interfere with bubble expansion, reduced the extensibility of the cell walls and caused premature rupture of steam cells in the extrudate microstructure [71, 72]. At higher addition levels (20%), brewers spent grain caused almost two-fold increase in the bulk density, and very low expansion. Also, thus obtained product was characterized by a specific after-taste and aroma of brewers spent grain, so it required an addition of flavouring agents [66].

Wheat milling by products can also be used in "all-bran" breakfast extruded products. These products contain almost exclusively insoluble dietary fibre. The mechanical stress during the extrusion process should be responsible for the breakdown of polysaccharide bonds, leading to the release of oligosaccharides and, therefore, to the increase of soluble dietary fibre [73]. The increase of soluble fibre during extrusion cooking of maize fibre was also observed, due to transformation of some insoluble fibre components into soluble fibre during extrusion. Insoluble dietary fibre and total fibre contents slightly decreased at the same time [74]. Esposito et al. [73] showed the increase of insoluble dietary fibre also, which could be explained by gelatinization and retrogradation of the starch, which occurred during extrusion, and part of it could be changed into non-degradable polysaccharides. Besides that, the Maillard reaction that took place during extrusion led to the formation of a protein-polysaccharide complex, which was resistant to enzymatic degradation. According to the definition, these products cannot be considered as dietary fibre, but they behave as dietary fibre at the analytical determination and also physiologically. On the other hand, Vasanthan et al. [64] showed that the content of insoluble dietary fibre from two different types of barley increased in one case and decrease in another during extrusion. Extrusion of the oat bran also led to the increase of soluble dietary fibre, from 89 $g\cdot kg^{-1}$ to 95–142 $g\cdot kg^{-1}$, depending on extrusion conditions. Higher temperature (140 °C compared to 100 °C), and lower moisture (10% compared to 30%) caused a higher increase in the soluble dietaryfibre content [75].

Addition of dietary fibre from legumes

In recent years, cereals were used to prepare soluble dietary fibre in a number of studies, but the information about soybean or other legumes is scarce. Soybean residue, which is the main by-product from soymilk and tofu production, represents a good dietary fibre source. The content of total fibre in soybean residue is around 60%, while the soluble dietary fibre content is only 2–3%. Under an extrusion temperature of 115 °C, moisture of 31% and screw speed of 18.8 $rad\cdot s^{-1}$, the soluble dietary fibre content increased by 10.6% compared with the unextruded soybean residue. Heating also modified the structural characteristics of the fibre, hence enhancing its water and oil uptake abilities [76]. Increased levels of bean flour resulted in a significant decrease in expansion, compared to fibres of cereal origin. However, the type of bean significantly influenced the expansion. Navy bean flour fortification of maize-based extrudates produced slightly less expanded products than small red beans. This was probably due to the higher amount of fibre from seed coats in the flour of navy beans (navy: 15.2 g, small red 27.2 g, based on the weight of 100 seeds). The research showed that the replacement of maize starch by bean flour, regardless of cultivar, was feasible at a level of 30% [4].

Food and Agriculture Organization recommends a 30 : 70 ratio of leguminous and cereal flours. However, the sensory characteristics of certain blends may be negatively affected in combinations following this ratio [77]. Studies of the usage of some other legumes like chickpea, lentil and fenugreek have also been conducted [78–80]. The hardness of the extrudates decreased as chickpea proportion increased from 50% to 70%. The extruded product containing 80% chickpea flour was harder than that containing 70% chickpea flour. The extruded products made from 70 : 30 blends of chickpea and rice flour had highest expansion and lowest hardness value [78]. The chickpea-based snack products with high expansion ratio and low bulk density and hardness were obtained at low moisture, high screw speed and medium to high barrel temperature within the range of 15.3–18.7% moisture, screw speed 23.7–36.0 $rad\cdot s^{-1}$ and a temperature of 143–177 °C [79]. The addition of fenugreek, however, may not be suitable even at very low inclusion levels (2%) due to the pronounced bitter taste. However, the product containing 15% fenugreek polysaccharide was acceptable [78].

In order to prepare soluble dietary fibre from legumes, twin screw extrusion is preferable, since it is possible to extrude at lower temperatures, which require less energy. Besides that, twin-screw extrusion may reduce the extrusion time by increasing the screw speed [76].

Addition of dietary fibre from fruits and vegetables

The addition of broccoli and olive paste to maize extrudates was examined by Bisharat et al. [8]. The independent variables of the extrusion process (temperature, screw speed, feed moisture content, broccoli or olive paste content) significantly influenced the extrudate structural characteristics. Increase in temperature and screw speed caused a reduced mixture viscosity and increased starch gelatinization, leading to more porous products. Increase in moisture had a negative impact on starch gelatinization and reduced the porosity of the extrudates. The increase in the addition level of broccoli and olive paste reduced the porosity of the products due to their high fibre and protein contents. Extrudate expansion decreased as moisture content and additon level increased, while the increase in the screw speed resulted in more expanded products. The most appropriate conditions that produced products with higher expansion were 14% initial moisture content, 4% material content and 26.2 rad·s^{-1} screw speed. For maize-broccoli extrudates, the optimum temperature was 140 °C and for maize-olive paste extrudates it was 180 °C.

Stojceska et al. [68] demonstrated that the hardness of the extruded products was not related to the level of cauliflower, which was the only source that increased the level of dietary fibre. Sensory evaluation of same samples showed that extrudates containing 0–10% cauliflower were judged to be significantly more acceptable than samples containing 15–20% cauliflower. Stojceska et al. [71] increased the level of total dietary fibre in gluten-free products by incorporating a number of fruits and vegetables such as apple, beetroot, carrot, cranberry and gluten free teff (*Eragostris tef*) flour cereal. All the samples showed an increase in dietary fibre under all tested conditions. Increasing temperature increased the level of total dietary fibre while decreased lateral expansion. This was not in agreement with study of Stojceska et al. [68], where the decrease of total dietary fibre was detected after extrusion. The decrease was probably a result of solubilization and degradation of pectic substances.

The extrusion of orange pulp led to an increase in total pectin. Longer residence time (lower screw speed of 14.3 rad·s^{-1}) and moisture content of 27–33% were sufficient to cause alterations in the structure of protopectin, allowing both solubilization and release of the pectin [81]. Higher levels of the soluble fraction in total dietary fibre were found in concentrates of vegetables than in cereals, because total dietary fibre from vegetables has a greater affinity for water than cereal bran [67]. The extrusion conditions increased the amount of total dietary fibre in a blend of maize flour and red cabbage, but decreased in a blend of wheat flour and red cabbage. This was probably because maize starch has high amylose content, which resulted in resistant starch formation [67]. The extrusion increased the amount of total and soluble dietary fibre of sweet potato, especially compared to freeze-dried and hot air-dried samples [82].

ADDITION OF BIOACTIVE COMPONENTS

Phytochemicals as the bioactive non-nutrient compounds in fruits, vegetables, grains and other plant foods have been linked to the reduction in the risk of major chronic diseases. More than 5 000 phytochemicals have been identified, but a large number still remains unknown. However, convincing evidence suggests that the benefits of phytochemicals in fruits and vegetables may be even greater than is currently understood because oxidative stress induced by free radicals is involved in the etiology of a wide range of chronic diseases [83, 84]. For example, flavonoids possess antimicrobial, antiviral, anticarcinogenic and vasodilatory effects [85]. There is a rapidly growing body of literature covering the role of plant secondary metabolites in food and consumers are increasingly aware of diet health problems, therefore demanding natural ingredients that are expected to be safe and health-promoting [86].

Bioactive compounds in cereal grains

Cereal grains contain a large variety of substances that are biologically active, including antioxidants. The major portion of phenolic compounds is located in the outer parts of grains, where they are involved in the defence against ultraviolet radiation, pathogen invasion and in modification of mechanical properties [87]. The dominant phenolic acid found in wheat, barley and rye is ferulic acid, whereas in oat it is cumaric acid. Rye and oat contain also small quantities of sinapic and caffeic acids. The ester-bound phenolic acids are dominant when compared to free acids. The highest contents of both forms were found in rye (54.6 mg·kg^{-1}) and oat (30.1 mg·kg^{-1}).

The extrusion (20% moisture content, screw speed 52.4 rad·s^{-1}, barrel temperature 120–200 °C) caused an increase in all analysed free and ester-bound phenolic acids, except for sinapic and caffeic acids. The latter was not found in the hydrothermically processed grains [88]. Sharma et al. [89] reported a significant decrease in total phenolic content during barley flour extrusion. The reduction in total phenolic content may be attributed either to the decomposition of phenolic compounds due to the high extrusion temperature or alteration in the molecular structure of phenolic compounds that may lead to reduction in the chemical reactivity of phenolic compounds or decrease their extractability due to a certain degree of polymerization. It has also been reported that the phenolics may interact with the proteins and may not exhibit their actual value. An increase in phenolic content during extrusion indicates that extrusion conditions may liberate phenolic acids and their derivatives from the cell walls. Then, as a result, the liberated phenolic acids may contribute to a higher antioxidant potential [88].

Oats are unique among the common cereal grains by having a high lipid and protein contents, their lipolytic enzymes being 10–15 times more active than those of wheat. Endogenous phenolics in oats provide some protection, but processing prior to extrusion may damage those compounds, reducing their antioxidant effects. Natural phenolic compounds added to grains prior to extrusion may synergize and protect the endogenous antioxidants [90]. It may lead to formation of new antioxidants as well [91]. These added antioxidants would be evenly dispersed within the food matrix and be less likely to sublimate than butylated hydroxytoluene (BHT) or butylated hydroxyanisole, resulting in a delayed onset of lipid oxidation. Ferulic acid and benzoin at levels of 1 $g\cdot kg^{-1}$ were effective in delaying the onset of oxidation, while chlorogenic acid was ineffective, perhaps due to complex formation with iron from the screw wear [90]. Addition of cinnamic acid and vanillin protected maize snacks against lipid oxidation better than BHT without impairment of physical characteristics [91].

Incorporation of brewers spent grain to maize and wheat starch has been previously mentioned. It was found that the addition of brewers spent grain to the formulation has no significant effect on the phenolic content and antioxidant properties of the samples [67, 69, 70]. Esposito et al. [73] showed that antioxidant activity of durum wheat by-products was comparable to that of fruits and vegetables, because of the presence of fibre-bound phenol compounds.

Bioactive compounds from legumes

The significant occurrence of bioactive phenolic compounds, the relevant antioxidant capacities along with the interesting functional properties of dehydrated bean flour, make them useful for effective inclusion in the human diet [92]. Total polyphenols content in whole bean flour found by Delgado-Licon et al. [93] varied from 4.3 $g\cdot kg^{-1}$ to 17.4 $g\cdot kg^{-1}$ on dry matter basis. Whole bean flour and nixtamalized maize were mixed in a 60 : 40 proportion and extrusion was performed in different moisture (14.5–18.0%) and temperature (150–190 °C) conditions. The results showed that, after the extrusion, the contents of polyphenols remained high (15.1 $g\cdot kg^{-1}$ on dry matter basis, expressed as gallic acid equivalents) in the mixture extruded at 142 °C and a moisture of 16.3%. A correlation was observed between the best extrusion procedure, the contents of bioactive compounds and the antioxidant capacity of the end product.

The effect of extrusion on the total phenolic content of beans depends on bean cultivar [4, 94]. Korus et al. [94] found that Rawela cultivar (dark-red cultivar of *Phaseolus vulgaris*) showed a 14% increase in the amount of phenolics in extrudates compared to raw beans, while Tip-Top (black-brown cultivar of *P. vulgaris*) and Toffi (cream cultivar of *P. vulgaris*) exhibited a decrease by 19–21%, respectively. The same authors showed that the beans of all three cultivars extruded at a lower temperature (120 °C) retained a higher content of phenolics in total than those extruded at 180 °C. At both extrusion temperatures, smaller losses were noted in samples of higher initial moisture. The addition of navy and red bean flours to maize starch gave denser, less expanded and harder extrudates. Total phenols and antioxidant activities determined in the cooked products showed significant variation with respect to bean flour content and bean cultivar. Bean flour addition had a positive impact on the levels of these phytochemicals. However, fortification with small red bean flours was, to a great extent, more effective in producing extrudates with higher nutritional functionality. Extrusion (15.7 $rad\cdot s^{-1}$, 22% moisture, 160 °C) caused the reduction of total polyphenols in both cultivar mixtures [4]. In another study [95], changes in screw speed, feed rate and moisture content of the feed had no effect on the content of total phenolic compounds in a mixture of chickpea flour (30%), maize flour (20%), oat flour (20%), maize starch (15%), carrot powder (10%) and hazelnut (5%). Although the total phenolic compounds did not change during extrusion, the antioxidant capacity values were affected, probably as a result of degradation of antioxidant compounds other than the phenolic compounds.

Bioactive compounds from fruits and vegetables

Anthocyanins

Anthocyanins are water-soluble pigments responsible for the red, blue and purple colours in many food crops [96]. They are well-known alternatives to synthetic dyes [97]. Natural colours have several disadvantages such as a high price, extraction difficulty and discolouration during processing. Artificial colours are inexpensive and are superior to natural extracts in tinctorial strength, hue and stability. Although the consumer awareness of health-related risks of artificial colour additives has increased, artificial colours are still used more frequently than natural colours in many processed foods [98].

Breakfast cereals coloured with natural fruits may appeal to consumers interested in healthy food. Whole yellow maize is a good source of phenolic compounds, but milling may remove some endogenous antioxidants such as phenolics and thus addition of other antioxidants to maize should improve the shelf life [99]. Moreover, as for flavonoids and related phenolics, both antiradical and antioxidant activities contribute to explaining the protective effect of vegetable-rich diets on coronary diseases [97].

When blueberry, cranberry, raspberry powder and Concord grape juice concentrate at a level of 1% were mixed with white maize meal, saccharose and citric acid, a significant loss of the phenolics occurred during extrusion. Considering the anthocyanin content of the fruit powders, there was an apparent loss of about 90% of the pigments in all fruits except for raspberry. However, blueberry cereals had the highest content of anthocyanins and phenolics. Antioxidant activity was not significantly correlated with either anthocyanin or phenolic contents. Possible explanation is that Maillard browning during extrusion and/or storage was suppressed by fruit powders, thus reducing one source of antioxidants [99]. Similar results were obtained by Camire et al. [96], who studied blueberry and grape juice concentrates mixed with maize meal. Extrusion caused a decrease in the content of blueberry anthocyanins by 90% and grape anthocyanins by 74%. Extrusion also decreased colour density in blueberry samples (by 78%) and grape samples (by 70%). Blueberry samples had a higher anthocyanin content (40 $mg\cdot kg^{-1}$, dry basis) and presented darker and redder colour than grape samples (26 $mg\cdot kg^{-1}$, dry basis).

Sensory evaluation showed that overall acceptability was highly correlated with sweetness, hardness and flavour. Blueberry samples received the lowest score on overall acceptability. Blueberry concentrate provided tartness that may have interfered with the sweetness of the product. Thus, if bright colour is major objective, blueberry should be used, but improvements in sweetness and flavour are needed [96]. Khanal et al. [100] showed that temperature and screw speed, but not their interaction, affected total anthocyanin contents during extrusion of grape pomace and white sorghum flour at a ratio of 30 : 70. Increasing the extrusion temperature decreased anthocyanin content linearly, and similar effect was found by White et al. [101]. Increase in the screw speed from 10.5 $rad\cdot s^{-1}$ to 20.1 $rad\cdot s^{-1}$ reduced the residence time of the material inside the extruder barrel, thus minimizing the exposure to high temperatures. The reduction in total anthocyanins content was between 18% and 53% [100].

The extrusion of cranberry pomace with maize starch in ratios of 30 : 70, 40 : 60 and 50 : 50, at temperatures 150–190 °C and screw speed 15.7 $rad\cdot s^{-1}$ and 20.9 $rad\cdot s^{-1}$ showed that anthocyanin losses were highly dependent on the level of pomace. The minimum loss in anthocyanins was observed in the mixture containing only 30% pomace, with only 50% of anthocyanins lost. Extrudates containing 50% pomace had only 35% retention. This suggests possible protection by the starch present in the extrudate mixture. The antioxidant capacity of the extrudates increased at higher temperatures due to the formation of Maillard reaction products, which possess reducing capacity [101]. Durghe et al. [102] showed that, besides temperature and screw speed, moisture content has a positive effect on anthocyanin retention.

Sensory evaluation of the extrudates obtained from red carrot powder (1–3%, w/w) and rice flour showed good acceptance of all samples. The best sensory score was not in correlation with the colour retention of the anthocyanins. The addition of 2% citric acid increased the colour retention from 41% to 63%, but the extrudates were very sour and sensorially unacceptable. The addition of 1% citric acid was also useful (retention 59%), and showed much better results. The addition of ascorbic acid (0%, 0.1% and 1%) to the mixture containing maize meal, saccharose (15%) and blueberry concentrate (17%) showed that fortification by ascorbic acid accelerated anthocyanin degradation during extrusion. This might be due to interaction of ascorbic acid oxidation products with anthocyanins or to a direct condensation and enhanced polymeric pigment formation. The sensory evaluation of samples showed that the fruit flavour was not strong enough, but the mild acidity provided by ascorbic acid contributed to the impression of fruit flavour [103].

Carotenoids

β-Carotene is not only an important and safe source of vitamin A, but also a useful food colour. There is considerable evidence that β-carotene, being a highly active singlet oxygen quencher, may play an important role in the prophylaxis of free radical-mediated diseases [104].

In order to investigate processing losses due to the sensitivity of phytochemicals, β-carotene was incorporated into an extrusion-cooked cereal-based products. Process-induced stresses were varied by using different dosing points, screw speeds and barrel temperatures. Results showed degradation of β-carotene by oxidation driven by thermal and mechanical stresses. When the solution was incorporated at the end of the extruder, the β-carotene molecules were exposed to mechanical and thermal stresses for a shorter time, which resulted in by 10% higher retention of the total content as compared to an application prior to starch plastification. Increasing the melt temperature from 135 °C to 170 °C did not show any influence on the β-carotene retention. Increasing the screw speed from 31.4 rad·s^{-1} to 52.4 rad·s^{-1} increased the retention significantly by about 25%. These results suggested that β-carotene losses were mainly caused by the generated mechanical stress rather than thermal stress [105].

Shih et al. [106] compared the β-carotene losses from sweet potato, during extrusion cooking, hot-air drying and freeze drying. For orange and yellow sweet potato, the β-carotene contents of hot air-dried and extruded samples were significantly lower than those of freeze-dried samples. The mixing of sweet potato flour with the rice flour showed that losses of carotenoids were lower in mixed flours (2.6–3.8% for the orange variety and 9.9–16.2% for the cream variety) than in the single sweet potato flour (20.8–27.9% for the orange variety and 41.0–60.4% for the cream one). Proteins and lipids from rice flour form a carotene-lipid-protein net protecting carotenoids from thermal denaturation. Losses of total carotenoids were higher in the extruded product with low feeder flow rate and low screw speed [107].

The addition of different antioxidants (BHT, rosemary oleoresin, α-tocoferol) in β-carotene-maize starch extrudates was investigated by Berset et al. [108]. In order to reach the level of BHT efficacy, natural antioxidants had to be used at high contents. In the case of aromatic herbs such as rosemary, the oleoresin at a dosage 1000 mg·kg^{-1} imparted a strong and undesirable taste to snacks.

Tomato derivatives (tomato skin powder, paste powder) were incorporated in maize, wheat and rice extruded snacks. Incorporation reduced the expansion values of up to 25% compared to the controls [109]. This was also confirmed by Altan et al. [65], in whose study increasing the level of tomato pomace (0–12.7%) in barley flour resulted in a decrease in expansion index of extrudates. Expansion was positively correlated with *SME* and, since the incorporation of tomato derivatives lubricated the melt and therefore dropped *SME* and torque, the expansion was also decreased. Rice flour produced the most expanded products due to the high starch and lower fibre and lipid contents compared to maize grits and wheat semolina. Although lycopene retention in products containing tomato skin was much higher than for products containing tomato paste, the mean value in products containing tomato skin was only about 15% that of products containing tomato paste, due to much higher initial content of lycopene in the tomato paste. The degradation of lycopene was greatest for extruded products containing wheat, which had a lower starch content that might provide some protection to lycopene. The effect of temperature (140–180 °C) on expansion was not significant [109]. Different results were obtained by Altan et al. [65] during extrusion of barley flour and tomato pomace. Sectional expansion index decreased when the temperature was increased (133.2–166.8 °C). This could be attributed to increased dextrinization and structure weakening.

Sensory evaluation showed that extrudates with 10% tomato pomace had the highest level of acceptance for colour, texture and overall acceptability. However, the tomato flavour was perceived as weak for the highest level of pomace. Huang et al. [110] incorporated tomato powder in maize grits. Results showed that moisture content (10–16%) had a significant effect on the expansion, the best expansion being obtained at a medium moisture level and at medium levels of tomato powder. The addition of tomato powder linearly increased the hardness of the extrudates.

INFLUENCE OF PROCESS CONDITIONS ON EXTRUDED FOOD PRODUCTS

As mentioned earlier, extrusion belongs to the family of HTST processes, which is advantageous for vulnerable food as exposure to high temperatures for only a short time will restrict unwanted effects on proteins, amino acids, vitamins and starch [2]. In the extrusion process, there are generally two main energy inputs to the system: energy transferred from the rotation of the screws and the energy transferred from the heaters [1]. Effects of various process variables (moisture content, temperature, screw configuration and rotation) on extrusion behaviour of extrudate components have been extensively studied [45, 53, 65, 93, 111, 112]. Tab. 2 presents changes of the extrudate nutrients taking place during the extrusion and

Tab. 2. Influence of process conditions on the content of nutrients in the extrudate during extrusion [2].

Increase of process component	Nutrient content					
	Protein (lysine)	Starch		Vitamin		
		Gelatinization	Depolymerization	B_1	B_2	C
Temperature	–	+	+	– x	+ x	–
Moisture content	+	+ *		+	– x	– **
Screw rotation	– x	–		– x	–	–
Screw geometry	–		+	–		–
Die diameter	+	–		+ x	x	+
Torque, extrusion pressure	–		+			x

(+) – increase, (–) – loss, (x) – no effect, (*) – high temperature, (**) – high temperature and low moisture content.

their dependence on the process conditions.

Temperature and moisture increase reduces viscosity of the mixture and increase starch gelatinization, leading to more porous products [8]. Increasing screw speed and the die size results in reduced gelatinization (due to a decrease in the retention time of the sample in the extruder), which leads to low swelling, low volume and high bulk density [1, 34]. A study [51] showed that by reducing the moisture and adding reverse screw elements, specific mechanical energy was increased, which increased product expansion. ALTAN et al. [111] reported that severe screw configuration produced more expanded product with low bulk density than that obtained at medium screw configuration.

WAI data for maize, wheat and rice products showed a gradual increase with an increase in the barrel temperature, reaching a maximum at around 180 °C [1]. *WAI* and soluble dietary fibre content of many extruded products increased with increasing temperature in the extruder [2, 75]. JOZINOVIĆ et al. [112] showed that lower moisture content and screw configuration 4:1 (compared to 1:1) resulted in more expanded products. Depolymerization of polysaccharides during extrusion increased with an increase in shear stress and temperature [2, 73]. In addition, lower moisture content of the raw material led to an increase in depolymerisation of polysaccharides as well.

Twin-screw extrusion is preferred for starch-protein blends [48]. In order to prepare soluble dietary fibre from legumes, twin-screw extrusion is preferable, since it is possible to extrude at lower temperatures, which require less energy. Besides that, twin-screw extrusion can reduce the extrusion time by increasing the screw speed [76]. Increasing *SME* can enhance the extent of breakdown of soya protein aggregates and increase the proportion of smaller fraction [20]. Extrusion of materials containing proteins and reducing saccharides usually leads to deterioration of the nutritional characteristics of proteins. This phenomenon is primarily due to Maillard reactions. Increasing temperature and pressure, or lowering moisture, promotes Maillard reactions during extrusion [2].

CONCLUSIONS

Enrichment of the extruded snacks with nutritionally valuable ingredients is increasingly practised. Incorporation of protein- or fibre-rich ingredients influences physical properties of the extrudates, but the influence cannot be generalized because it strongly depends upon the cereal and the additional material used. Optimization of the process parameters such as temperature, moisture content or screw speed, is the key for developing nutritious extruded products with the adequate consumer acceptance. Although this review summarizes results of many studies on this topic, there is still a long way from research to commercial production of this kind of products.

REFERENCES

1. Brennan, J. G. – Grandison, A.: Food processing handbook. 2nd ed. Weinheim : Wiley-VCH, 2012. 777 pp. ISBN 978-3-527-32468-2.
2. Moscicki, L.: Extrusion-cooking techniques: Applications, theory and sustainability. Weinheim: Wiley-VCH, 2011. 234 pp. ISBN 978-3-527-32888-8.
3. Steel, C. J. – Leoro, M. G. V. – Schmiele, M. – Ferreira, R. E. – Chang, Y. K.: Thermoplastic extrusion in food processing. In: El-Sonbati, A. Z. (Ed.): Thermoplastic elastomers. Rijeka : Intechopen, 2012, pp. 265–290. ISBN 978-953-51-0346-2. DOI: 10.5772/2038.
4. Anton, A. A. – Fulcher, R. G. – Arntfield S. D.: Physical and nutritional impact of fortification of corn starch-based extruded snacks with common

bean (*Phaseolus vulgaris* L.) flour: Effects of bean addition and extrusion cooking. Food Chemistry, *113*, 2009, pp. 989–996. DOI: 10.1016/j.foodchem.2008.08.050.
5. Arias-Aranda, D. – Romerosa-Martinez M. M.: Innovation in the functional foods industry in a peripheral region of the European Union: Andalusia (Spain). Food Policy, *35*, 2010, pp. 240–246. DOI: 10.1016/j.foodpol.2009.12.008.
6. Spence, J. T.: Challenges related to the composition of functional foods. Journal of Food Composition and Analysis, *19*, 2006, pp. S4–S6. DOI: 10.1016/j.jfca.2005.11.007.
7. Annunziata, A. – Vecchio, R.: Functional foods development in the European market: A consumer perspective. Journal of Functional Foods, *3*, 2011, pp. 223–228. DOI: 10.1016/j.jff.2011.03.011.
8. Bisharat, G. I. – Oikonomopoulou, V. P. – Panagiotou, N. M. – Krokida, M. K. – Maroulis, Z. B.: Effect of extrusion conditions on the structural properties of corn extrudates enriched with dehydrated vegetables. Food Research International, *53*, 2013, pp. 1–14. DOI: 10.1016/j.foodres.2013.03.043.
9. Verbeke, W.: Functional foods: Consumer willingness to compromise on taste for health? Food Quality and Preference, *17*, 2006, pp. 126–131. DOI: 10.1016/j.foodqual.2005.03.003.
10. Guy, R.: Extrusion cooking technologies and applications. Boca Raton : CRC Press, 2001. 199 pp. ISBN 1-85573-559-8.
11. Cheftel, J. C.: Nutritional effects of extrusion cooking. Food Chemistry, *20*, 1986, pp. 263–283. DOI: 10.1016/0308-8146(86)90096-8.
12. Camire, M. E. – Camire, A. L. –Krumhar, K.: Chemical and nutritional changes in foods during extrusion. Critical Reviews in Food Science and Nutrition, *29*, 1990, pp. 35–57. DOI: 10.1080/10408399009527513.
13. Areas, J. A. G.: Extrusion of proteins. Critical Reviews in Food Science and Nutrition, *32*, 1992, pp. 365–392. DOI:10.1080/10408399209527604.
14. Singh, S. – Gamlath, S. – Wakeling, L.: Nutritional aspects of food extrusion: a review. International Journal of Food Science and Technology, *42*, 2007, pp. 916–929. DOI: 10.1111/j.1365-2621.2006.01309.x.
15. Brennan, C. – Brennan, M. – Derbyshire, E. – Tiwari, B. K.: Effects of extrusion on the polyphenols, vitamins and antioxidant activity of foods. Trends in Food Science and Technology, *22*, 2011, pp. 570–575. DOI: 10.1016/j.tifs.2011.05.007.
16. Robin, F. – Schuchmann, H. P. – Palzer, S.: Dietary fiber in extruded cereals: limitations and opportunities. Trends in Food Science & Technology, *28*, 2012, pp. 23–32. DOI: 10.1016/j.tifs.2012.06.008.
17. Brnčić, M. – Ježek, D. – Rimac Brnčić, S. – Bosiljkov, T. – Tripalo, B.: Influence of whey protein concentrate addition on textural properties of corn flour extrudates. Mljekarstvo, *58*, 2008, pp. 131–149.
18. Shahidi, F. – Ho, C. – Von Chuyen, N.: Process-induced chemical changes in food. New York : Plenum Press, 1998. 361 pp. ISBN 0-306-45824-1.
19. Chen, F. L. – Wei, Y. M. – Zhang, B.: Chemical cross-linking and molecular aggregation of soybean protein during extrusion cooking at low and high moisture content. Food Science and Technology, *44*, 2011, pp. 957–962. DOI: 10.1016/j.lwt.2010.12.008.
20. Fang, Y. – Zhang, B. – Wei, Y. – Li, S.: Effects of specific mechanical energy on soy protein aggregation during extrusion process studied by size exclusion chromatography coupled with multi-angle laser light scattering. Journal of Food Engineering, *115*, 2013, pp. 220–225. DOI: 10.1016/j.jfoodeng.2012.10.017.
21. Nwabueze, T. U.: Effect of process variables on trypsin inhibitor activity (TIA), phytic acid and tannin content of extruded African breadfruit-corn-soy mixtures: A response surface analysis. LWT–Food Science and Technology, *40*, 2007, pp. 21–29. DOI: 10.1016/j.lwt.2005.10.004.
22. van den Haut, R. – Jonkers, J. – van Vilet, T. – van Zuilchem, D. J. – van ‘T Riet, K.: Influence of extrusion shear forces on the inactivation of trypsin inhibitors in soy flour. Food and Bioproducts Processing, *76*, 1998, pp. 155–161. DOI: 10.1205/096030898531972.
23. Mesa, D. M. – Silvan, J. M. – Olza, J. – Gil, A. – del Castillo, M. D.: Antioxidant properties of soy protein-fructooligosaccharide glycation systems and its hydrolyzates. Food Research International, *41*, 2008, pp. 606–615. DOI: 10.1016/j.foodres.2008.03.010.
24. Girgih, A. T. – Myrie, S. B. – Aluko, R. E. – Jones, P. J. H.: Is category A status assigned to soy protein and coronary heart disease risk reduction health claim by the United States Food and Drug Administration still justifiable? Trends in Food Science and Technology, *30*, 2013, pp. 121–132. DOI: 10.1016/j.tifs.2012.12.003.
25. Marsh, T. G. – Straub, R. K. – Villalobos, F. – Young Hong, M.: Soy protein supports cardiovascular health by downregulating hydroxymethylglutaryl-coenzyme A reductase and sterol regulatory element-binding protein 2 and increasing antioxidant enzyme activity in rats with dextran sodium sulphate-induced mild systemic inflammation. Nutrition Research, *31*, 2011, pp. 922–928. DOI: 10.1016/j.nutres.2011.09.027.
26. Wang Y. – Jones, P. J. H. – Ausman, L. M. – Lichtenstein, A. H.: Soy protein reduces triglyceride levels and triglyceride fatty acid fractional synthesis rate in hypercholesterolemic subjects. Atherosclerosis, *173*, 2004, pp. 269–275. DOI: 10.1016/j.atherosclerosis.2003.12.015.
27. Bong Chang, J. – Moon, W. – Balasubramanian, S. K.: Consumer valuation of health attributes for soy-based food: A choice modelling approach. Food Policy, *37*, 2012, pp. 335–342. DOI: 10.1016/j.foodpol.2012.03.001.
28. Molina, V. – Medici, M. – Font de Valez, G. – Taranto, M. P.: Soybean-based functional food with vitamin B12-producing lactic acid bacteria. Journal of Functional Foods, *4*, 2012, pp. 831–836. DOI: 10.1016/j.jff.2012.05.011.
29. Zhang, J. – Mungara, P. – Jane, J.: Mechanical and thermal properties of extruded soy protein sheets. Polymer, *42*, 2001, pp. 2569–2578. DOI: 10.1016/

S0032-3861(00)00624-8.
30. Obatolu Veronica, A. – Omueti Olusola, O. – Adebowale, E. A.: Qualities of extruded puffed snacks from maize/soybean mixture. Journal of Food Processing Engineering, *29*, 2006, pp. 149–161. DOI: 10.1111/j.1745-4530.2006.00054.x.
31. Chaiyakul, S. – Jangchud, K. – Jangchud, A. – Wuttijumnong, P. – Winger, R.: Effect of extrusion conditions on physical and chemical properties of high protein glutinous rice-based snask. LWT–Food Science and Technology, *42*, 2009, pp. 781–787. DOI: 10.1016/j.lwt.2008.09.011.
32. Li, S. – Zhang, H. Q. – Jin, Z. T. – Hsieh, F.: Textural modification of soya bean/corn extrudates as affected by moisture content, screw speed and soya bean concentration. International Journal of Food Science and Technology, *40*, 2005, pp. 731–741. DOI: 10.1111/j.1365-2621.2005.00993.x.
33. Da Costa, P. F. P. – Ferraz, M. B. M. – Ros-Polski, V. – Quast, E. – Collares Queiroz, F. P. – Steel, C. J.: Functional extruded snacks with lycopene and soy protein. Ciencia e Technologia de Alimentos, *30*, 2010, pp. 143–151. DOI: 10.1590/S0101-20612010005000017
34. Yu, L. – Ramaswamy, H. S. – Boye, J.: Protein rich extruded products prepared from soy protein isolate-corn flour blends. LWT–Food Science and Technology, *50*, 2013, pp. 279–289. DOI: 10.1016/j.lwt.2012.05.012.
35. De Mesa, N. J. – Alavi, S. – Singh, N. – Shi, V. – Dogan, H. – Sang, Y.: Soy protein-fortified expanded extrudates: Baseline study using normal corn starch. Journal of Food Engineering, *90*, 2009, pp. 262–270. DOI: 10.1016/j.jfoodeng.2008.06.032.
36. Lobato, L. P. – Anibal, D. – Lazaretti, M. M. – Grossman, M. V. E.: Extruded puffed functional ingredient with oat bran and soy flour. LWT–Food Science and Technology, *44*, 2011, pp. 933–939. DOI: 10.1016/j.lwt.2010.11.013.
37. Iwe, M. O. – Zuilichem, D. J. – Stolp, W. – Ngoddy, P. O.: Effect of extrusion cooking of soy-sweet potato mixtures on available lysine content and browning index of extrudates. Journal of Food Engineering, *62*, 2004, pp. 143–150. DOI: 10.1016/S0260-8774(03)00212-7.
38. Guerrero, P. – Beatty, E. – Kerry, J. P. – de la Caba, K.: Extrusion of soy protein with gelatine and sugars at low moisture content. Journal of Food Engineering, *110*, 2012, pp. 53–59. DOI: 10.1016/j.jfoodeng.2011.12.009.
39. Solina, M. – Johnson, R. L. – Whitfeld, F. B.: Effect of soy protein isolate, acid hydrolysed vegetable protein and glucose on the volatile components of extruded wheat starch. Food Chemistry, *104*, 2007, pp. 1522–1538. DOI: 10.1016/j.foodchem.2007.02.031.
40. Abd El-Hady, E. A. – Habiba, R. A.: Effect of soaking and extrusion conditions on antinutrients and protein digestibility of legume seeds. LWT–Food Science and Technology, *36*, 2003, pp. 285–293. DOI: 10.1016/S0023-6438(02)00217-7.
41. Ruiz-Ruiz, J. – Martinez-Ayala, A. – Drago, S. – Gonzalez, R. – Betancur-Ancona, D. – Chel-Guerrero, L.: Extrusion of a hard to cook bean (*Phaseolus vulgaris* L.) and quality protein maize (*Zea mays* L.) flour blend. LWT–Food Science and Technology, *41*, 2008, pp. 1799–1807. DOI: 10.1016/j.lwt.2008.01.005.
42. Pastor-Cavada, E. – Drago, S. R. – Gonzalez, R. J. – Juan, R. – Pastor, J. E. – Alaiz, M. – Vioque, J.: Effects of the addition of wild legumes (*Lathyrus annuus* and *Lathyrus clymenum*) on the physical and nutritional properties of extruded products based on whole corn and brown rice. Food Chemistry, *128*, 2011, pp. 961–967. DOI: 10.1016/j.foodchem.2011.03.126
43. Madureira, A. R. – Pereira, C. I. – Gomes, A. M. P. – Pintado, M. E. – Malcata, F. X.: Bovine whey proteins – Overview on their main biological properties. Food Research International, *40*, 2007, pp. 1197–1211. DOI: 10.1016/j.foodres.2007.07.005.
44. Jakubowicz, D. – Froy, O.: Biochemical and metabolic mechanisms by which dietary whey protein may combat obesity and Type 2 diabetes. Journal of Nutritional Biochemistry, *24*, 2013, pp. 1–5. DOI: 10.1016/j.jnutbio.2012.07.008.
45. Qi, P. X. – Onwulata, C. I.: Physical properties, molecular structures, and protein quality of texturized whey protein isolate: Effect of extrusion moisture content. Journal of Dairy Science, *94*, 2011, pp. 2231–2244. DOI: 10.3168/jds.2010-3942.
46. Ha, E. – Zemel, M. B.: Functional properties of whey, whey components, and essential amino acids: mechanisms underlying health benefits for active people. Journal of Nutritional Biochemistry, *14*, 2003, pp. 251–258. DOI: 10.1016/S0955-2863(03)00030-5.
47. Nalesnik, C. A. – Onwulata, C. I. – Tunick, M. H. – Phillips, J. G. – Tomasula, P. M.: The effects of drying on the properties of extruded whey protein concentrates and isolates. Journal of Food Engineering, *80*, 2007, pp. 688–694. DOI: 10.1016/j.jfoodeng.2006.06.029.
48. Matthey, F. P. – Hanna, M. A.: Physical and functional properties of Twin-screw extruded whey protein concentrate- corn starch blends. LWT–Food Science and Technology, *30*, 1997, pp. 359–366. DOI: 10.1006/fstl.1996.0189.
49. Onwulata, C. I. – Konstance, R. P. – Smith, P. W. – Holsinger, V. H.: Physical properties of extruded products as affected by cheese whey. Journal of Food Science, *63*, 1998, pp. 814–818. DOI: 10.1111/j.1365-2621.1998.tb17906.x.
50. Brnčić, M. – Karlović, S. – Bosiljkov, T. – Tripalo, B. – Ježek, D. – Cugelj, I. – Obradović, V.: Enrichment of extruded snack products with whey proteins. Mljekarstvo, *58*, 2008, pp. 275–295.
51. Onwulata, C. I. – Smith, R. P. – Konstance, R. P. – Holsinger, V. H.: Incorporation of whey products in extruded corn, potato or rice snacks. Food Research International, *34*, 2001, pp. 679–687. DOI: 10.1016/S0963-9969(01)00088-6.
52. Onwulata, C. I. – Konstance, R. P. – Smith, P. W. – Holsinger, V. H.: Co-extrusion of dietary fiber and milk proteins in expanded corn products. LWT–

Food Science and Technology, *34*, 2001, pp. 424–429. DOI: 10.1006/fstl.2000.0742.

53. Onwulata, C. I. – Konstance, R. P.: Extruded corn meal and whey protein concentrate: effect of particle size. Journal of Food Processing and Preservation, *30*, 2006, pp. 475–487. DOI: 10.1111/j.1745-4549.2005.00082.x.
54. Sharma, A. – Yadav, B. S. – Ritika, A.: Resistant starch: physiological roles and food applications. Food Reviews International, *24*, 2008, pp. 193–234. DOI: 10.1080/87559120801926237.
55. Kaczmarczyk, M. M. – Miller, M. J. – Freund, G. G.: The health benefits of dietary fiber: Beyond the usual suspects of type 2 diabetes mellitus, cardiovascular disease and colon cancer. Metabolism Clinical and Experimental, *61*, 2012, pp. 1058–1066. DOI: 10.1016/j.metabol.2012.01.017.
56. Elleuch, M. – Bedigian, D. – Roiseux, O. – Besbes, S. – Blecker, C. – Attia, H.: Dietary fibre and fibre-rich by-products of food processing: Characterisation, technological functionality and commercial applications: a review. Food Chemistry, *124*, 2011, pp. 411–421. DOI: 10.1016/j.foodchem.2010.06.077.
57. Williams, C. L.: Dietary fiber in childhood. Journal of Paediatrics, *149*, 2006, pp. S121–S130. DOI: 10.1016/j.jpeds.2006.06.066.
58. Robin, F. – Schumann, H. P. – Palzer, S.: Dietary fiber in extruded cereals: limitations and opportunities. Trends in Food Science and Technology, *28*, 2012, pp. 23–32. DOI: 10.1016/j.tifs.2012.06.008.
59. Wolf, B.: Polysaccharide functionality through extrusion processing. Current opinion in Colloid and Interface Science, *15*, 2010, pp. 50–54. DOI: 10.1016/j.cocis.2009.11.011.
60. Huth, M. – Dongowski, G. – Gebhardt, E. – Flamme, W.: Functional properties of dietary fibre enriched extrudates from barley. Journal of Cereal Science, *32*, 2000, pp. 115–128. DOI: 10.1006/jcrs.2000.0330.
61. Havrlentova, M. – Kraic, J.: Content of β-D-glucan in cereal grains. Journal of Food and Nutrition Research, *45*, 2006, pp. 97–103.
62. Faraj, A. – Vasanthan, T. – Hoover, R.: The effect of extrusion cooking on resistant starch formation in waxy and regular barley flours. Food Research International, *37*, 2004, pp. 517–525. DOI: 10.1016/j.foodres.2003.09.015.
63. Sayago-Ayerdi, S. – Tovar, J. – Blancas-Benitez, F. J. – Bello-Perez, L. A.: Resistant starch in common starchy foods as an alternative to increase dietary fibre intake. Journal of Food and Nutrition Research, *50*, 2011, pp. 1–12.
64. Vasanthan, T. – Gaosong, J. – Yeung, J. – Li, J.: Dietary fiber profile of barley flour as affected by extrusion cooking. Food Chemistry, *77*, 2002, pp. 35–40. DOI: 10.1016/S0308-8146(01)00318-1.
65. Altan, A. – McCarthy, K. L. – Maskan, M.: Evaluation of snack foods from barley-tomato pomace blends by extrusion processing. Journal of Food Engineering, *84*, 2008, pp. 231–242. DOI: 10.1016/j.jfoodeng.2007.05.014.
66. Makowska, A. – Mildner-Szkudlarz, S. – Obuchowski, W.: Effect of brewers spent grain addition on properties of corn extrudates with an increased dietary fibre content. Polish Journal of Food and Nutrition Science, *63*, 2013, pp. 19–24. DOI: 10.2478/v10222-012-0061-9.
67. Stojceska, V. – Ainsworth, P. – Plunkett, A. – Ibanoglu, S.: The effect of extrusion cooking using different water feed rates on the quality of ready to eat snacks made from food by-products. Food Chemistry, *114*, 2009, pp. 226–232. DOI: 10.1016/j.foodchem.2008.09.043.
68. Stojceska, V. – Ainsworth, P. – Plunkett, A. – Ibanoglu, E. – Ibanoglu, S.: Cauliflower by-products as a new source of dietary fibre, antioxidants and proteins in cereal based ready-to-eat expanded snacks. Journal of Food Engineering, *87*, 2008, pp. 554–563. DOI: 10.1016/j.jfoodeng.2008.01.009.
69. Ainsworth, P. – Ibanoglu, S. – Plunkett, A. – Ibanoglu, E. – Stojceska, V.: Effect of brewers spent grain addition and screw speed on the selected physical and nutritional properties of an extruded snack. Journal of Food Engineering, *81*, 2007, pp. 702–709. DOI: 10.1016/j.jfoodeng.2007.01.004.
70. Stojceska, V. – Ainsworth, P. – Plunkett, A. – Ibanoglu, S.: The recycling of brewers processing by-product into ready-to-eat snacks using extrusion technology. Journal of Cereal Science, *47*, 2008, pp. 469–479. DOI: 10.1016/j.jcs.2007.05.016.
71. Stojceska, V. – Ainsworth, P. – Plunkett, A. – Ibanoglu, S.: The advantage of using extrusion processing for increasing dietary fibre level in gluten-free products. Food Chemistry, *121*, 2010, pp. 156–164. DOI: 10.1016/j.foodchem.2009.12.024.
72. Lobato, L. P. – Anibal, D. – Lazaretti, M. M. – Grossmann, M. V. E.: Extruded puffed functional ingredient with oat bran and soy flour. LWT–Food Science and Technology, *44*, 2011, pp. 933–939. DOI: 10.1016/j.lwt.2010.11.013.
73. Esposito, F. – Arlotti, G. – Bonifati, A. M. – Napolitano, A. – Vitale, D. – Fogliano, V.: Antioxidant activity and dietary fibre in durum wheat bran by-products. Food Research International, *38*, 2005, pp. 1167–1173. DOI: 10.1016/j.foodres.2005.05.002.
74. Wang, Y.-Y. – Ryu, G.-H.: Physicochemical and antioxidant properties of extruded corn grits with corn fiber by CO_2 injection extrusion process. Journal of Cereal Science, *58*, 2013, pp. 110–116. DOI: 10.1016/j.jcs.2013.03.013.
75. Zhang, M. – Bai, X. – Zhang, Z.: Extrusion process improves the functionality of soluble dietary fiber in oat bran. Journal of Cereal Science, *54*, 2011, pp. 98–103. DOI: 10.1016/j.jcs.2011.04.001.
76. Jing, Y. – Chi, Y.-J.: Effects of twin screw extrusion on soluble dietary fibre and physicochemical properties of soybean residue. Food Chemistry, *138*, 2013, pp. 884–889. DOI: 10.1016/j.foodchem.2012.12.003.
77. Gimenez, M. A. – Gonzalez, R. J. – Wagner, J. – Torres, R. – Lobo, M. O. – Samman, N. C.: Effect of extrusion conditions on physicochemical and sensorial properties of corn-broad beans (*Vicia faba*) spaghetti type pasta. Food Chemistry, *136*, 2013, pp. 538–545. DOI: 10.1016/j.foodchem.2012.08.068.

78. Shirani, G. – Ganesharanee, R.: Extruded products with fenugreek (*Trigonella foenum-graecium*) chickpea and rice: Physical properties, sensory acceptability and glycaemic index. Journal of Food Engineering, *90*, 2009, pp. 44–52. DOI: 10.1016/j.jfoodeng.2008.06.004.
79. Meng, X. – Threinen, D. – Hansen, M. – Driedger, D.: Effects of extrusion conditions on system parameters and physical properties of a chickpea flour-based snack. Food Research International, *43*, 2010, pp. 650–658. DOI: 10.1016/j.foodres.2009.07.016.
80. Patil, R. T. – Berrios, J. D. – Tang, J. – Swanson, B. G.: Evaluation of methods for expansion properties of legume extrudates. Applied Engineering in Agriculture, *23*, 2007, pp. 777–783.
81. Larrea, M. A. – Chang, Y. K. – Bustos, F. M.: Effect of some operational extrusion parameters on the constituents of orange pulp. Food Chemistry, *89*, 2005, pp. 301–308. DOI: 10.1016/j.foodchem.2004.02.037.
82. Shih, M. – Kuo, C. – Chiang, W.: Effects of drying and extrusion on colour, chemical composition, antioxidant activities and mitogenic response of spleen lymphocytes of sweet potatoes. Food Chemistry, *117*, 2009, pp. 114–121. DOI: 10.1016/j.foodchem.2009.03.084.
83. Liu, R. H.: Health benefits of fruit and vegetables are from additive and synergistic combinations of phytochemicals. American Journal of Clinical Nutrition, *78*, 2003, pp. 7S–20S.
84. Kris-Etherton, P. K. – Hecker, K. D. – Bonanome, A. – Coval, S. M. – Binkosi, A. E. – Hilpert, K. F. – Griel, A. E. – Etherton, T. D.: Bioactive compounds in foods: their role in the prevention of cardiovascular disease and cancer. American Journal of Medicine, *113*, 2002, pp. 71S–88S. DOI: 10.1016/S0002-9343(01)00995-0.
85. Viskupičová, J. – Ondrejovič, M. – Šturdík, E.: Bioavailability and metabolism of flavonoids. Journal of Food and Nutrition Research, *47*, 2008, pp. 151–162.
86. Schieber, A. – Stintzing, F. C. – Carle, R.: By-products of plant food processing as a source of functional compounds – recent developments. Trends in Food Science and Technology, *12*, 2001, pp. 401–413. DOI: 10.1016/S0924-2244(02)00012-2.
87. Mikulajova, A. – Takacsova, M. – Rapta, P. – Brindzova, L. – Zalibera, M. – Nemeth, K.: Total phenolic contents and antioxidant capacities of cereal and pseudocereal genotypes. Journal of Food and Nutrition Research, *46*, 2007, pp. 150–157.
88. Zielinski, H. – Kozlowska, H. – Lewczuk, B.: Bioactive compounds in the cereal grains before and after hydrothermal processing. Innovative Food Science and Emerging Technologies, *2*, 2001, pp. 159–169. DOI: 10.1016/S1466-8564(01)00040-6.
89. Sharma, P. – Gujral, H. S. – Singh, B.: Antioxidant activity of barley as affected by extrusion cooking. Food Chemistry, *131*, 2012, pp. 1406–1413. DOI: 10.1016/j.foodchem.2011.10.009.
90. Viscidi, K. A. – Dougherty, M. P. – Briggs, J. – Camire, M. E.: Complex phenolic compounds reduce lipid oxidation in extruded oat cereals. LWT–Food Science and Technology, *37*, 2004, pp. 789–796. DOI: 10.1016/j.lwt.2004.03.005.
91. Camire, M. E. – Dougherty, M. P.: Added phenolic compounds enhace lipid stability in extruded corn. Journal of Food Science, *63*, 1998, pp. 516–518. DOI: 10.1111/j.1365-2621.1998.tb15776.x.
92. Aguilera, Y. – Estrella, I. – Benitez, V. – Esteban, R. M. – Martin-Cabrejas, M. A.: Bioactive compounds and functional properties of dehydrated bean flours. Food Research International, *44*, 2011, pp. 774–780. DOI: 10.1016/j.foodres.2011.01.004.
93. Delgado-Licon, E. – Martinez Ayala, A. M. – Rocha-Guzman, N. E. – Gallegos-Infante, J. A. – Atienzo-Lazos, M. – Drzewiecki, J. – Martinez-Sanchez, C. E. – Gorinstein, S.: Influence of extrusion on the bioactive compounds and the antioxidant capacity of the bean/corn mixtures. International Journal of Food Sciences and Nutrition, *60*, 2009, pp. 522–532. DOI: 10.1080/09637480801987666.
94. Korus, J. – Gumul, D. – Czechowska, K.: Effect of extrusion on the phenolic composition and antioxidant activity of dry beans of *Phaseolus vulgaris* L. Food Technology and Biotechnology, *45*, 2007, pp. 139–146.
95. Özer, E. A. – Herken, E. N. – Güzel, S. – Ainsworth, P. – Ibanoglu, S.: Effect of extrusion process on the antioxidant activity and total phenolics in a nutritious snack food. International Journal of Food Science and Technology, *41*, 2006, pp. 289–293. DOI: 10.1111/j.1365-2621.2005.01062.x.
96. Camire, M. E. – Chaovanalikit, A. – Dougherty, M. P. – Briggs, J.: Blueberry and grape anthocyanins as breakfast cereal colorants. Journal of Food Science, *67*, 2002, pp. 438–441. DOI: 10.1111/j.1365-2621.2002.tb11425.x.
97. Espin, J. C. – Soler-Rivas, C. – Wichers, H. J. – Garcia-Viguera, C.: Anthocyanin-based natural colorants: a new source of antiradical activity for foodstuff. Journal of Agricultural and Food Chemistry, *48*, 2000, pp. 1588–1592.
98. Suh, H. J. – Choi, S.: Risk assessment of daily intakes of artificial colour additives in food commonly consumed in Korea. Journal of Food and Nutrition Research, *51*, 2012, pp. 13–22.
99. Camire, M. E. – Dougherty, M. P. – Briggs, J. L.: Functionality of fruit powders in extruded corn breakfast cereals. Food Chemistry, *101*, 2007, pp. 765–770. DOI: 10.1016/j.foodchem.2006.02.031.
100. Khanal, R. C. – Howard, L. R. – Prior, R. L.: Procyanidin content of grape seed and pomace, and total anthocyanin content of grape pomace as affected by extrusion processing. Journal of Food Science, *74*, 2009, pp. H174–H182. DOI: 10.1111/j.1750-3841.2009.01221.x.
101. White, B. L. – Howard, L. R. – Prior, R. L.: Polyphenolic composition and antioxidant capacity of extruded cranberry pomace. Journal of Agricultural and Food Chemistry, *58*, 2010, pp. 4037–4042. DOI: 10.1021/jf902838b.
102. Durghe, A. V. – Sarkar, S. – Singhal, R. S.: Stability of anthocyanins as pre-extrusion colouring of rice

extrudates. Food Research International, *50*, 2013, pp. 641–646. DOI: 10.1016/j.foodres.2011.05.017.

103. Chaovanalikit, A. – Dougherty, M. P. – Camire, M. E. – Briggs, J.: Ascorbic acid fortification reduces anthocyanins in extruded blueberry-corn cereals. Journal of Food Science, *68*, 2003, pp. 2136–2140. DOI: 10.1111/j.1365-2621.2003.tb07032.x.
104. Killeit, U.: Vitamin retention in extrusion cooking. Food Chemistry, *49*, 1994, pp. 149–155. DOI: 10.1016/0308-8146(94)90151-1.
105. Emin, M. A. – Mayer-Miebach, E. – Schuchmann, H. P.: Retention of β-carotene as a model substance for lipophilic phytochemicals during extrusion cooking. LWT–Food Science and Technology, *48*, 2012, pp. 302–302. DOI: 10.1016/j.lwt.2012.04.004.
106. Shih, M. C. – Kuo, C. C. – Chiang, W.: Effects of drying and extrusion on colour, chemical composition, antioxidant activities and mitogenic response of spleen lymphocytes of sweet potatoes. Food Chemistry, *117*, 2009, pp. 114–121. DOI: 10.1016/j.foodchem.2009.03.084.
107. Fonseca, M. J. de O. – Soares, A. G. – Junior, M. F. – de Almeida, D. L. – Ascheri, J. L.: Effect of extrusion cooking in total carotenoids content and orange flesh sweet potato cultivars. Horticultura Brasileira, *26*, 2008, pp. 112–115. DOI: 10.1590/S0102-05362008000100022.
108. Berset, C. – Trouiller, J. – Marty, C.: Protective effect of the oleoresin of rosemary (*Rosmarinus officinalis* L.) and of several other antioxidants on β-carotene. Lebensmittel Wissenschaft und Technologie, *22*, 1989, pp. 15–19.
109. Deghan-Shoar, Z. – Hardacre, A. K. – Brennan, C. S.: The physico-chemical characteristics of extruded snacks enriched with tomato lycopene. Food Chemistry, *123*, 2010, pp. 1117–1122. DOI: 10.1016/j.foodchem.2010.05.071.
110. Huang, R. C. – Peng, J. – Lu, F. J. – Lui, W. B. – Lin, J.: The study of optimum operating conditions of extruded snack food with tomato powder. Journal of Food Process Engineering, *29*, 2006, pp. 1–21. DOI: 10.1111/j.1745-4530.2006.00047.x.
111. Altan, A. – McCarthy, K.. – Maskan, M.: Effect of screw configuration and raw material on some properties of barley extrudates. Journal of Food Engineering, *92*, 2009, pp. 377–382. DOI: 10.1016/j.jfoodeng.2008.12.010.
112. Jozinović, A. – Šubarić, D. – Ačkar, Đ. – Babić, J. – Planinić, M. – Pavokovic, M. – Blažić, M: Effect of screw configuration, moisture content and particle size of corn grits on properties of extrudates. Croatian Journal of Food Science and Technology, *4,* 2012, pp. 95–101.

Received 26 September 2013; 1st revised 9 December 2013; accepted 8 January 2014; published online 27 May 2014.