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Pulse flaking: Opportunities and challenges, a review

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Abstract

Pulses provide economic and health benefits to people in many countries around the world; however, their adoption in western diets, particularly in processed and formulated foods, is limited. One strategy to increase the level of pulses in western diets is to improve pulse accessibility to the ready-to-eat (RTE) food market sector. Pulses have compositional and structural differences when compared to cereals and behave differently during processing. While there have been numerous studies on pulses processed using traditional processing methods, there are limited studies describing processing of pulses as a major ingredient in RTE forms such as flakes. To understand the full processing potential of pulses, systematic studies are required using commercial-scale RTE pilot processing equipment coupled with fundamental property determination techniques to evaluate the effects of processing and pulse material on pulse flake attributes. In-depth studies of pulse properties and their processability are likely to result in the production of high-quality pulse-based foods with superior health benefits. This review explores the current and potential opportunities for processing pulses with a focus on flake products. The roles of pulse type and major structure-forming components such as fiber, carbohydrates, and proteins on end-product quality of processed pulses are discussed.

KEYWORDS
flaking, processing, pulses, ready-to-eat, value addition

1 | INTRODUCTION

Pulses are the mature, edible dry seeds of nonoilseed legume plants and provide consumers with a rich source of nutrients (Rebello et al., 2014). Pulses are typically high in protein, low in fat, and have a low glycemic index (Cuvelier et al., 2017). They are important dietary sources of protein, fiber, minerals, and B vitamins, and have been shown to protect against certain cancers, high cholesterol, type 2 diabetes, and obesity (Hall et al., 2017). While pulses have been heralded as a "superfood," some have barriers to their use that need to be addressed, such as long cooking times and a "sometimes unpleasant" off-flavor. Sozer et al. (2017) highlighted the paradox that the consumption of pulses is declining in countries that are traditionally high consumers of pulses (Messina, 1999), while there is an increased interest in Western countries where pulses are considered an alternative to gluten-based foods. Research would assist in enabling pulse foods to benefit from recent food market trends, enabling them to contribute to a sustainable worldwide food supply. This review aims to provide information on recent research on processing of commercially important pulses, in particular, chickpea and faba bean. Furthermore, a summary is provided on the opportunities and challenges associated with manufacturing healthy pulse products with acceptable consumer attributes.

1.1 | Global market trends

There is an increasing interest worldwide in pulse-based foods with 5% of new product launches containing a pulse ingredient in 2020 (Pulse Canada, 2021). The United States has seen a strong consumer demand for highly nutritious convenience meals and snack foods (AAFC, 2017a). In Europe, marketing of pulse products commonly focuses on factors such as being vegetarian, allergen and gluten free as well as high in fiber (AAFC, 2015, 2017a). These worldwide trends are driving new or reformulated products containing pulses. There has been a 275% increase in foods containing pulses from 2010 to 2020, at around 12,000 new product launches per year (Pulse Canada, 2021).

The increase in consumption of pulses includes India and China who are the largest importers and consumers of pulses in the world (AAFC, 2017b). Pulses are already a major source of protein in home cooking in India. At least 30% of the world's pulse product launches occurred in India, where pulses are marketed as vegetarian, low in cholesterol, and having no preservatives (AAFC, 2015). While pulses are not consumed daily in China, its rising middle class is looking for premium, innovative health and wellness foods. This is reflected in the increased use of pulse starch and protein as an ingredient and presents marketing opportunities for processed pulses (AAFC, 2017b). Australia is one of the major exporters of pulses (AEGIC, 2016), yet has one of the lowest levels of pulse consumption in the world (Broom, 2016).

1.2 | Chickpea

Chickpeas (*Cicer arietinum* L.) are the third-most commonly consumed legume in the world, and are one of the most important sources of vegetable proteins in the human diet (Nasir & Sidhu, 2012). World annual chickpea production has been as much as 14 million tonnes in recent years with a gross production value of US$ 9 billion per year on average from 2016 to 2019 (Kao et al., 2020). Chickpeas are thought to be one of the most difficult pulses to cook because of their large size and chemical composition (Xu et al., 2016). Chickpeas contain a high portion of nondigestible carbohydrates, including resistant starch and fiber. They have a rich variety of phytochemicals, such as natural antioxidants and bioactive compounds, which may be reduced or enhanced after hydrothermal treatments (Fares & Menga, 2014; Rochfort & Panozzo, 2007). Of the many types of chickpea, the most common are the large Kabuli chickpea and smaller Desi chickpea. Chickpeas are commonly sold whole or processed as dhal, kibble, puffed, whole flour, roasted flour, and flour fractions (CIGI, 2013; Maskus, 2010).

Desi chickpeas are the most popular chickpea consumed in the world. They are consumed after de-hulling, splitting, and cooking, or used as besan flour, an ingredient in sweet and savory foods. Some parts of India flake Desi chickpeas, but this is not a widespread practice in the rest of the world (Jha et al., 2016). Desi flakes are present in the patent literature and are produced in some markets; however, minimal information is available as to how processing conditions impact on flake quality (Jha et al., 2016; Malhotra, 2012).

1.3 | Faba bean

Originating in North Africa and Southwestern Asia, Faba beans (*Vicia faba* L.) are grown worldwide (Sozer et al., 2017) and are also known as broad beans, fava bean, horse bean, and windsor bean. Faba beans are commercially available as whole deshelled kibble or flours and are widely consumed in the Middle East and Mediterranean. Faba bean world production averaged 5.3 million tonnes in recent years with a gross production value of US$ 1.7 billion per year on average from 2016 to 2018 (Kao et al., 2020). Despite their popularity in some regions, faba bean consumption has plateaued with world production stalling at approximately 10 million tonnes per year (FAO, 2018). One issue associated with faba bean consumption is the development of "favism," a hemolytic disease that occurs in a small proportion of the population as a result of consuming the faba bean proteins divicine and convicine (Hussein et al., 1986).

Faba beans vary in size and shape depending on variety. Shapes include large flattened beans (also known as broad beans) through to medium-sized and smaller, rounded seeds similar to field peas. Varieties with medium-sized seeds are the main types grown in Australia, while the smaller seed types are common in Europe (Matthews, 2003).

2 | PULSE STRUCTURE AND COMPOSITION

2.1 | Cellular structures

Chickpeas and faba bean seeds comprise two cotyledons inside a seed coat. The seed coat consists of several

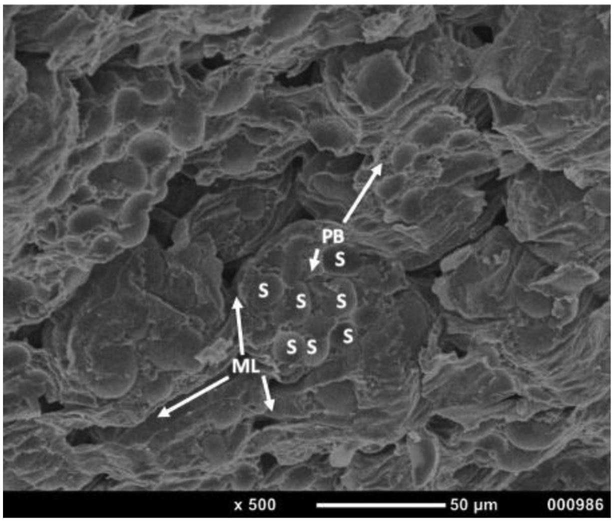

FIGURE 1 Scanning electron microscopy (SEM) showing the visible microstructure on a cross-section of cotyledon of a Faba bean. ML, middle lamella boundaries between cells; PB, protein body encasing the S, round starch granules (unpublished authors work)

anatomical layers and is commonly referred to as the seed "hull" or "testa." The outermost part of the hull is a thin waxy cuticle layer that overlays thick-walled palisade cells, which (when dried) restrict water movement in proportion to the thickness of the hull (Stanley & Aguilera, 1985). Underneath the hull is a layer of palisade, (hourglass) cells which surround the epidermal cells of the cotyledon. The cotyledons are the largest parts of the seed. The cotyledon has a single outer epidermal layer of smaller protein-filled cells, which (unlike the subepidermal cells) are devoid of starch granules (Wood et al., 2011). The cotyledon cells are surrounded by cell walls consisting of a complex arrangement of linked biopolymers (Cosgrove, 2018). Cell wall biopolymers include cellulose, hemicellulose, lignin, and pectin. The cells are bound by the middle lamella, rich in pectin polymers. Inside the cells are round starch granules embedded in a protein matrix (Figure 1) (Wood et al., 1998). The protein matrix is bound by a polypeptide layer containing lectin membrane (Stanley & Aguilera, 1985).

The cotyledon composition is quite different between pulses and cereals. The composition of selected pulses is compared to the commonly flaked cereals of maize, wheat, and oats in Table 1. The uniqueness of each pulse has important ramifications when selecting and applying traditional cereal-processing methods. In general, pulses are higher in protein, fiber, amylose, and oligosaccharides when compared to cereals (Viguiliouk et al., 2017). The major compositional factors (protein and carbohydrates) are likely to affect pulse processing. Minor constituents may be important in specific processing situations, or when a specific functional property is important to a market niche. For example, phytochemicals such as phenolic compounds have perceivable impacts on color and odor.

2.2 | Starch

Starch is the major storage carbohydrate in pulse seeds, making up approximately 30–50% of dry mass (Table 1). Like many pulses, starch in chickpeas and faba beans is found in densely packed round granules consisting of amylose and amylopectin surrounded by a protein matrix in the inner cotyledon cells (Figure 1) (Wood et al., 2014). Pulse starches are higher in amylose content, which, in the raw form, have a higher degree of crystallinity than cereal starches (Table 1). Crystalline starch granule regions have three main types of structure (A, B, and C). Starch C is a mixture of both A and B patterns and is common for pulses (Gallant et al., 1992; Hoover et al., 2010). These differences change the processing conditions required to disrupt the starch granule to favorably change its physicochemical properties. For instance, gelatinization of high amylose starches may require temperatures of more than 120°C. The gelatinization temperature is also compounded by the presence of a resilient food matrix (e.g., cell wall structures or a protein network) in pulses. A protective effect of intact cells on starch gelatinization was observed by Wood et al. (1998) with pureed black beans flakes. The presence of enclosing protein matrix and cell walls may therefore restrict the gelatinization of starch, by limiting water and heat transfer, or space available for granular swelling (Lovegrove et al., 2017).

2.3 | Fiber

Up to one quarter of dry matter in pulses can be fiber, which is twice that of many cereals (Table 1). Many pulses require long soaking and cooking times because of the higher fiber content that is found in hulls and cell walls. Dietary fiber consists of a complex and assorted group of substances including a diverse range of nonstarch polysaccharides and carbohydrates that have different physical, chemical, and physiological properties (Macagnan et al., 2016). Properties that are functionally relevant for fiber are the particle size and bulk volume, the surface area characteristics, the hydration and rheological properties, and the adsorption or entrapment of minerals and organic molecules.

The soluble fraction of fiber consists of peptic polysaccharides like galacturonic acid, which is found in lentils and chickpeas, or hemicellulose (xyloglucan and xylans) found in navy and pinto beans (Hall et al., 2017). Pectins are the major fraction in soluble dietary fiber. Desi

TABLE 1 Proximate composition of selected pulses and cereals

	Pulses		Cereals		
Composition % d.b.	**Chickpea**	**Faba bean**	**Wheat**	**Maize**	**Oats**
Total carbohydrate %	**52–72** [3,7–10]	**66–68** [7]	**60–70** [15–17]	**63–71** [16,17]	**58–63** [26,17]
Starch %	30–56 [2,3,12–14]	32–50 [4–6,14]	46–60 [14]	54–73 [21]	50–61 [14,18]
Amylose (% starch)	23–35 [1,3]	30–33 [19]	19–31 [17,21]	24–38 [17,21]	19–34 [17]
Crude fiber %	1–3 [11]	NA	1–3 [16,21]	1–4 [16,21]	2–3 [16]
Total dietary fiber %	6–25 [1–3]	7–24 [4,6]	9–15 [15,17,21]	4–14 [17,21]	9[17]
Insoluble fiber %	18–24 [1–3]	NA	8–9 [17]	4–5 [17]	3–4 [17]
Soluble fiber %	1–8 [1–3]	NA	1–3 [17,21]	<1–2 [17,21]	4–5 [17]
Sugars %[a]	3–8 [2,3,12,13]	NA	2–3 [21]	1–3 [21]	NA
Protein	**13–29** [2,3,7–14]	**24–36** [3–7,14]	**8–18** [14–17,21]	**8–15** [16,17,21]	**9–20** [14,16–18]
Albumins (% protein)	39–54 [14]	45–50 [14]	9–20 [14,16]	4–8 [16]	10–24 [14,16]
Globulins (% protein)	43–60 [3,14]	45–80[3,14]	6–42 [14,16]	3–4 [16]	12–80 [14–17]
Legumin/Vicilin (as ratio of globulin content)	0.8 [3]	0.97–0.95 [22]	NA	NA	NA
Glutelin (% protein)	18–24 [3]	10–15 [3]	40–46	38–45 [16]	21–54 [16,17]
Prolamin (% protein)	3–7 [3,14]	1–6 [3,14]	33–49 [14,16]	47–55 [16]	12–35 [14,16]
	1–7 [2,7–14]	**1–4** [4–7,14]	**1–3** [14–17,21]	**3–9** [16,17,21]	**4–11** [14,16–18]
Ash	**3–4** [2–4,7–14]	**<1–4** [7,14,19]	**1–3** [14,16,17]	**1–2** [16,17]	**1–5** [14,16,17]

Notes: NA, Not available in the references cited. Desi and Kabuli composition values are represented by Chickpea.
[a]Sugar total of monosaccharides and oligosaccharides.
Sources: (1) M. Kaur & Singh, 2006; (2) Marengo et al., 2016; (3) Hall et al., 2017; (4) Rosa-Sibakov et al., 2016; (5) Hejdysz et al., 2016; (6) Guillon & Champ, 2007; (7) Güzel & Sayar, 2012; (8) Mondor et al., 2009; (9) Boye et al., 2010; (10) M. Kaur & Singh, 2005; (11) Ravi & Harte, 2009; (12) S. Kaur et al., 2014; (13) Wood et al., 2014; (14) Stone et al., 2019; (15) Kouris-Blazos & Belski, 2016; (16) Haard et al., 1999; (17) Welch, 2011; (18) Zhou et al., 1999; (19) Ambigaipalan et al., 2011; (20) Hoover et al., 2010; (21) Saldívar & Othón, 2010; (22) Schwenke et al., 1998.

chickpeas have half the pectin (raw 2.4%, dehulled 3.3%) of kabuli chickpeas (raw 5.1%, dehulled 6.3%) (Vasishtha et al., 2014). Interestingly, the pectin content does not change significantly after cooking in boiling water (Vasishtha et al., 2014). Hemicellulose comprises a range of noncellulosic cell wall polysaccharides that are soluble in alkali treatments. This includes arabinoxylans, which have significant processing effects in cereals because of increased solubility and viscosity (Lovegrove et al., 2017).

Insoluble fiber is the major fiber fraction in chickpeas and faba beans (Table 1) and is typically found in cell walls in the form of cellulose and lignin. Cellulose consists of unbranched chains in the order of 15,000 (1,4)-β-linked D-glucose units that associate by hydrogen bonding and Van der Waals interactions to form crystalline supramolecular complexes. In plant cells, cellulose complexes occur in two main polymorphs (Iα and Iβ) that take the form of microfibrils. Cellulose microfibrils form more complex structures from elementary microfibrils to microfibril bundles and aggregated macrofibrils (Silveira et al., 2016). These cellulose structures confer strength to the cell wall (Lovegrove et al., 2017). Lignin is the other major insoluble fiber (Desi 2.6%, Kabuli 1.5%) (Vasishtha et al., 2014).

2.4 | Protein

Pulses generally have high protein contents and often have twice as much protein as cereals. Additionally, pulse proteins are more soluble, partly as they have more hydrophilic amino acids. Proteins are often classed by their solubility in either 70% ethanol (prolamins), detergent (glutelin), water (albumins), or in a weak salt solution (globulins). Pulses are high in proteins that are easily digestible such as globulins and albumins (Lima et al., 2016) but low in glutelins that are more commonly found in cereals (Table 1). This protein composition results in amino acid profiles rich in lysine but low in methionine and cysteine. The two main globulin proteins which are classified by their sedimentation coefficients are legumin (11S) and vicilin (7S) (Table 1) (Hall et al., 2017). The albumin protein group includes several important types of proteins including lectins and enzyme inhibitors (Sathe, 2002).

3 | PROCESSING PULSES INTO FLAKES

3.1 | Purpose of pulse processing?

Pulses are processed and consumed in domestic settings using procedures such as atmospheric or pressure cooking and soaking to soften the texture (Clemente et al., 1998). For some pulses, the degree of cooking is important as it deactivates antinutritional factors and modifies the digestibility of carbohydrates and proteins, while preserving the beneficial functional aspects of pulses (Patterson et al., 2017; Revilla, 2015).

The purpose of processing pulses prior to retailing is to add value that customers are prepared to pay for. Low domestic consumption has been attributed to the time and effort required to soften the pulse, by soaking and boiling for a minimum of one hour. The degree of cooking achieved through processing may reduce the time required to prepare the pulses for consumption or present them as ready-to-eat (RTE). Manufacturing markets also value processing characteristics such as hydration rate, cooking times and dehulling, splitting and milling efficiency. Value adding of pulses by separating functional proteins, starches, and phytochemical ingredients is gaining momentum due to increased awareness of the health benefits of pulses, and trends for increased consumption of whole foods and wheat avoidance.

Processing methods use heat, moisture, and pressure to change molecular enthalpy, mobility, and solubility. These result in overall softening and molecular degradation, the loss of soluble fractions through water extraction to waste, and the reduced extraction of chemicals due to increased binding. The degree of binding may explain conflicting reports on compositional changes due to processing. For example, total starch has been reported to either increase or not change after cooking, roasting, and extrusion (Hall et al., 2017).

3.2 | Benefits of flaking pulses

In today's fast food culture, RTE breakfast foods have a global value of more than US$ 33 billion annually, of which 30% is in the flake form (NewsRx, 2015; Puppala, 1998). RTE breakfast foods are classified by the process through which they pass: Rolled flaked (whole grain, grit and extruded grit); extrusion puffed (direct expanded); oven puffed (whole grain and extruded); gun puffed (whole grain and extruded), shredded (whole grain and extruded), hot cereals (regular and precooked), and baked (Miller, 1994). These processes are well established for cereals, especially corn, wheat, and rice. Cereal flakes make up a third of the RTE breakfast food market and use many of the preconditioning and secondary processes also used for other RTE foods (Miller, 1994). An RTE pulse flake may address consumer demands for healthy, whole foods and clean ingredient labels, with the convenience of shelf stability and reduced cooking time. Insight into the adaptation of established cereal flaking processes to pulses may therefore help processor uptake of flaked pulses and their adoption into the RTE food market.

The application of flaking to pulses is not new. Patents for pulse flaking date from the early 1900s (Edward, 1914). Many pulse flake patents claim to reduce flatulence and flavor issues using drum and roller flaking (Bachler, 1931; Edward, 1914). Over the last century, a wide range of processing steps have been used to make pulse flakes ranging from simple soaking, heating, rolling and drying, through to multi-ingredient blends utilizing high-pressure steam or extrusion cooking and cold pellet formation. More recent patents have emulated the same process used for cereal flakes, including formulation, cooking, drying, pellet forming, flaking, drying, and toasting/frying the flakes (Table 2). Sattar et al. (2021) reported improved sensory qualities and bioactive properties with the inclusion of either germinated green gram (*Vigna radiata*), black gram (*Vigna mungo*), and lentils (*Lens culinaris*) at 15% in a cereal flake.

Pulse flake patents and literature report on the effects of processing in terms of subjective flake qualities such as texture, flatulence effects, flavor, and structural integrity. Little is reported on objective measurements such as the degree of gelatinization or protein denaturation, contributions of starch, protein, or fiber on the final integrity and sensory quality, or on why certain temperature and moisture levels are selected other than that derived from processing trials. Riantiningtyas and Sri (2017) made flakes formulated with different ratios of red kidney beans to corn flour, pelletized and flaked using a noodle maker and roller, and then oven dried at 150°C for 15 min and reported that a 30:70 ratio of bean to corn flour provided the best sensory evaluations with and without milk.

Commercial examples of flaked pulses include: Lupin flakes (Lupins for life Co, 2020), flaked peas (eFeed, 2010), Infra-ready flaked lentils and chickpeas (CIGI, 2013), and Masham Micronized Feed's flaked beans (Masham Micronized Feeds, 2011). There are also extruded flake cereal made of navy beans, garbanzo beans, and lentils (Love Grown Foods, 2020). While there are a few commercial products available, there is only a limited number of peer reviewed studies about the material science of flaked pulses. Table 2 highlights selected cited methods developed to overcome some important processing and product

TABLE 2 Examples of pulse flaking, their processing conditions, and claimed properties

Product and reference	Processing steps
Process for preparing leguminous products for edible purposes (naval bean and field beans) **Remove harmful substances/flavor. Maintain wholesome appetizing qualities lost in dehulling**. **Eaten with boiling milk or water** (Edward, 1914)	1. Parboiling 45 kg covered with water and sodium bicarbonate 340 g or soaking. for 8–12 h in brine solution. 2. Rinsing of beans with fresh water. 3. Cooking again in brine solution 2.5 kg salt to "near done" while keeping structure. 4. Drying surface. 5. Rolling (conditions not stated). 6. Drying to crisp and brittle (conditions not stated).
Leguminous flakes **Highly palatable, light fluffy texture**. **Reduced flatulence and digestive disturbance** (Bachler, 1931)	1. Soaking, continuous flow leaching of flavors 6–24 h. 2. Deodorization by steaming (<5 psi, <15 min). 3. Pressure cooking 25 psi to complete disintegration, blowing off odor (1–3 min). 4. Milling into paste and mixing with partial saccharization or seasoning. 5. Rotary drum drying and forming of flakes by scraping off film of dried material. 6. Oven baking flaked product to crisp texture.
Continuous flow apparatus for producing soybean flakes **Edible soybean flakes (removed toxic and odorous compounds). Improved protein digestibility. Controls moisture content and reduces process stickiness. More economical due to lower pressure heating and drying process** (Hiroshima, 1988)	1. Preheating with live steam. 2. Flow through pressure cooking with super-heated steam 0.5–0.7 kg/cm^{2}G at 125–130°C for 2–3 min. Undercooking does not remove odor of toxic substances; over cooking increases moisture content producing sticky flakes. 3. Drying by deaerator. 4. Rolled into flakes at moisture content (not specified) where they are at soft state for economical rolling. 5. Dehumidified at >80°C. 6. Air cooled.
Cell structure and starch nature as key determinants of the digestion rate of starch in legume **Disrupting the cells prior to cooking increases digestibility of leguminous seeds** **Effective to control the blood plasma glucose and hunger in people** **<3 % rancid on storage, >8 % turns brown from Maillard reaction**. **Digestion index less than 30**. (Wursch et al., 1986)	Patent US4853248 1. Soaking beans and lentils 0.6 to 24 h at 20–65°C. 2. Soaking in Ca solution at less than 3 mmoles/L for 10–24 h. 3. Cooked 40–60 min with saturated steam at atmospheric pressure. 4. Draining of water from seeds and forming puree by passing through a plate screen 3–5 mm. 5. Legume puree is drum dried at 110–115°C for 8–25 s to flake of surface area of 4 mm^2 with 3–8 % moisture.
Dehydrated refried bean product and methods of manufacture **Whole bean minimizes gritty and grainy texture. Thickness allows rapid rehydration to similar texture of cooked beans**. (Sterner et al., 1988)	1. Destone, wash, split. 2. Cook at 10–15 psi 63 % water (15–20 min) adding 20 % by weight of steam with 2–4% salt. 3. Drained and blast ambient air drying. 4. Rolling to 250–1270 μm. 5. Dehydration by hot air belt dryer 60°C–150°C to 7–10% w/w moisture.
Dehydrated precooked flaked pinto beans **Edible after adding hot water for 5 min**. **<20% moisture results in shattering of seed at roller stage**. (Nickels, 2005)	1. Cleaning and presoaking in 98°C water (time not stated). 2. Pressure cooking with water added to 110°C for 40–45 min at 15 psi so that all water is absorbed. 3. Dehydration to 20 %. 4. Covering with oil to soften skin. 5. Rolled to flakes with corrugated steel heated rollers (temperature not stated). 6. Dried to 7 –9 %w/w moisture and air cooled.

(Continues)

TABLE 2 (Continued)

Product and reference	Processing steps
Micronized flaked lentils in a bar format **Improved sensory characteristics and customer acceptability**. **Increasing dietary fiber, protein, iron, and folate**. **Shelf stability over 3 weeks**. (Ryland et al., 2010)	1. Tempered to 16 % moisture for 16 h. 2. Heated by gas-fired microniser (Model MR20). 3. Roller mill set to produce a thickness of 1.35 ± 0.5 mm. 4. Dry to final moisture of 8 % at 126°C 5. Mixed with other ingredients and formed into a snack bar.
Legume flakes (chickpea flakes) **Suitable for use in breakfast cereal or snack bar**. **Skin is darker than the white inside. Brittle at room temperature**. **High fiber, low GI, high satiety** (Malhotra, 2012)	1. Soaking for 10–12 h. 2. Cooking for 4 h at 77°C. 3. Compressing into a sheet of 2–3 mm depth. 4. Drying by either: Drum > 100°C, 100°C Oven for 1 h 45 minutes or 700–850 W Microwave for 2 min and cooled to produce a flake
RTE cereal flakes containing legumes **10–50% legume content**. **Bulk density 130–163 g/L**. **Structural integrity and bowl life similar to conventional RTE flakes**. **RTE flakes have a desirable taste with no beany flavor**. (Gandhi & Wenk, 2012)	1AAdded protein isolates and processing aid, flavor (sugar, salt, spice) to cereal grains. 2. Pressure cooking 60 min at 20–25 psi (125–130°C) to 30–35 %w/w moisture. 3. Cooling. 4. Fluidized bed drying to 20–26 %w/w, milling to 3.2–16 mm. 5. Addition of legumes (black bean). OR B. Combine all ingredients in extrusion cooker producing nonexpanded rope form. THEN 1. Cold pellet formed with w/w moisture at 30–40 g per 100 pellets. 2. Fluidized bed drying at 88°C for 4 min to 17–19% moisture. 3. Flaking at 43–66°C with rollers running at 550–650 rpm. 4. Drying and toasting to 1–5% moisture. 5. Application of flavor coating and packaging.
RTE green chickpea flakes **Favorable color retention, trypsin inhibitor breakdown and organoleptic results**. **Minimal grain breakage**. (Jha et al., 2016)	1. Soaked at 60°C to 30% moisture. 2. Microwaved 18 W/g 3 min. 3. Rolling. 4. Roasting with 48.1 W/g microwave power for 1 min.
Chickpea food composition and preparation process **Affording nutritional benefits of chickpeas, amino acids, and polyunsaturated fat content in a snack or cereal form** (Devinder pal Singh Chahal, 2017)	1. Formulation: 25–35 % chickpea flour, plus lipids, sugar flavoring, additives (fiber, minerals, vitamins), and nuts. 2. Extrusion cooking 100–185°C and forming into breakfast cereal form or bar. 3. Fried and flavored.

issues, such as improving digestibility, reducing odors, and improving texture, integrity, and bowl life.

3.3 | Impact of processing on pulses

Care needs to be taken by food manufacturers when processing pulses. Optimization of processing parameters is needed to ensure end products are digestible, maintain their integrity, and not become "grainy" due to being overcooked (Ravi et al., 2011; Sterner et al., 1988). Pulse processing generally aims to improve digestibility, control strong "beany" off-flavors, and reduce the need for consumers to use long soaking times or higher cooking temperatures and pressures (Jiang et al., 2015; Revilla, 2015).

Value adding to pulses by improving digestibility has been well studied. Many different moisture and thermal treatments have demonstrated changes in starch digestibility that impact postprandial glucose levels, protein digestibility, and the availability of minerals (Alonso et al., 2001; Cuvelier et al., 2017). Improvements in digestibility have also been demonstrated through the deactivation of antinutritional factors such as protease inhibitors (trypsin, chymotrypsin), lectin activity, and tannins and iron chelation (Muzquiz et al., 2012; Patterson et al., 2017).

Off-flavors in pulses is a recognized issue, which is either inherent in the pulse or developed during harvesting, storage, or processing. The Roland et al. (2017) review on flavor aspects of pulse ingredients highlighted that these off-flavors are usually due to lipid oxidation or some form of heat reactions between several compounds including sugars, amino acids, phenolic acids, carotenoids, and thiamine. These undesirable flavors can often be removed, changed, or masked with processing. For example, steam venting during cooking is commonly used to remove volatile odors in pulses (Bachler, 1931). Microwave heating with 1- to 2-min heating times has been shown to reduce Faba bean peroxidase and lipoxygenase, both of which are associated with the development of off-flavors (Jiang et al., 2015). Roland et al. (2017) found that there is a gap in knowledge about off-flavor compounds in pulses, limiting the ability to determine the effects processing and food structures have on flavor chemistry.

3.4 | Impact of pulse composition on processing and flaking

3.4.1 | Cell walls

The cellulose, lignin, and hemicellulose matrix in plant cell walls are collectively known as lignocellulose. Lignin and hemicellulose form a noncrystalline matrix around the cellulose fibrils (Silveira et al., 2016). As lignin is more hydrophobic than polysaccharides, it reduces the water permeability of cell walls and vacuoles (Wolter, 1973) and hinders enzymatic breakdown. Restriction of water absorption into the cell's starch granules and protein bodies may also have an impact on the degree of processing required to disrupt these structures and to form a new matrix. Lignin, along with phenolics, has been reported to contribute to faba bean hardening associated with being hard-to-cook. Such hardening is associated with the lignification of cotyledon cell walls and seed coats in conjunction with high (>25°C) seed storage temperatures over a period of 12 months (Nasar-Abbas et al., 2008).

Leguminous cells are still largely intact following processing. Cooking partially depolymerizes and partially solubilizes hemicellulose and insoluble pectic substances, resulting in the disappearance of the middle lamella and allowing the cells to separate after cooking treatments (Noah et al., 1998; Tosh & Yada, 2010). The removal of the middle lamella is a normal stage in the cooking process. Hard-to-cook pulses have also been associated with the failure of heat treatments to remove the middle lamella (Stanley & Aguilera, 1985). Cell walls show increased elasticity, plasticity, and loosening in response to internal turgor and external physical forces. Cosgrove (2018) highlighted that the molecular mechanisms for cell wall loosening are poorly understood. Therefore, cell wall properties and configuration are an important consideration in processing pulses.

3.4.2 | Protein

The most abundant globulin protein fractions of pulse seeds include legumin and vicillin, which have unique aggregation and processing interactions. Legumin melts at 89.8°C and is not coagulated by heat (Schwenke et al., 1998). Vicilin starts to lose tertiary structure above 60°C, denatures at 90°C, and coagulates at 95°C (Derbyshire et al., 1976; Mundi, 2012) (Table 4). Globulins and albumins do not form an elastic network like the gliadins and glutenins of wheat (Rosa-Sibakov et al., 2016); however, Ben-Hdech et al. (1991) found that pea protein bodies can be disrupted in high shear extrusion processes to form protein fibrillar matrixes. Proteins are also most thermally stable at their isoelectric region of pH 4–5 where net charge is low. Changing pH outside this region is known to dramatically reduce denaturation temperatures (Biliaderis, 1983). Chickpea proteins at pH of 6 or above can have solubility of over 90% (Withana-Gamage et al., 2011). These differences in solubility, interactions, and stability present processing-efficiency and product-quality challenges and opportunities for pulse flakes.

Proteins undergo hydrothermal reconfiguration during processing, and this can change their ionic, hydrogen, and hydrophobic bonding and cross-linking (Chanvrier et al., 2005). Wood et al. (2014) reported that proteins may play a role in difficult-to-mill chickpea genotypes due to changes in cotyledon cellular adhesion.

4 | MATERIAL SCIENCE ASPECTS OF FLAKE PROCESSING

Prior to flaking, grits are commonly processed using a range of formulation, preconditioning, cooking, and tempering steps. These processes change the food's composition, structure, and thermal processing properties to produce a new amorphous matrix of starches, protein, and fiber. Different processes vary in their ability to soften or break cell walls, denature proteins, gelatinize starch, and mobilize soluble materials of pulses. Formulation involves the selection of raw materials and additives, such as salt or sugar, which can influence how the pulse responds to processing. Next, the pulse is conditioned by hydration to decrease materials glass transition temperature. Further hydration will also occur during cooking where the heat may result in starch gelatinization and protein denaturation. Tempering by allowing the material to cool and dry near the glass transition leads to the formation of new moisture and temperature distributions, such as a dry skin. Forming applies physical forces to shape the material into flakes; this may include pelletization and flaking. Secondary processing then will dry (and coat) the flake for stability, texture, and flavor. As shown in Table 2, there is significant scope for different approaches to process pulses into flakes.

4.1 | Formulation

Formulation has an impact on the raw material matrix composition (Bachler, 1931). Processing may change the composition by removal of hull and leaching of soluble materials. For example, increases in protein are attributed by Vasishtha et al. (2014) to the removal of hull or the loss of soluble solids during cooking. Processing has been shown to change the fiber content of chickpeas (Vasishtha et al., 2014). Dehulling reduces the cellulose by 25% for Desi chickpeas and 12.5% for Kabuli chickpeas. Conversely, cooking can lead to an increase in the proportion of cellulose, likely due to the loss of soluble material. Cooked Desi chickpeas have two and a half times more cellulose than cooked Kabuli chickpeas (Vasishtha et al., 2014). Formulation also includes the addition of ingredients such as sugar, salt, or malt (Levine et al., 2004) or the addition of more starch, protein, or fiber (Chaunier et al., 2007). Many applications of pulse extrusion or traditional baking processes overcome the poor structural contribution of pulses by including rice starch or hydrocolloid gums.

4.2 | Temperature and moisture control in flake processing

Flake processing uses heat, water, and pressure to transition ingredients from a hard and unreactive state into a soft and reactive state. Food molecules—according to their structure, polarity, and chemical composition—form structures with a range of states. States range from a metastable crystalline solid or stable amorphous glassy state to an interactive plastic/rubbery state, and then to a reactive melted state. The glass transition is influenced by the rate of heating or cooling, pressure, molecular weight, water availability, composition, and pH of the food material (Balasubramanian et al., 2016). Water has a very low glass transition temperature (~ −140°K) and acts as a strong plasticizer, reducing the glass transition temperature.

Starch, fiber, and proteins have unique intermolecular properties driven by their composition, size, and structural configuration. As such, the thermal properties of chickpea fiber are different to chickpea starch or proteins. Likewise, the thermal properties of chickpea starch will be different to Faba bean starch or corn starch. Therefore, the quantity, quality, and location of these molecules affect the thermal properties of a food matrix. A prime example is the effect of water on the glass transition. Table 4 lists some selected glass transition (T_g) and melting temperatures (T_m) cited for pulses, cereals, and their components, at specified moisture contents. This implies that a wide range of glass transitions are present in a food matrix, due to the wide range of molecular sizes and interactions present, resulting in different thermal properties of the outer hull, cell walls, cellular protein, and starch. Proteins and starch have different moisture sorption isotherms. Where protein and starch have been exposed to similar relative humidity, the starch part has a higher moisture content than the protein (Chanvrier et al., 2005) and this can impact their behavior under pressure or shear forces. Large molecular weight glass-forming biopolymers such as starch and protein have similar glass transition curves, with T_g around 200°C when anhydrous; increasing the water content to 15–25% reduces the Tg to room temperature at a rate of around 10°C per 1% moisture (Slade et al., 1993).

For flake processing to modify molecular structures and the final flake form, the process must be conducted above the glass transition temperature. To illustrate the processing importance of glass transition, Figure 2 shows the moisture and temperature targets for processing steps found in legume flaking Patent US 201213488715 A (Gandhi & Wenk, 2012). The moisture and temperature dependence of the patent is demonstrated by mapping against the glass transition for barley starch, gluten, pea starch, and pea protein (Pelgrom et al., 2012; Toufeili et al., 2002; van Donkelaar et al., 2015). Only the first and last steps of the flaking process for Patent US-201213488715-A occur below the starch and gluten protein glass transition temperatures. Pelgrom et al. (2012) argue that the pea matrix containing protein and starch may occur in three states: first, protein and starch in a glass or crystalline state; second, with protein in a rubbery state and starch in a glass state; or third, both starch and protein in a rubbery state. The pea protein and starch transition curves sit below those of the cereal barley starch and wheat gluten. While moisture and temperature vary significantly throughout the process, most steps are just above the glass transition temperature, except for the cooking step. As the legume starch and protein glass transitions may be below that found in cereals, pulses may not need to have the same degree of temperature exposure or moisture content to change their starch and proteins.

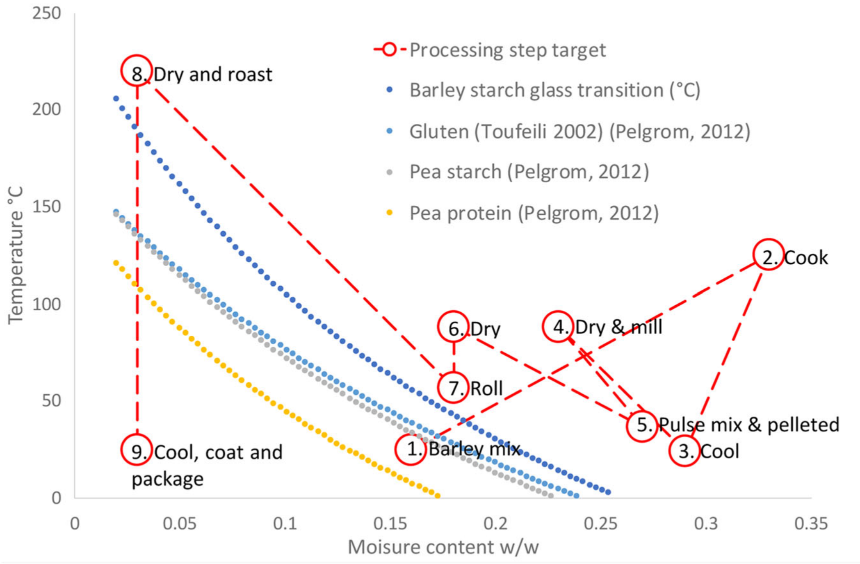

FIGURE 2 Heat and moisture process targets for cereal flakes containing legumes patent US 201213488715 A (Gandhi & Wenk, 2012) mapped to the glass transition of barley starch, pea starch, pea protein, and gluten (Pelgrom, Schutyser, et al., 2012; Toufeili et al., 2002; van Donkelaar et al., 2015)

The following sections will explore these process steps further.

4.3 | Preconditioning and cooking

Preconditioning the unprocessed grain through soaking, live steam injection, or heating is often an effective way to increase the moisture content and temperature of grains prior to more intensive cooking. The grain may be partially cooked in the preconditioning process when it is heated above its melting temperature. Cooking degrades cellular structures, denatures proteins, and gelatinizes starch. There are many forms of cooking used in grain processing ranging from boiling, pressure cooking, vacuum steaming, steaming, and mechanical extrusion (Bahrani et al., 2014). Each process may apply thermal energy through conduction (jacketed steam, hot plate), convection (live steam, boiling water, hot air), or conversion (mechanical friction or shear, microwave, pressure, infrared energy) (Miller, 1994).

The methods for cooking prior to flaking are kilning, batch pressure cooking, and the extrusion cooking method. Kiln heating involves heating the grain with live steam and then drying. Kilning is used with oats to reduce lipase activity and microbial activity, which affects flavor formation (Gates, 2007) and pasting characteristics (Zhou et al., 1999). The choice and application of moisture and heat are critical for desired cooking outcome. Batch cooking (Figure 2: step 2) can reach temperatures of 110–130°C and is preferred over boiling or steaming as some starch granules, protein bodies, and cellular structures are thermotolerant below 100°C. Legume flaking Patent US 201213488715-A (Gandhi & Wenk, 2012) shows significantly increased water content in a batch pressure cooker (Figure 2: step 2). The patent also includes an extrusion cooking processing path that can combine steps 2, 3, and 4 by blending all the material in an extrusion screw that is heated (to higher than 130°C) at lower moisture contents for shorter cooking times.

There are several manufacturing advantages of extrusion cooking. These include smaller plant size, lower energy requirements, faster continuous cooking at lower moisture contents, plus the ability to form grits to a specific size and shape. Extrusion can mechanically shear crystalline starch and protein into shorter more soluble molecules with lower molecular bonding. Extruded flakes examined under a microscope were found to have less matrix formation and thinner bubble cell walls than traditional flakes. Huang (1998) proposes two explanations: First, that the extrusion process with high shear forces is breaking up the starch molecules by dextrinization, or second, that batch cooking involves not only low shear and excess moisture, but also includes a significant tempering step allowing the retrogradation required for matrix formation. Chaunier et al. (2007) compared corn flakes from batch cooking and extrusion cooking and found that the flakes develop quite different puff cell morphologies when toasted. Batch cooked roasted flake cells are more randomly distributed, smaller, and thicker walled, while extruded roasted flakes were much larger (Sumithra & Bhattacharya, 2008).

4.4 | Water uptake, tempering, and steaming

The rate of water uptake is an important parameter for processing and is different for legumes and cereals (Kader, 1995). Hydration is well documented for Desi chickpeas, Kabuli chickpeas, and Faba beans (Costa et al., 2018; Kader, 1995). It is commonly reported that the rate of water uptake is influenced by the presence of a seed coat (Ross et al., 2010). Water uptake by the seed coat is affected primarily by the glass transition temperature of the seed coat and can vary from 22 to 33°C, meaning both heating and water are needed during food processing (Ross et al., 2008). Water uptake occurs by diffusion and is also dependent on the moisture differential, diffusion coefficient, the dimensions (volume, surface area) of the material, and the concentration of additives used to change solubility (Prasad et al., 2010). For example, Costa et al. (2018) reported that chickpeas heated to 100°C had three times higher water diffusion rates than heated at 25°C.

Tempering is the process of adding or removing a specific quantity of water and letting the material equilibrate. In grain processing, tempering lets the grits cool slowly to just above the glass transition temperature and allows water to equilibrate and amorphous regions to anneal (Jayakody & Hoover, 2008). Tempering corn, oat, or wheat grits may be performed at 10–20% moisture, at a temperature between 20 and 65°C and involving holding the materials at these conditions for 90 min to 1 week. This is a key step in the flaking process, after cooking (28–30 % moisture) and drying. Tempering is traditionally used to soften the dried outside grits so they are taken up by the rollers, and to reduce the stickiness of the inner part that would otherwise gum up the flaking rollers (Gonzalez, 2005). Tempering was used prior to micronization (Cenkowski et al., 2006; Patterson et al., 2017), dehulling (Ma et al., 2011), and intermittent drying (Gonzalez, 2005; Kumar et al., 2014). Conditioning by adding water prior to steaming has been shown to be more expensive compared to adding the water with live steam (Heimann, 1999). Tempering has been recognized to also affect the degree of matrix formation through processes like starch retrogradation. Low moisture (10–20%) and elevated temperature (90°C) treatments can increase the degree of polymer to polymer interactions (Brent et al., 1997; Gonzalez, 2005).

During tempering, the degree of retrogradation has been linked to final flake texture properties like strength and crispiness. Retrogradation at low temperatures with purified starch or protein gels is well documented and Gonzalez (2005) highlights that there are a few examples of retrogradation with whole grits. Adjusting the heat and moisture to 20°C above the glass transition has been shown to accelerate retrogradation effects in cornflake grits, when compared to tempering at the glass transition (Gonzalez, 2005). Therefore, the choice of tempering conditions with knowledge of glass transition will be valuable to improve the rate of moisture equilibration and retrogradation effects in pulse flake processing.

The limited published glass transition data for pulses (Table 3) and perception that pulses take longer to cook (Table 2) than cereals may contribute to the difficulty in producing pulse flakes that are comparable to cereals, such as corn flakes. The ability of cereal flakes to form new matrix structures through cooking and tempering is widely reported in cereals such as corn (Batterman-Azcona & Hamaker, 1998; Hundal & Takhar, 2009); however, reports on how the same matrix structures can be formed within a pulse flake are limited. The glass transition of pea starch and protein is lower than barley starch, which highlights that lower temperatures may be sufficient to process pulses that share similar proteins and starch to peas (Figure 2). Further work with shorter steaming times is therefore required to explore the capability and limitations of pulse flakes to replicate cereal flakes.

4.5 | Flake formation

A primary aspect of flake formation is the passing of a grit between two counter rotating metal rollers (Chaunier et al., 2007). A grit may consist of whole grain kernels, parts of kernels, or finer materials (such as flours) that are formed into pelleted flaking grits by extrusion (Fast, 2000). For the grit to pass efficiently through the rollers, it needs to be preconditioned into a rubbery state by controlling moisture and temperature by passing between two counter rotating rollers.

Flaking has several purposes in the processing of grain. The forces applied to form flakes result in cellular and molecular deformations. Increasing the surface area and rupturing the cell walls may improve the water movement that is needed for cooking or drying. Conversely, however, the compression process is also reported to increase the density of the grit (Levine et al., 2004).

Prior to flaking, the material is first cooked and then left to cool (Figure 2: step 3) to just above the glass transition temperature. At this point, the grit is in a suitable viscoelastic state to form a flake. Flaking at conditions well above the glass transition temperature (i.e., rubbery state) can result in stickiness that will gum up the rollers, while flaking in the glassy state results in excessive force and energy being needed to pull the grit through the rollers. On cooling, the outside layer dries, forming a "skin." The material may be left to temper for some hours to equilibrate the internal moisture content and temperature before rolling into a flake. Levine et al. (2003) demonstrated that the key factors in flake rolling includes the size and shape of the material being fed into the rollers (the "grit"), the diameter of the rollers, the gap between the rollers, and the viscoelastic state of the grit. Levine et al. (2004) reported that rolling affected the physicochemical properties of the

TABLE 3 Selected glass–rubber phase transitions of cereals, pulses, and components at specific moisture

Material	Glass transition T_g (°C) (moisture % w/w)	Source
Pea protein	40°C (10 %) 25°C (15 %)	(Pelgrom, Schutyser, & Boom, 2012)
Pea starch	45–60°C (10–14 %) 30–45°C (15–17 %)	(Pelgrom, Schutyser, et al., 2012)
Corn starch	100°C (10 %) 91°C (13 %) <30°C (30 %)	(Chanvrier et al., 2005) (Ditudompo et al., 2013) (Ditudompo et al., 2013)
Amorphous corn starch	107°C (10 % at 33 % RH) 98°C (12 % at 59 % RH)	(Chanvrier et al., 2005)
Zein—Corn storage protein	85°C (4.5 % at 33 % RH) 100°C (7.1 % at 59 % RH)	(Chanvrier et al., 2005)
Corn 85 % starch and 15 % zein blend	100°C (10 %)	(Chanvrier et al., 2005)
Corn kernels	26–58 (12 %) 21–64 (20 %) 23–54 (25 %)	(Hundal & Takhar, 2009)
Heat set wheat gluten	39.3°C (11.8 %)	(Nicholls et al., 1995)
Cooked wheat starch	73.4°C (14.7 %)	(Nicholls et al., 1995)
Cooked waxy maize starch	73.7°C (14.0 %)	(Nicholls et al., 1995)
Lignin (wheat straw)	50°C (Saturated) 80°C (atmospheric)	(Ibbett et al., 2011)
Lignin	110 and 160°C (dry)	(Olsson & Salmén, 1992)as cited by (Ten & Vermerris, 2013)
Corn Hemicellulose	101°C (10 %) 87°C (20 %) 72°C (30 %)	(Georget et al., 1999)
Hemicellulose	190–195°C (wet degradation) 240°C (dry pyrolysis)	(Ibbett et al., 2011)
Cellulose	220–247°C (dry) 356°C (dry) 246°C (4.6 %) −34°C (~15 % and 66 % crystallinity index). Room temperature recrystallization (19 %, RH > 80 %)	(Wu et al., 2015) (Mazeau, 2015) (Paes et al., 2010) (Paes et al., 2010)
Extruded cereal starch (gelatinized)	50–60°C (14 %) 90–100°C (10 %) 150–165°C (5 %)	(Bindzus et al., 2002)
Soy seedling cell wall	60°C (saturated)	(Lin et al., 1991)

flake by the amount of roller energy delivered to the flake. A number of physical effects also occur with smaller roller gaps such as increased flake density, and a decrease in air bubbles in the flake to act as nucleation sites for puffing (Levine et al., 2004).

The opportunity to use whole seed or seed fragments as grits for rolling is limited by the size and shape of the seed. Extrusion formation of pellets allows for customization of not only size and shape, but also the grit formulation. For example, Gandhi and Wenk (2012) included a legume and water mixture after cooking and milling a barley mix (Figure 2: step 4), which was then formed into pelleted grits (Figure 2: step 5) and dried (Figure 2: step 6). At step 5, the pellets moisture content may result in a glass transition below room temperature and allowed them to be dried, prevents forming sticky paste on the rollers (Figure 2: step 7).

4.6 | Drying, toasting, and coating

Reducing the moisture content forms crispy glassy structures and generates new flavors. As seen in spray drying (Bhandari et al., 1997), drying flakes will be more effective above the glass transition temperature where there is sufficient molecular mobility for water to move freely out of the flake (Figure 2: step 8). Higher drying temperatures are used to toast the flake, changing the flavor profile. Toasting may be carried out at later stages of drying as rapid heating to toasting temperatures may result in the formation of plastic surfaces, reducing mobility and decreasing drying efficiency (Bhandari et al., 1997).

Temperature and time conditions for drying and toasting are key influencers on the final flake structure, texture, and eating experience. Toasting has been shown to cause structural puffing that increases corn flake height, gives greater porosity, and decreases bulk density. The degree of puffing in corn is mostly dependent on moisture content, temperature, and time of cooking (Sumithra & Bhattacharya, 2008).

After drying or toasting, the flakes are cooled, coated, and packaged (Figure 2: step 9). The flake matrix then moves to below the glass transition temperature to form a crisp texture. The final coating of flavors or sugar has been shown in cereal flakes to protect the flake from moisture absorption during storage, as well as to increase bowl life.

5 | INFLUENCE OF MATERIAL AND PROCESSING ON FLAKE ATTRIBUTES

The effect of processing on cereal flakes, especially corn flakes, is well studied. For pulses, the effect of soaking, cooking, and drying is also well documented; however, there is limited published data on pulse flaking and the resulting flake quality. The following sections compare published data on cereal flakes and pulse-based foods to explore the expected quality of pulse flakes. The comparisons are grouped into physical attributes, mechanical performance, and physicochemical properties. Physical attributes of flakes are the quality factors that are discernible by our human senses such as dimension, shape, structure, and color. Mechanical performance of flakes refers to its hardness, durability, and bowl life. Physicochemical properties include the molecular interactions observed with change in moisture content, hydration capacity, solubility, and the degree of gelatinization and denaturation.

5.1 | Dimensions

Levine and coworkers report that the flake dimensions are proportional to the size of the grit, the size of the rollers, and the gap between them (Levine, 2003; Levine & Levine, 1997). As grits pass through the roller gap (Figure 2: step 7), shear and pressure forces cause a significant flattening of their overall dimensions. The change in dimensions during rolling occurs in conjunction with cellular disruption, air expulsion (decreased porosity), further denaturation of protein, and degradation of starches (Levine et al., 2004). Smaller roller diameters also produce lower pressures compared to similar gaps on larger diameter rollers, which increases the widening of the flake (Levine et al., 2003). When the size of the grit used is significantly larger than the roller gap, a variation in flake dimension may also occur due to the application of excessive roller forces. Excessive roller forces result in damaged starch, higher aspect ratios, edge tearing, cellular disruption, and decreased puffing (Cenkowski et al., 2006). Despite the importance of roller to grit ratio, this information is not widely reported in the general literature cited.

5.2 | Shape

Flake shape may be useful for evaluating the efficiency of the roller settings and provide insight into internal adhesion properties. Levine et al. (1997, 2003) reported the appearance of tears near the edge of flakes as a symptom of excessive roller forces. Excessive forces may occur during rolling by decreasing the roller gap, increasing the pellet viscosity, or increasing the pellet size. Work conducted by Gates (2007) with oat flakes found an increase in flake cracks was associated with a more brittle fracture, rather than a plastic flow. Increased brittleness and stiffness of the grits may be due to heat treatment increasing the adhesion between starch granules (Gates, 2007). Gates (2007) suggested that, at small deformations (e.g., a larger rolling gap), the interaction of the cell walls and the strength of the bonds between the starch granules define the mechanical properties, while at higher deformations (e.g., a smaller rolling gap), the mechanical properties during rolling would be increasingly affected by the properties of the starch granules and protein bodies. The quantification of flake shape is limited in the literature.

5.3 | Microstructural changes

Structures commonly seen with food processing scanning electron microscopy (SEM) include starch granules, cell walls, protein bodies, starch–protein matrices, and leached solutes (Gowen et al., 2006). Ben-Hdech et al. (1991) observed different phases of transformation of the protein matrix due to decreasing distances from the heat source in pea flour. They also found that the fusing of the protein bodies occurred before starch, resulting in protein-encased starch granules. It is therefore expected that heat and moisture treatment of pulses will progress with the loss of the middle lamella, an aggregation of protein bodies around starch, and a final formation of starch–protein networks.

5.4 | Puff structures

Puffing in the form of bubbles or voids is a desirable characteristic of snack foods (Gupta & Bhattacharya, 2017). The high surface area to volume ratio of the flake form allows efficient heat and mass transfer during toasting (drying), causing a rapid expansion of air and loss of water. The rapid movement of the water out of the flake and expansion of hot air forms pores and vacuoles (Gupta & Bhattacharya, 2017). Sumithra and Bhattacharya (2008) observed that as moisture moves out, the pores and vacuoles join and form cell-like voids in the flake that rapidly transition to a stable glassy state. The degree of puffing was predominately associated with a higher flake moisture content. The cell-like puffed structures varied in size and wall thickness. Increased puffing may also increase macro scale features of the flake, including thickness, crispiness, mechanical strength, and lower bulk density (González et al., 2018; Sumithra & Bhattacharya, 2008). The composition (degree of gelatinization or protein aggregation) and morphology (cell wall thickness, porosity) of the kernel are key factors with puffing effect on starch gelatinization and water mobility (De Fátima Machado et al., 1998; Mariotti et al., 2006). Pulses such as chickpeas are traditionally puffed in hot sand in India. Similar to puffed popcorn, the variety is important, with notable puffing variety yielding around 50% puffing with 0.6 to 2.1 ml/g expansion and other varieties yield as low as 7% (Mukhopadhyay et al., 2015). Extrusion of pulse flour and cereal blends has been shown to result in puffing to varying extents (Portman et al., 2020; Simons et al., 2015). In contrast, puffing has not been widely reported for pulse flakes (Gupta & Bhattacharya, 2017). It is expected that drying should produce vapor pressures required for puffing; however, without a coherent gel forming starch or protein matrix, it is unclear if and how puff void spaces might form (van der Sman & Broeze, 2013).

6 | MECHANICAL PERFORMANCE

Mechanical performance relates to how flakes respond to real-world physical forces. For example, flake "durability" during packaging and transport, and the rate at which the flakes become soggy in a bowl of milk ("bowl life") are important quality characteristics. Commercial and customer (including consumer) considerations are often impacted by these mechanical performance criteria (Multari et al., 2015). Pulses with their unique structures and chemical compositions are expected to show different mechanical properties to cereals. Research is required to identify the key factors that limit the mechanical performance of pulse flakes and to draw correlations with the reported performance of other formed pulse products such as pelletization and extrusion.

6.1 | Flake durability

With the absence of gluten proteins that provide functionality in cereal products such as elasticity and structure formation and texture, flake durability is a critical parameter for commercial viability. Transportation causes flakes to collide with the machinery and other flakes. These vibrational or tumbling forces can damage the flakes. Flake damage results in various sizes of broken flakes including fine flour-like material (Mina-Boac et al., 2006). Broken flakes may be of lower value to the customer and fine materials can cause issues with processing machinery. Removing the broken and fine material reduces revenue and increases costs. Therefore, understanding the factors that can improve the ability of the pulse flake to physically survive the process is foundational to the commercial production of pulse flakes.

The resilience of a flake during processing is termed "durability" and can be characterized by simulated tumbling, bending, and bulk compression (Fahrenholz, 2012). For example, the Pfost tumbling can simulate process conditions by tumbling flakes at a constant fall distance, rate, and time (Yang et al., 2008). A durability index is the measure of the percentage of product that can withstand breakage and disintegration after defined exposure to a tumbling motion or pneumatic handling (Singh, 2016). A high degree of gelatinization is desirable for improved digestibility and gel matrix; however, Yang et al. (2008) reported that increased degree of starch gelatinization proportionally decreases pea flake durability (87–35%) which was an issue as flakes of less than 4 mm were considered unmarketable. There is limited durability data available for pulse flakes. Some inference may be drawn by looking at corn flakes (thickness; Sumithra & Bhattacharya, 2008) or processes such as pelletization and extrusion.

Durability index is commonly performed for pelletized material and the use of this index with pulse flakes may identify factors required to improve flake durability.

Various processing conditions have been reported to improve the durability of densified biomass products such as pellets and flakes. For example, the durability of animal feed pellets containing soy improved by increasing soy content (21–59%), lowering the extrusion temperature (100–150°C), and increasing the die aspect ratios (3.33–7.25 at 25% moisture) (Singh, 2016). Higher moisture contents have been associated with improved pellet durability of densified biomass products due to improved cohesive forces between particles (Kaliyan & Vance Morey, 2009). A suitable increase in final moisture in the pulse flakes may therefore increase the plasticity of the proteins or facilitate increased degree of hydrogen bonding. The flake dimensions are also important for durability. In oats, thick flakes are reported to have high durability with increased tempering time. This is due to starch pasting at the flake surface that encases the "floury" endosperm (Gates, 2007).

6.2 | Hardness

Texture analyzers can detect the physical force, resistance, and breakage of the micro cellular structures present in flakes (Chaunier et al., 2007). Bending individual flakes with a three-point bend rig is a means of determining flake hardness or resistance to breaking and changes to these microstructures. Texture analysis of flakes can be evaluated individually using a spherical probe (Sumithra & Bhattacharya, 2008) or in bulk with a multiple plate probe like a Kramer Shear Cell (Puppala, 1998).The force required to break the flake is a measure of hardness, while "degree of flex before breaking" defines brittleness. Number and frequency of fractures define the crispness of the structure. Like a bridge, the ability of the flake to resist breakage and the way that it fractures is a function of the material form, physicochemical composition, and arrangement within the microstructures. Chaunier et al. (2007) used a Kramer Shear Cell to find that the size of corn flakes is also a significant factor for mechanical strength. Many pulse flake patents process the pulse to modify the natural cellular structure and molecular configuration; however, the changes in the material hardness are not well reported.

Works completed on corn pellet and corn flakes have highlighted the importance of macromolecular structure, composition, and the capability of the heat, moisture, and physical treatments to form new structures. Hardness and degree of puffing in toasted corn flakes was studied by Sumithra and Bhattacharya (2008). They found toasted corn flake puncture forces were the highest when toasting raw corn flakes with a lower moisture content. By increasing roasting temperature from 200 to 300°C, there was also a decrease in puncture forces. A lower moisture content correlates to a higher glass transition point that with the rapid drying may result in a reduced time for melting and reconfiguration of macromolecules such as proteins. Moreover, a higher drying temperature may increase the rate of melting and reconfiguration.

A common formulation practice is to use starch gelatinization and gluten to produce desirable textures in flakes and extruded products. Pulses with globulin protein contents between 10% and 35% (dry weight basis) are well known to have issues with extrudate strength, limiting their formulation inclusion rate. It is therefore important to consider the effect of the nongluten proteins on the product hardness. Chanvrier et al. (2005) doubled the formulated content of zein (the major storage protein of corn) to 10% dry weight in extrusion cooking and found significant reductions in corn extrudate strength as compared to native corn extrudate. They hypothesized that since zein has similar glass transitions to corn starch (Table 3), the decrease in strength was not due to changes in molecular mobility of glass transition, but to the nanostructures formed. During extrusion, zein denatures into agglomerate protein bodies that form an immiscible binary polymer structure within the gelatinized starch matrix. The cohesion of a two-part matrix was therefore limited by the cohesion between protein aggregates and starch matrix. As the protein content increased, the starch matrix was structurally compromised resulting in a decrease in product strength. The degree that pulse proteins interact with its starch will therefore be a factor in the tensile strength associated with pulse extrudates and flakes.

6.3 | Flake bowl life

The time taken for flakes to become soggy when placed in cold milk is termed "bowl life" and is dependent on the rate of moisture absorption and the resulting rate of change in the flake's glass transition (Gregson & Lee, 2002). Typically, breakfast flakes are eaten with cold milk or after cooking, as a porridge. These applications result in the flake's transition from crisp to a soggy texture over time. The mass of milk absorbed by a breakfast flake is characterized by its liquid uptake behavior, with an initial fast uptake rate and then a progressively decreased rate of liquid uptake (Sacchetti et al., 2003).

A bowl life test evaluates the flake's ability to keep crispy structures when exposed to milk (De Brier et al., 2015; Sumithra & Bhattacharya, 2008). Bowl life is qualitatively determined for flakes soaked for 2 min by sensory panel or by quantified changes in flake crispiness with a Kramer Shear Cell (Gregson & Lee, 2002). Measuring the amount

TABLE 4 DSC enthalpy of starch gelatinization and protein denaturation of different pulses

Starch source	T_o (°C)	T_p (°C)	T_e (°C)	Enthalpy J/g starch	Source
Faba bean	62–67	66– 80	73–85	7.5–12.5	(Priyatharini Ambigaipalan, Hoover, Donner, & Liu, 2014; P. Ambigaipalan et al., 2011)
Desi chickpea	62–70	63–73	73–79	8.8–10.7 10.6–13.2	(Alamri et al., 2015; Biliaderis, 1983; M. Kaur & Singh, 2006; Milán-Noris et al., 2016)
Kabuli chickpea	65	71	77	8.9	(M. Kaur & Singh, 2006)
Protein source (isolate %)	**T_o°C**	**T_p°C**	**T_e°C**	**Enthalpy J/g protein**	**Source**
Faba whole seed (27%)		91		7.0	(Murray et al., 1985)
Faba dehulled (32%)		91		8.2	Murray et al., 1985
Faba (isoelectric 84%)		91		9.0	Murray et al., 1985
Faba (micelle 86%)		91		21	Murray et al., 1985
Faba (86.6%)		88		18.4	(Arntfield & Murray, 1981)
Chickpea legumin 11S		80–99		2.6	(Withana-Gamage et al., 2011)
Chickpea vicilin 7S		80–85		0.5	Withana-Gamage et al., 2011
Desi (72–75% protein) Desi (79–81% protein)	77–8079	9390		2.8–3.3 3.3	Withana-Gamage et al., 2011
Kabuli (85% protein) Kabuli (74–77% protein)	80.280–85	8993		3.4 3.1–3.6	Withana-Gamage et al., 2011
C. arietinum var. thiva	57–80	92–103		4.0–7.7	(Papalamprou et al., 2009)
Chickpea proteins at 69% purity and 15 % moisture		170 and 240°C			(Pelgrom, Schutyser, et al., 2012; Ricci et al., 2018)
Legume globulins: 7S vicilin 11S legumin		70–75 >95°C			(Carbonaro et al., 2015)
Oat (45.5%)		112		18.8	(Arntfield & Murray, 1981)
Field pea (86.4%)		86		15.6	(Arntfield & Murray, 1981)
Field pea (isoelectric 70%) Field pea (micelle 88%)		94 89		18.7 20.1	(Murray et al., 1985)
Pea protein isolate	73.6	82		1.6	(Withana-Gamage et al., 2011)
Soy (85.0%)		93		14.6	(Arntfield & Murray, 1981)
Soy (isoelectric 81%) Soy (micelle 76%)		78,98 74,95			(Murray et al., 1985)

Notes: T_o, T_p, T_e stand for the onset, peak, and end temperature, respectively. Gelatinization or denaturation enthalpy of starch/protein expressed in J/g of dry starch/protein.

of moisture absorbed and the change in hardness provides an insight into the comparative bowl life of various flake-processing conditions.

Low moisture, high shear extrusion, or roller shear processing is associated with the fragmentation and dextrinization of starch granules, resulting in reduced flake crispiness and bowl life (Levine et al., 2004). Degraded starch has an increased rate of water absorption, resulting in a soggy flake with a slimy or sticky mouthfeel and "strange" taste (Puppala, 1998). For example, damaged starch and decreased bowl life were observed in corn flakes rolled with hard grits (Gonzalez, 2005). Puppala (1998) reported that flakes with a long bowl life also had a high dry compression force, while their water absorption index was similar.

7 | PHYSICOCHEMICAL PROPERTIES

The level of structural damage is termed "degree of cook"; this is a characteristic of extruded products (Gonzalez et al., 2001) and flaking is a form of rapid extrusion. The degree of cook depends on the response of ingredients to process moisture, heat, and pressure applied over a length of time.

The structural damage to cellular components, such as starch granules, protein bodies, and fibrous cell walls is achieved by milling flakes and determining their pasting properties and enthalpy of heating. Microwave heat treatments (1–2 min) have been shown to improve milling efficiency of Faba beans (Jiang et al., 2015). The swelling of starch on heating may be hindered by the high solubility of albumin proteins, which interact and compete with starch for the available water (Ghumman et al., 2016). Pasting properties, assessed by RVA (Rapid Visco Analyser) primarily respond to starch damage, but may also be affected by the presence of sufficient quantities of hydrophilic fiber and proteins (Santos et al., 2018). Proteins can also reduce the hydration of starch due to an encapsulation of the starch granules, which physically hinders viscosity development (Ai et al., 2016).

7.1 | Moisture and temperature during processing

The absorption of water reduces the cotyledons' glass transition temperature, which then enables the physical and chemical changes to occur during processing. Final moisture level is a key variable in defining flake quality or stability. For example, oats with moisture contents below 5% have increased risk of oxidation spoilage, while moisture contents above 12% risk microbial spoilage (Gates, 2007).

7.2 | Flake water-holding capacity and solubility index

How flakes interact with water affects flake qualities such as bowl life or their performance as an ingredient. Water absorption capacity and water solubility are gravimetric performance measurements commonly reported in processed ingredients, such as pulse flours. Hydration has important implications for the ability to further cook the flake or to change the flake's hardness and texture (Gregson & Lee, 2002). Flake hydration and solubilization can be an indicator of the degree of processing achieved.

Water holding capacity (WHC) has been shown to increase significantly for boiled Kabuli chickpea flour, (1.8 ml/g), and boiled Desi chickpea flour (1.5 ml/g) when compared to raw flour (Kabuli 1.0 ml/g, Desi 0.8 ml/g) and lightly roasted flour (Kabuli 0.9 ml/g, Desi 0.81 ml/g) (Ma et al., 2011). Similar changes in water solubility index (WSI) show an increase in either the liberation of soluble molecules or the degradation of insoluble molecules through disintegration or degradation.

Pulses are well known for their highly soluble proteins and oligosaccharides. Variation in the WHC and WSI of the cotyledon due to processing conditions may highlight changes in protein or carbohydrate solubility, variability in flake density or internal voids, and have implications in the rate of water absorption that can affect the cooking time or bowl life. Chickpeas are reported to release 2% of their mass on soaking at 25°C and up to 6% when boiled in water (Sabapathy, 2005). Kaur and Singh (2006) reported a chickpea water absorbance index of between 2.39 and 2.66 and WSI between 22.0 and 22.9 kg/100 kg of starch. Unheated Faba bean flour has been reported to have a protein extraction rate of 87%, which reduces to 25% with 3-min microwaving (116°C) or 80% with 30 min of dry heating (170°C) (Jiang et al., 2015).

7.3 | Pasting properties

The pasting properties of pulse flour reflect the propensity of starch granules to absorb water, swell, and disintegrate. Starch damage may increase the cold viscosity or decrease the final viscosity (Sarawong et al., 2014). Additionally, steaming can also increase the peak and final viscosity. For example, Zhou et al. (1999) reported steamed oats peak viscosity (before processing) increase from 470 RVU (rapid viscosity units or 5640 mPa.s) to 620 RVU (7440 mPa.s) after steaming and rolling.

During compression, decreasing the roller gap or increasing the roller speed increases the energy input into the flaking process. Increased energy input at rolling also increases the starch gelatinization and decreases glass transition temperature of corn flakes (Levine et al., 2004). Levine's evidence for starch degradation was an increased RVA peak viscosity, a decrease in the RVA final to peak viscosity ratio, and a decrease in the glass transition temperature of the flakes. Levine hypothesized that this degradation of the starch would alter the texture and bowl life in the toasted flake.

Short microwave heat treatments have been shown to decrease particle size after milling and increase the peak viscosity significantly, when compared to the unheated and dry heated Faba beans (Jiang et al., 2015). Longer heating times have been shown to increase the formation of insoluble protein–starch aggregates consisting of denatured protein and ungelatinized starch granules (Jiang et al., 2015).

Processing conditions can also affect how the starch and protein bind or disrupt the flake structure. Chaunier et al. (2007) found that the viscosity of batch-cooked roasted cornflakes was inhibited until temperatures of 70°C (restricted hydration) were reached. Milling peas with their protein in a rubbery state and their starch in a glassy state was suggested by Pelgrom et al. (2012) to improve the separation of protein from glassy starch granules. In contrast, the extruded cornflakes (specific mechanical energy = 150 J/g, die temperature = 130°C) presented immediate and increased RVA viscosity, independent of temperature (unrestricted hydration). Chaunier et al. (2007) concluded that there was a protein matrix present in batch cooked flakes that inhibited hydration of the starch, while extrusion with 26 % moisture, high shear, and elevated temperature conditions (130°C) had formed more independent protein aggregates. Using microscopy, Chaunier et al. (2007) confirmed that batch-cooked corn flakes had remnants of the original endosperm starch and protein bodies, while extruded flakes had a starch gel matrix embedded with round zein-based protein aggregates. They hypothesized that the distribution of protein and gelatinized starch determine the flake's mechanical properties, such as hardness.

7.4 | Enthalpy of gelatinization and denaturation

The effect of processing on the degree of gelatinization and protein denaturation has been extensively studied (Table 4). The temperature and heat energy, absorbed by starch and protein structures, are unique to their molecular weight, composition, and structural and conformational stability (Shevkani et al., 2015). For example, gelatinization has been attributed to melting starch granules (Biliaderis, 1983). Protein denaturation includes a range of unfolding of tertiary, secondary, and primary protein structures. In addition to endothermic loss of structure, denaturation can lead to formation of new bonds and structures such as the formation of new aggregates with proteins and nonprotein molecules such as phenols (Arntfield & Murray, 1981; Biliaderis, 1983; Murray et al., 1985). The thermal properties of pulse proteins have been studied using DSC which has shown that some areas of energy absorption overlap with that of starch (Table 4, Ross et al., 2008). The most prevalent proteins in pulses are the globulins (10–15 g/g) legumin 11S and vicilin 7S (Hall et al., 2017). Vicilin denatures between 80 and 85°C with an enthalpy of 0.5 J g^{-1}, and coagulates at 95°C (Derbyshire et al., 1976; Withana-Gamage et al., 2011).

8 | SUMMARY AND FUTURE WORK

There exists a range of cereal-based flakes from the large, puffed cornflakes to the soft dense whole rolled oats. Some key ideal properties are shared with all popular flaked cereal products, which include high degree of resistance to breakage during transport (durability >70% whole flakes after tumbling for 10 min), resistance to going "soggy" when placed in milk for 3-min (long bowl life), a minimal ingredient list (clean label), and acceptable sensory experience (mouthfeel and taste). The addition of fiber and protein ingredients to breakfast cereals to levels naturally found in pulses has resulted in RTE processing and sensory problems, resulting in flakes that are not acceptable to the consumers. Pulse flake RTE processes are described in the patent literature (Table 2), with process claims based on subjective sensory evaluations for degree of cook and flavor. However, objective evaluation of the material science aspects of flake processing is limited to studies on cereal flakes, such as the degree of hydration, cellular separation, enthalpy of heating, and effects on final flake properties such as texture, puffing, and durability. A significant body of pulse-processing research is available on the common effects of heat and moisture in processes such as traditional cooking, extrusion, and milling but pulse flaking and its corresponding processing challenges have not been addressed. The cellular structures and composition of pulses may restrict hydration and increase the heat enthalpy required for denaturation and gelatinization compared to cereals. However, overcooking may result in poorer quality attributes such as durability and integrity. Therefore, further work must explore the hypothesis that pulses, due to their unique composition and structure, will respond differently compared to cereals when flaked and will produce flakes with unique attributes. To minimize the risk of costly process issues due to raw material batch-to-batch variation, a deeper understanding of the raw material quality is essential to ensure the development of robust pulse material and process specifications. The degree of binding between starch, protein, and other cellular material may play a vital role in flake quality and requires investigation. To unlock the processing potential of pulses, systematic material science investigations are needed with commercial scale RTE pilot processing equipment to evaluate the effects of processing and pulse material on pulse flake attributes.

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Stephen D. Cork: Conceptualization; data curation; formal analysis; methodology; project administration; writing – original draft; writing – review & editing. **Chris Blanchard**: Conceptualization; funding acquisition; project administration; resources; supervision; writing – review & editing. **Andrew John Mawson**: Conceptualization; funding acquisition; methodology; supervision; writing – review & editing. **Asgar Farahnaky**: Conceptualization; funding acquisition; project administration; resources; supervision; writing – review & editing

CONFLICT OF INTEREST

There is no conflict of interest to declare.

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