Legume Use in Extrusion Cooking

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The traditional perception that legumes would not be suitable for extrusion cooking is now completely outdated. In the recent years an increasing number of researches have been conducted to assess the behavior of various types of legume flours in extrusion cooking, proving that legumes have excellent potential for the production of extruded ready-to-eat foods by partially or totally replacing cereals. There are optimal processing conditions for legume-based and legume-added extruded foods, which allow to improve the expansion ratio and give the extrudates the spongy and crisp structure expected by consumers. The extrusion cooking process has also a positive effect on the nutritional characteristics of legumes, because induces important modifications on starch and proteins, enhancing their digestibility, and reduces the content of trypsin inhibitors, lectins, phytic acid, and tannins. Therefore, the extrusion of legume flours is a viable strategy to improve their nutritional features while reducing home preparation time, so as to increase the consumption of these sustainable crops.

Keywords: pulses ; extrudate ; expansion ratio ; starch ; gelatinization ; phytate ; α-galactoside ; bean ; chickpea ; pea

1. Introduction

Extrusion cooking is a technique largely used for the production of several ready-to-eat products, such as crisp expanded snacks (e.g. puffs, runs, collets, etc.), breakfast cereals, instant soups, meat analogues and sport foods [1]. High temperature and pressure (up to 200 °C and 20 MPa, respectively) are the usual conditions for extrusion cooking. Raw materials must be properly ground and conditioned at a certain moisture percentage before being fed to the extruder, which is basically composed of one or two rotating screws fitted in a heated barrel. In the initial part of the barrel (feed zone), the raw material is conveyed and mixed by the rotating screw. Then, with the help of shear energy, the material is further kneaded and compressed (kneading zone) and, by friction and additional heating of the barrel, reaches its melting point and plasticizes, particularly in the final part of the machine (cooking zone) [1]. As the plasticized starchy material exits from the die of the extruder, the air bubbles entrapped within the matrix expand due to instant pressure drop. In addition, being the extruded material heated to temperatures above 100 °C, a moisture flash-off occurs at the exit of the extruder, further improving the puffing effect. The expansion ceases upon cooling, when the plasticized matrix becomes glassy and develops a desirable crispy texture. Extrusion cooking, indeed, is an effective means of aerating foods, thereby converting dense, hard materials into lighter and more appealing forms. The quality of the extruded product is therefore defined mostly by its expansion degree.

2. Legume Flours in Extrusion Cooking

Consumer demand for ready-to-eat foods is increasing due to the time-saving needs of the modern lifestyle. The raw materials for extrusion cooking are mostly cereals, due to their good expansion characteristics. However, in addition to providing energy from starch, extruded foods could act as carrier of other nutrients, if enriched with other ingredients [2].

Legumes are a good source of proteins, starch, dietary fiber, vitamins and minerals, and are particularly important when the consumption of animal proteins is restricted due to limited affordability, or religious, dietary and ethical habits. Furthermore, legumes are sustainable crops adaptable to marginal lands. In the past, only soybean was used for the development of extruded food products. In recent years, instead, several studies have taken into account the incorporation of other legumes (such as bean, lentil, pea, chickpea, and faba bean) to improve the nutritional value of extruded foods. Nutrient dense extruded multi-legume bars, mixed with whey protein concentrate, honey and palm oil, have been proposed to mitigate malnutrition in the developing countries [2].

The extrusion cooking technology is also known to reduce the levels of some anti-nutrients contained in legumes such as tannins, phytic acid, trypsin inhibitors and lectins [3]. In addition, extrusion cooking is able to increase the digestibility of starch and proteins.

In this framework, it is important to identify the optimal processing conditions for each type of legume and define the effect of processing parameters on the physical-chemical and nutritional properties of the extruded products.

The main parameters to be adjusted in the extrusion cooking process are the temperature, the screw speed and the moisture content of the fed ingredients. These parameters strongly influence the characteristics of the extruded product. Therefore, several studies have been carried out to compare sundry combinations of those parameters, in order to point out the optimal conditions for each type of legume (Table 1). Beside the processing parameters, however, also the content of legume flour, its refining degree and particle size, as well as the type of legume, influence the expansion performance of the extrudates. Prior to extrusion, indeed, legumes are milled to flour either using the entire cotyledons or after removal of the hulls (split flours). Hull removal lowers the content of fibers and minerals but improves the expansion during extrusion [4]. Fibers, particularly the insoluble ones, surround the air bubbles preventing their maximum expansion, whereas proteins and lipids reduce puffing due to interactions with swelling starch [5].

In addition, there are differences in the attitude to extrusion of different legumes, based on their compositional features. Compared with lentil and chickpea flours, split yellow pea flour reaches expansion ratio and bulk density similar to corn meal due to its higher starch and lower protein content [5]. Chickpea extruded snacks, instead, show the lowest expansion properties, which can be attributed to lower starch and higher fat content compared with other pulses [4].

Table 1. Main results of the studies aimed at identifying the optimal processing conditions for the extrusion cooking of legumes. The optimal values for each parameter, among the tested ones, are those highlighted in bold.

		Tested values						
Legume type	**Extrude type**	**Legume content (g/100 g)**	**Flour particle size (mm)**	**Maximum temperature (die zone) (°C)**	**Feed moisture (g/100 g)**	**Screw speed (rpm)**	**Quality indices considered for optimization**	**Ref.**
Bean (*Phaseolus vulgaris* L.)	SS	30	0.4	120–170, **157**[1]	**15**–25	50–240, **238**	ER, BD, H	[6]

	TS	15, **30**, 45	0.5	160	22	150	ER, H, NP, C	[7]
	SS	**25**, 50, 75	0.5	160	15.5	150	ER, BD, H, NP	[5]
Pea (*Pisum sativum* L.)	TS	100	NS	150	**14**, 16, 18	200	ER, BD	[8]
	TS	9	NS	90, 100, **110**[1]	**12**, 14, 16	100, 150, **200**	ER, BD, H, WAI, WSI	[9]
	SS	5, 10, **15**	NS	180	12	210	NP	[10]
Chickpea (*Cicer arietinum* L.)		100	NS	110, 120, 135, **150**	19, 20, **22**, 24, 26	260, **300**, 340	ER, BD	[11]
	TS	50	1.25	130, **140**, 150	17	266, 300, 350, 400, **434**	ER, H, SP, NP	[12]
	SS	10, **20**, 30	0.25	160	16	250	ER, BD, WAI, WSI, NP	[13]
	SS	5, 10, **15**	NS	180	12	210	NP	[10]
Lentil (*Lens culinaris* L.)	TS	100	0.25	140, **160**, 180	14, **18**, 22	150, **200**, 250	ER, BD, H, WAI, WSI, SP, NP	[14]
	SS	5, 10, **15**	NS	180	12	210	NP	[10]
Cowpea (*Vigna unguiculata* L.)	SS	100	0.8	160-**180**	**16**-24	160-**200**	BD, H, WAI, WSI, SP	[15]
Faba bean (*Vicia faba* L.)	TS	100	**0.5**, 1.5, 2.5	140	NS	200, **300**	ER, H, SP	[16]
Mung bean (*Vigna radiate* L.)	TS	30	0.2	130-170, **148**[1]	**14**-18	400-**550**	BD, H, WAI, WSI	[17]

Everlasting pea (*Lathyrus sativus*)	TS	35, **50**, 65	0.6	110, 140, 180, 170, 130	**18**, 21, 24	75	ER, BD, NP	[18]
Pigeon pea (*Cajanus cajan* L.)	SS	19	0.07	160-200, **171**	12-**24**	100-140, **104**	C	[19]

[1] barrel temperature. SS = single-screw; TS = twin-screw; NS = not specified; ER = expansion ratio; BD = bulk density; H = hardness; WAI = water absorption index; WSI = water solubility index; SP = sensory properties; NP = nutritional properties; C = color.

3. Effect of Extrusion Cooking Parameters on the Physical-Chemical Properties of the End-Product

The structural characteristics of an extruded food product, such as bulk density (BD) and hardness, are related to the size and number of gas bubbles developed within the expanded rigid starchy matrix. High screw speed and die temperature, coupled to low moisture content, are the best conditions for enhancing expansion degree, while reducing BD and hardness of the extrudates (Table 2).

Hardness is related to the acceptability of the final product, being less hard and more expanded extrudates the most appreciated. Also BD of extruded foods should be as low as possible, indicating a proper increase in volume of the extrudate. Low moisture content reduces both hardness and BD because raises the friction within the matrix and therefore increases the drag force, resulting in higher temperature and greater pressure on the die [20]. High pressure on the die, in turn, causes a greater expansion of the compressed bubbles at the exit of the extruder, and therefore results in a greater puffing of extrudate [17]. Along with low moisture, also high temperature increases the pressure inside the extruder and then positively influences the expansion, reducing both hardness and BD [17]. An amylose/amylopectin ratio accounting for 1:3–1:4 in the starchy fraction of the raw materials is needed to obtain optimally puffed and crunchy products [21].

Table 2. Effect (positive/negative) of the increase of the main processing parameters of extrusion cooking on the physical-chemical characteristics of legume extrudates.

	Expansion ratio	Bulk density	Hardness	WAI	WSI	Color		
						Lightness (*L**)	Redness (*a**)	Yellowness (*b**)
Legume content	-	+	+	NS	NS	-	+	+
Temperature	+	-	-	+	+	-	+	+
Feed moisture	-	+	+	+	-	-	+	-
Screw speed	+	-	-	-	+	NS	NS	NS

WAI = water absorption index; WSI = water solubility index; NS = not studied.

Another parameter to be considered is the water absorption index (WAI), which measures the weight of starch after swelling in excess water [22]. In instant soups and infant foods, WAI should be as high as possible, because it is related to the ability of extruded flours to be easily reconstituted with water in a thick suspension. High WAI is observed at high extrusion temperature [14], high moisture content [9], and low screw speed [17]. High screw speed have harsher effects on starch polymers, leading to molecule breakdown and affecting gelatinization and, therefore, ability to bind water.

Water solubility index (WSI) is related to the presence of water-soluble molecules deriving from polymer breakdown induced by extrusion. It is used as an indicator of the starch degradation. High WSI results in sticky extrudates [23]. WSI increases with the raise of temperature and screw speed (Table 2), because more severe thermo-mechanical conditions cause a greater extent of dextrinization. Less severe processing conditions or high content of lipids, which form complexes with amylose, contribute to reduce starch degradation leading to lower amounts of low molecular weight water-soluble products. Similarly, high feed moisture results in low WSI because moisture plasticizes the extruding material, reducing its viscosity and therefore lowering friction phenomena with a consequent 'protective' effect on flour constituents [17].

Color is mostly influenced by die temperature. High temperature, indeed, cause Maillard and caramelization reactions, with a consequent increase in browning and redness.

4. Effect of Extrusion Cooking Parameters on the Nutritional Characteristics of the End-Product

4.1 Effect on proteins and starch

The thermal treatment associated to extrusion cooking is effective in improving protein and starch digestibility compared with traditional thermal processes. Lysine loss may however occur, depending on the extrusion conditions. In particular, starch and protein digestibility take advantage from temperature and feed moisture increase, whereas lysine loss increases as the temperature raises (Table 3).

Humans cannot easily digest non-gelatinized starch [24]. Extrusion cooking results in starch gelatinization, total or partial, at much lower moisture levels (12–22%) than is needed by other processing technologies [24]. In addition, extrusion cooking causes a cleavage of amylose and, particularly, of amylopectin molecules induced by the shear, resulting in smaller and more digestible fragments, i.e. dextrins and reducing sugars. Starch digestibility can be therefore modulated by regulating the processing parameters of extrusion, because some extruded foods, such as infant flours, have to be highly digestible, whereas other, such as extruded snacks for obese people, should contain little digestible material.

Table 3. Effect (positive/negative) of the increase of the main processing parameters of extrusion cooking on the nutritional characteristics of legume-based extruded products.

	Protein digestibility	Starch digestibility	Lysine loss
Temperature	+	+	+
Feed moisture	+	+	-
Screw speed	+	+	NS

NS = not studied.

Generally, also the digestibility of proteins increases with extrusion cooking [25]. The denaturation of proteins, in fact, induced by heat and by high friction and shear forces, may improve the accessibility of sites sensitive to proteolysis. The surface area also increases, further enhancing the exposure of sites to the enzymes [2]. On the other hand, digestibility can be compromised by the formation of protein aggregates via hydrogen bonds, hydrophobic interactions and disulfide bonds with consequent decrease of solubility. In addition, Maillard complexes may be formed during extrusion, particularly at high temperature and low feed moistures. Maillard reaction particularly affects the bioavailability of lysine, which is limiting in cereals and increases upon legume incorporation, because of the presence of two available amino groups. Furthermore, also arginine, tryptophan, cysteine and histidine might be affected [24]. To lower the incidence of Maillard reaction, mild extrusion conditions should be adopted (<180 °C and >15% moisture) [24].

The improvement of protein digestibility is probably mostly due to the reduction of trypsin inhibitors, which interfere with proteolysis and are heat-labile. In addition, the anti-nutritional factors, such as phytic acid, tannins, and polyphenols, which contribute to lower protein digestibility by linking proteins and decreasing their solubility and susceptibility to proteolysis, are reduced by thermal treatments [26] (Table 4). Finally, a decrease of insoluble dietary fiber (IDF) in favor of an increase of soluble dietary fiber (SDF) has been observed in extruded legume-based formulations [27]. Since cell wall rigidity and fiber content may influence the protein digestibility, a positive effect of extrusion cooking related with the redistribution of fiber fractions has to be considered.

4.2 Effect on Anti-Nutritional Factors

Regarding anti-nutritional factors, an increase in temperature and feed moisture lowers the content of inositol hexaphosphate, trypsin inhibitors and lectins, which is a desired effect, but also that of antioxidants such as phenolic compounds and tocopherols (Table 5). In contrast, an increase in temperature raises the content of total α-galactosides.

Significant destruction of trypsin inhibitors can be achieved by extrusion at elevated temperatures or by increasing residence time when extrusion is done at lower temperatures [28].

Table 4. Effect (positive/negative) of the increase of the main processing parameters of extrusion cooking on the content of functional and anti-nutritional compounds of legume-based extruded products.

Parameter	Phenolics	Tocopherols	Antioxidant activity	α-Galactosides	Anti-nutritional compounds			
					Trypsin inhibitors	Phytate (IP6)	Tannins	Lectins
Temperature	-	-	+	+	-	-	NS	-
Feed moisture	-	-	NS	NS	-	-	-	-
Screw speed	NS	NS	NS	NS	-	-	-	NS

NS = not studied; IP6 = inositol hexaphosphate.

The extrusion conditions influence the overall impact on phenolics: the adoption of low moisture (<14%) and low temperature (<140 °C) can help retaining them [8]. However, the effect of extrusion cooking on the various classes of phenolic compounds is controversial: some studies report an increase of anthocyanins [29] and total phenolics [30], whereas other studies report a decrease of anthocyanins [29], an insignificant variation of flavonols [30], and a decrease of total phenolics [8]. Anthocyanins, in particular, are present in black beans [31] and in black chickpeas [32][33][34]. An effect of the composition of starting flour was observed. If the starting flour is rich of fiber, then phenolics increase because the extrusion process partially disrupts fiber releasing bound phenolic compounds [6]. In addition, the activity oxidative enzymes in the raw material is also influent, since extrusion cooking inactivates them thus preventing the oxidation of phenolic compounds [6]. Other antioxidant compounds, such as Maillard reaction products, may arose from the thermal modifications related to the extrusion cooking process [29]. Therefore, generally the antioxidant activity increases during the extrusion cooking process.

Other compounds influenced by extrusion cooking are the α-galactosides, such as raffinose, stachyose, and verbascose. These compounds cause flatulence due to the lack of α-galactosidase in the human intestinal mucosa, but at the same time they have a prebiotic effect because are easily fermented by the colonic flora, resulting in the production of short chain fatty acids that stimulate bifidobacterial growth. It has been observed that extrusion cooking causes a significant increase of total α-galactosides, compared to the not extruded raw material [35]. These oligosaccharides, indeed, are relatively heat-stable [36]. Therefore, mechanical-structural modifications in the cell walls (such as partial ruptures with increase of porosity) coupled to the increase of surface area, taking place during the extrusion cooking, may probably increase their availability in the extrudates.

5. Conclusions

Legumes have shown excellent potential for the production of extruded ready-to-eat foods by partially or totally replacing cereals. The traditional perception that legumes would not be suitable for extrusion cooking is now completely outdated. By accurately selecting the optimal processing parameters it is possible to improve the expansion ratio and give the extrudates the spongy and crisp structure expected by consumers. Moreover, the addition of legume flours improves the nutritional value of cereal-based end-products by increasing the content of essential aminoacids, fibers, proteins, and micronutrients, while extrusion cooking inactivates the nutritionally undesirable compounds typically present in legumes.

Therefore, the extrusion of legumes is a viable strategy to add value to underexploited legumes and reduce home preparation time, so as to increase the consumption of these sustainable crops.

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