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Pulse Flour Characteristics from a Wheat Flour Miller's Perspective: A Comprehensive Review

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Abstract: Pulses (grain legumes) are increasingly of interest to the food industry as product formulators and consumers seek to exploit their fiber-rich and protein-rich reputation in the development of nutritionally attractive new products, particularly in the bakery, gluten-free, snack, pasta, and noodle categories. The processing of pulses into consistent high-quality ingredients starts with a well-defined and controlled milling process. However, in contrast to the extensive body of knowledge on wheat flour milling, the peer-reviewed literature on pulse flour milling is not as well defined, except for the dehulling process. This review synthesizes information on milling of leguminous commodities such as chickpea (kabuli and desi), lentil (green and red), pea, and bean (adzuki, black, cowpea, kidney, navy, pinto, and mung) from the perspective of a wheat miller to explore the extent to which pulse milling studies have addressed the objectives of wheat flour milling. These objectives are to reduce particle size (so as to facilitate ingredient miscibility), to separate components (so as to improve value and/or functionality), and to effect mechanochemical transformations (for example, to cause starch damage). Current international standards on pulse quality are examined from the perspective of their relationship to the millability of pulses (that is, grain legume properties at mill receival). The effect of pulse flour on the quality of the products they are incorporated in is examined solely from the perspective of flour quality not quantity. Finally, we identify research gaps where critical questions should be answered if pulse milling science and technology are to be established on par with their wheat flour milling counterparts.

Keywords: baking, drying, extrusion, fiber, GxE effects, particle size distribution, physicochemical changes, pretreatment, protein, pulse flour, starch, storage

Introduction

There are a number of texts on the milling of pulses (grain legumes)—one of note being Wood and Malcolmson (2011). The purpose of this critical assessment of the literature on pulse milling is not to repeat the previously published body of work. Rather, we seek a wheat flour miller's perspective on what is already known in this area, and what needs to be known, in order that pulses can be milled into consistent, high-quality ingredients for the food industry. In doing this, we primarily focus on pulses (chickpea, lentil, and bean) as ingredients for baked goods, noodles, pastas, and snacks. These products are starch-rich (48% to 66% is a typical range, with bread an outlier at 25%), and they are predominantly made from wheat or maize, but also from potato or rice.

Displacing all or part of the cereals from these products to imbue them with the healthful attributes of pulses requires good miscibility of pulse ingredients with existing ingredients. This is the domain of milling—reducing the size of the grain legume to sizes that allow pulse ingredients to be blended well. In milling wheat to flour, a typical median particle diameter is 60 μm (Sullivan, Engebretson, & Anderson, 1960), so that some 300000 particles will be created from 1 single wheat grain. Therefore, key questions to be answered for pulse milling include: Is there a desired degree of size reduction so that good miscibility of ingredients is attained? Does target size differ according to pulse type and according to the product being made from the pulse flour?

A second feature of milling, both modern and historically, is that size reduction permits components previously locked together to be separated (Campbell, Webb, Owens, & Scanlon, 2012). In wheat flour milling, the ideal separation objective is partitioning of all starchy endosperm from the endosperm aleurone cells and other grain tissues. The reality is a compromise, where the miller aspires to maximize flour yield while minimizing incorporation of nonstarchy endosperm particles into the flour. Because mineral content is low in the starchy endosperm of wheat, a practical means of assessing how well separation has been achieved is to measure the ash content of the flour; a typical upper limit of 0.50% corresponds to a flour yield of 75% to 80% (Posner & Hibbs, 2005). In pulse milling, separation of components may also be desired. The classic separation objective is to remove hulls (seed coats)

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from cotyledons (Vishwakarma et al., 2018; Wood & Malcolmson, 2011), an operation that can be achieved reasonably efficiently and easily for peas, but not for most other pulses. Therefore, are there key separation concerns for the pulse miller? How do they differ according to pulse type? Are there reliable measurements that will define separation efficacy?

Additional separation objectives may be required in milling. For example, in the production of some wheat flour noodles, a patent flour, rich in starch and low in protein, is required for high-quality products (Edwards, Scanlon, Kruger, & Dexter, 1996; Hatcher, Edwards, & Dexter, 2008). Millers producing such flours must have customers for the flour costreams. Likewise, for pulses, sieving and air classification have been used for many years alongside milling processes to separate streams enriched in protein from streams enriched in starch (Tyler, Youngs, & Sosulski, 1981). Therefore, when milling pulses for different products, are there enriched millstream targets? Are the costreams still valuable if enriched millstream targets are met?

A third outcome of milling is stress-induced changes to the physicochemical properties of components within the pulse seed. The classic example in wheat flour milling is starch damage—an alteration of granule structure (BeMiller & Huber, 2015; Scanlon, Dexter, & Biliaderis, 1988), the immediate impact of which is to alter how readily water is taken up by flour particles (Evers & Stevens, 1985), but with additional quality consequences for products into which the flour is incorporated. The properties of protein and fiber are also potentially subject to stress-induced modifications. Therefore, a key question in pulse milling is, what are desirable degrees of stress-induced changes during milling? A corollary question is, which simple tests can determine the appropriate degree of component modification by the milling process?

The success of the miller in attaining these objectives depends on the characteristics of the in-coming materials, that is, the grain legume seeds. This requires consideration of what specifications need to be imposed on pulse grain suppliers to ensure a consistent in-coming raw material. The mill must then be set up to produce product(s) as efficiently as possible, so consideration of easy changes of mill configuration and the flow of stocks within the mill will dictate the cost of milling. As an example, tempering and conditioning are the miller's prime means of manipulating the mechanical properties (hardness) of wheat grains to ensure cleaner separations and easier size reduction (Hemery, Rouau, Lullien-Pellerin, Barron, & Abecassis, 2007). However, pulses often require multiple temperings with prolonged conditioning periods (Arntfield et al., 1997), all of which add to milling costs.

The final consideration is the transactional arrangement between miller and customer. To ensure consistency of pulse flour quality, specifications, preferably determined by rapid and easy tests, are paramount. Therefore, a key question for pulse milling is, what are the minimum number of tests required to define pulse flour quality and its consistency for a particular end-purpose in the food industry?

Grain Legumes Entering the Mill

Defining incoming grain legume quality

A number of agencies already have tests that define the quality of pulses. In this section, we examine the extent to which the definitions of the quality of these grain legumes (coming from the field or from storage) are relevant to milling performance or to desired end applications of the resulting flours.

Pulse grading in different jurisdictions. The USA Dry Pea and Lentil Council lists the United States Standards for peas (whole dried, split, and feed), chickpeas, beans, and lentils (USA Dry Pea & Lentil Council, 2018). For categorization of whole dry peas into U.S. grades 1 to 3, the grading factors emphasize defects (weevil-damaged, heat-damaged, split, or shriveled), foreign material, and minimum color requirements. An additional factor for grading split peas includes the round-hole sieve sizes that they should pass through to be graded. Lentil categorization involves additional classification into skinned (removal of at least three-quarters of the seed coat) and contrasting lentils (very irregular shape and size). Bean requirements vary for the different kinds of beans (cranberry, yellow-eye, chickpea, cowpea, and so on). Common factors include moisture and total defects (damage, total foreign matter, contrasting classes, and splits) along with maximum limits for contrasting classes and classes that blend. Therefore, standards for grain legumes are not pronouncedly different from U.S. standards for grains such as wheat, which were developed about 100 years ago (Hill, 2014).

The Canadian Grain Commission (CGC) follows a different approach to grading pulses. Its quality parameters include seed color, cooking time, dehulling characteristics, firmness of cooked seeds, 100-seed weight, protein content, seed size distribution, starch content, and water absorption (Canadian Grain Commission, 2018).

The Intl. Pulse Quality Committee (IPQC) parameters for quality assessment of pulses are seed size, moisture, crude protein, fiber and starch contents, water absorption, split yield and dehulling efficiency, cooking quality and time, trypsin inhibitor activity, seed coat integrity, and content of tannins (Gupta, Tiwari, & Bawa, 2011).

The Codex Alimentarius Commission (CAC) grades pulses from Grade 1 to 4 depending on their moisture content, freedom from toxic seeds (harmful to human health), presence of contaminants, pesticide residue levels, and several physical characteristics such as purity, size, defects, maturity level, contrasting classes, classes that blend (beans with more than 15% classes that blend are graded mixed beans), sprouting ability, color, foreign matter, and objectionable material (Gupta et al., 2011).

Relevance of grain legume quality to milling. A number of the aforementioned quality parameters relate directly to milling performance. For instance, dehulling efficiency has a direct effect on yield, as does the foreign matter content in a sample. The 100-seed weight and size specifications would have relevance to setting of the milling machines, and the seed size distribution determines the extent to which proportions of seeds are excessively ground or that are subject to inadequate size reduction. The various compositional specifications for grain legumes have relevance if the miller is to meet target specifications for a flour, for example, protein content if the flour is to be further processed into a concentrated protein product. Firmness of the cooked seed does not directly relate to millability, but one would expect that there is a relationship between firmness of the cooked seed and seed hardness (Pelgrom, Schutyser, & Boom, 2013; Ross, Arntfield, Cenkowski, & Fulcher, 2010).

Important quality parameters, categorized in terms of their relevance to milling performance versus cooking of the whole seed, are listed in Table 1. None of the national or global committees governing the quality parameters lay out specifications on the millability of pulses. It is important to define the quality parameters that are relevant to milling performance (Rosentrater

Table 1–Quality parameters with respect to milling and whole pulse end-use applications (US = USA Dry Pea & Lentil Council; CAN = Canadian Grain Commission; IPQC = International Pulse Quality Committee; CAC = Codex Alimentarius Commission).

Quality parameter	Standard committee	Relevance to quality—milling (M) or whole pulse (P)
Seed size/shape/weight	US, CAN, IPQC	Both
Color	US, CAN, CAC	P
Moisture content	US, IPQC, CAC	Both
Crude protein content	CAN, IPQC	Both
Starch content	CAN, IPQC	Both
Water absorption	CAN, IPQC	Both
Firmness of cooked seeds	CAN, IPQC	P
Fiber content	IPQC	Both
Dehulling characteristics	CAN, IPQC	Both
Purity	US, CAC	Both
Defectiveness	US, CAC	Both
Split yield	IPQC	P
Antinutrient factors	IPQC	Both
Maturity	CAC	Both

& Evers, 2017) since this will help establish the creation of pulse flours with specific consistency and quality attributes.

Factors affecting grain legume millability

Considering the wealth of information available in the wheat milling literature, it should be an ideal template for setting a framework for pulse millability. It is worth noting that millability of wheat is not defined by one parameter. It is affected by cleanliness (freedom from foreign material), hardness, uniformity of kernel size and shape, test weight, response to conditioning, thickness of bran and aleurone layer, behavior during milling (break roll release, stocks flowability, and overall power requirements), ash content of the grain, and color of the wheat endosperm (Li, 1987; Posner & Hibbs, 2005). Consensus on the factors affecting grain legume millability is yet to be reached, but several studies have investigated the aforementioned factors to better understand pulse milling processes.

Composition, structures, and stress application. The components (starch, protein, and fiber) in a grain legume and the nature of their structural organization are major determinants of the millability of the grain legume. For instance, components and/or structures that enhance brittleness allow ready fracture propagation, thereby improving size reduction and often component separation. In addition, the type of stresses applied dictates fracture paths and the extent of plastic deformation and their consequent effects on the functional characteristics of the flour particles. Since the introduction of roller milling in the 1870s, there have been a number of systematic examinations in wheat flour milling of how components, structures, and stress application affect the properties of flour. There has been less concerted effort in examining these parameters in pulse milling with the exception of dehulling, where the primary objective is not size reduction and mechanochemical change, but separation.

The effects of composition on grain legume milling performance have revolved primarily around fiber, protein, and lipid. The toughness of the fiber emanating from the hull, and also from the cell walls in the cotyledons, is well recognized as an impediment to efficient milling. For example, in preparing wheat-chickpea flour blends for cakes, Gómez, Oliete, Rosell, Pando, and Fernández (2008) had to regrind the fiber-rich coarse fraction from stone-milled chickpea on a hammer mill so that they could create a "whole flour." Similarly, roller milling of yellow pea produced a hull-rich fraction on the break side of the mill that needed to be reduced in size by pin milling so that it could be blended with the roller mill output from the reduction side of the mill (Ribéreau, Aryee, Tanvier, Han, & Boye, 2017). Pelgrom, Vissers, Boom, and Schutyser (2013) found that the air-classified coarse fraction from both impact and jet mills was rich in fiber. Protein also has been implicated in size reduction difficulties for grain legumes. From fracture propagation tests at low-moisture contents, pea samples with greater amounts of protein and lipid were more ductile and required more energy to create new fracture surfaces (Dijkink & Langelaan, 2002b). The authors then correlated fracture energy from the tests with energy consumed in grinding the pea samples in an impact mill.

Although some materials are intrinsically tough or friable, composition alone does not explain differences in the millability of grain legumes (Schutyser, Pelgrom, van der Goot, & Boom, 2015). Structural organization of components, or their reorganization during grain storage, strongly influences the mechanical properties of grain legumes (van der Sman & van der Goot, 2009). The classic manifestation of this for grain legumes is the development of the hard-to-cook phenomenon in stored beans. Depending on a number of factors (Reyes-Moreno & Paredes-Lopez, 1993), especially storage conditions (Aguilera & Ballivian, 1987; Coelho, de Mattos Bellato, Santos, Ortega, & Tsai, 2007), components (starch, protein, and fiber) within the grain legume undergo molecular rearrangement, impairing bean quality as a result of developing unacceptable hardening that cannot be softened by cooking (Reyes-Moreno, & Paredes-Lopez, 1993).

At a macroscopic structural level, uniformity in seed size is desired for "millable" pulses to achieve optimal processing efficiency (Wood & Malcolmson, 2011). Harden and Wood (2017) proposed a new method to determine the parameters, mean seed size (SS_{norm}), and variability within a sample (SV_{norm}). They fitted a normal distribution to the frequency distribution of sizes in an investigation of chickpea (desi [Indian origin] and kabuli [Mediterranean or Middle-Eastern origin]), faba bean, lentil, and mung bean samples. By understanding the distribution of sizes, sieve size intervals that were appropriate for classifying pulse seeds could then be recommended; for example, sieves for faba or mung beans do not work to separate chickpeas (Harden & Wood, 2017). Accordingly, sieve adjustments are required in mills that process both chickpeas and faba beans. Alternatively, based on a comprehensive assessment of different mills to create faba bean flour, Watson, McEwen, and Bushuk (1975) recommended that a preliminary size reduction operation be carried out to resize the faba beans so that they could be efficiently reduced in size by roller milling.

Although the role of protein as a structural element should not be downplayed (Dijkink & Langelaan, 2002b; Tyler, 1984), fiber is likely the main culprit in either embrittling or toughening grain legumes during size reduction. Two areas of structural importance for fiber are its location at the interface of cotyledons and hull, and its distribution within the cotyledons themselves. A scanning electron microscopy (SEM) study of chickpea cultivars showed that differences in seed structure and surface topography at the junctions between the seed coat and cotyledons were likely responsible for milling differences in easy-to-mill and difficult-to-mill cultivars (Wood, Knights, & Choct, 2017). In a comprehensive study of chickpea cultivars (desi, kabuli, and a hybrid), compositional differences in soluble and insoluble nonstarch polysaccharides and pectins and the lignin content of the seed coat significantly affected

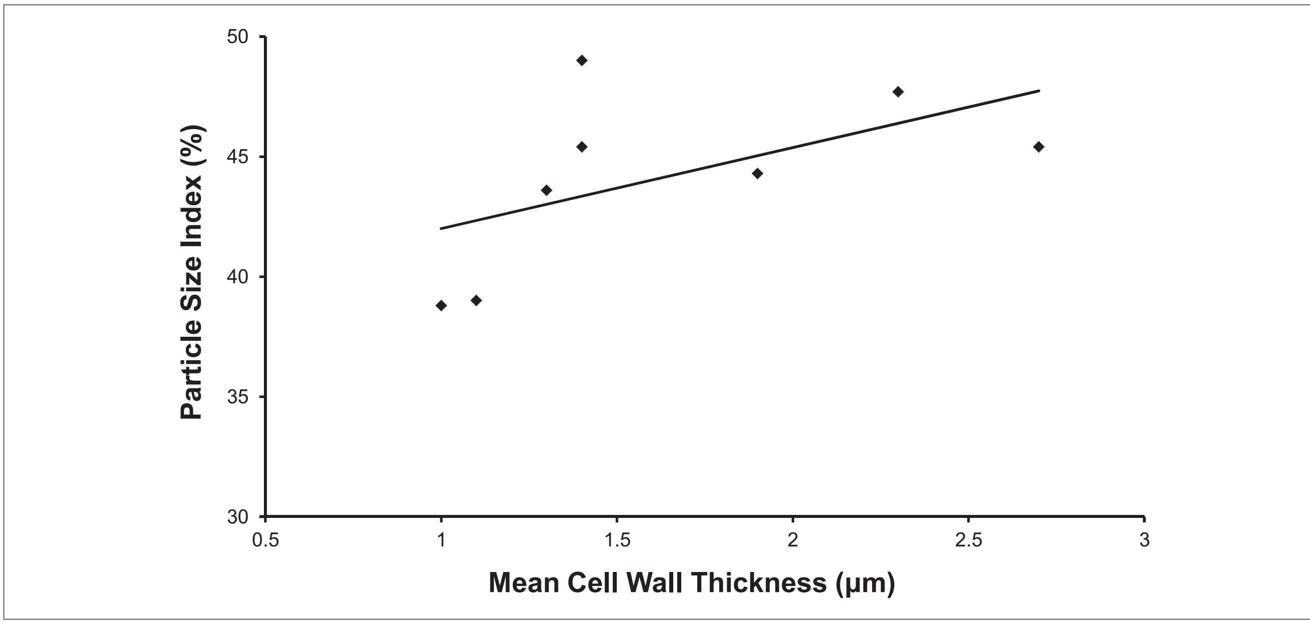

Figure 1–Relationship between particle size index (proportion of material passing 74 μm sieve) and thickness of cell walls (from photomicrographs of seed sections) of 8 types of grain legumes derived from Tyler (1984). Line represents best-fit relationship.

dehulling characteristics (Wood, Knights, Campbell, & Choct, 2014a,b,c).

Within the cotyledons themselves, the fiber-rich cell walls are a distinct structural feature of grain legumes (Dhital, Bhattarai, Gorham, & Gidley, 2016; Tyler, 1984). SEM analyses of several pulses were used to show that impact milling efficiency could result from differences in the thickness and structural rigidity of cell walls and the degree of adhesion between the cell contents and the cell wall (Tyler, 1984). An appreciation of structure versus composition can be obtained from Figure 1, which is an examination of the results reported by Tyler (1984) for different grain legumes. A positive relationship between mean cell wall thickness and particle size index is evident, which indicates that cell walls are thicker in samples that break down more readily in an impact (Udy) mill.

The nature of stress application has enormous implications for how new particles are created from grain legumes. For a model starchy food material subject to hammer milling, distinctly different particle shape distributions arose depending on whether a screen was present or absent (Scanlon & Lamb, 1995). Stress waves interacted with specific internal structural features to create elongated particles that were reground when a screen was present. For the same material subject to impact breakage, higher impact velocities induced greater ductility rather than creating new particle surface area (Scanlon & Lamb, 1993). One also expects differences in particle sizes and shapes when grain legumes are subject to impact versus roller milling (Tyler, 1984; Tyler & Panchuk, 1982) and to differences in impact mill energy input (Dijkink & Langelaan, 2002b; Pelgrom et al., 2013).

Measurements of the hardness of grain legumes represent a composite of all of these factors (materials, structures, and stress application). For wheat, grain hardness is viewed as the single most important parameter related to end-use performance (Pasha, Anjum, & Morris, 2010; Pomeranz & Williams, 1990). Vishwanathan and Subramanian (2014) showed that the mean particle size of dehulled red gram (pigeon pea) flour milled by a fixed system depended on the initial seed hardness. Harder seeds impede milling and hardness is influenced by various genotype and environment (G $\times$ E) factors that govern physical properties and chemical constituents, particularly fiber, lignin, cellulose, and hemicellulose (M. Singh, Sekhon, Bajwa, & Gopal, 1992). The hardness of mung bean seed was determined using a single kernel characterization system (Erkinbaev, Derksen, & Paliwal, 2017). The authors found that the hardness index of mung beans increased with greater moisture content in the range from 9.2% to 15.9%. In a study to attain protein-enriched streams from pulses, Pelgrom, Boom, and Schutyser (2015) showed that higher protein content was found in the fine fraction of milled lentil flour. The authors attributed this to lower initial seed hardness compared to that of chickpea, pea, and bean. Therefore, initial seed hardness is an important variable that affects pulse millability and the characteristics of the resulting flour, just as it does for soft and hard wheats.

Factors such as moisture evaporation, deformation rates and temperature differences affect energy consumption during impact milling. A study conducted by Dijkink and Langelaan (2002a) established that green field peas soaked prior to dehulling and dried to a range of moisture contents from 9% to 17% consumed three times more energy during milling; therefore, milling at 11% moisture was recommended to minimize energy consumption. Additionally, milling capacity was found to be moisture-dependent at higher milling speeds (greater than 18000 rpm). Higher moisture content (15% to 35%, d.b.) changed pigeon pea seed behavior from brittle to ductile based on force-deformation tests (N. Singh, Vishwakarma, Shivhare, Basu, & Raghavan, 2017). Sakhare, Inamdar, Gaikwad, Indrani, and Vekateswara (2014) conducted roller milling fractionation of green gram and found an increase in flour yield when moisture content was lowered from 16% to 10%; higher lightness values also were recorded for the flour streams. At fixed milling conditions, grain legumes at a lower moisture content produced finer flour (smaller particle size) for pea and lupin (Pelgrom, Wang, Boom, & Schutyser, 2015). Therefore, seed moisture content is a key factor that affects grain legume millability.

With respect to separation of components, a few researchers have characterized milling efficiency by protein separation efficiency (PSE), defined as the proportion of protein shifted into

Table 2–Some parameters that have been reported to change with G × E conditions for different pulses.

Parameter	G factor	E factors	Pulse type	Variation (within type or sample)	Reference
Seed hardness	√		Pea		Dijkink and Langelaan (2002b)
Chemical composition	√		Chickpea	Both	Wood et al. (2014a,b,c)
	√		Pea	Both	Wang et al. (2008)
	√	√	Bean	Both	Wang et al. (2017)
	√	√	Chickpea	Both	Jambunathan and Singh (1979)
Yield	√	√	Pigeon pea	Both	Joshi et al. (2011)
	√	√	Redgram	Both	Kodanda et al. (2011)
Seed size	√	√	Lentil	Both	Ruiz et al. (1997)
	√	√	Redgram	Both	Kodanda et al. (2011)
	√		Chickpea	Both	Singh et al. (2010)
	√	√	Lentil	Both	Subedi (2018)
Seed density	√		Chickpea		Tikle and Mishra (2018)
Off-flavor	√	√	Pea	Both	Malcolmson et al. (2014)

the fine fraction upon air classification and impact grinding. Significant relationships have been found between PSE values and crude fiber content, water-insoluble cell wall content of the seed, and seed hardness (defined by flour particle size index) for grain legumes (Tyler, 1984). Moreover, high PSE relies on cellular disruption caused by milling to effectively separate protein and starch components (Pelgrom et al., 2013). Crude fiber, an estimate of cell wall content, has been significantly correlated with PSE; however, neutral detergent fiber, a better representative of cell wall content, did not correlate well with PSE (Tyler, 1984). Another study showed that differences in PSE during pin milling and air classification depend on the type of pulse (Tyler et al., 1981). Ash content cannot be used as an indicator of milling efficiency (as in wheat milling) as the cotyledons can contain high mineral content (Watson et al., 1975).

Based on the aforementioned studies, it has been established that the millability of grain legumes is affected by composition (especially fiber, moisture, and protein content), by macrostructural features such as seed size, seed weathering, and hull content, and by microstructural features such as cell wall thickness. The type of mill used for hardness determination will also affect assessment of grain legume millability. More research is required to correlate composition, structure, and hardness tests to pulse milling, particularly with respect to reduction in size and separation efficacy.

Effects of grain legume characteristics on milling performance. The characteristics of both grains and grain legumes (pulses) vary according to genotypic (G) and environmental (E) factors, where E factors are mainly defined by growing location, year, and weather (Nleya et al., 2000). Information on the interaction of G × E is paramount for estimating how variability in grain legume characteristics affect intrinsic milling quality, and hence the milling performance of a specific grain legume entering the mill that may be composed of seeds that are of different genotypes and from different locations (Wood, Knights, & Harden, 2008). Examples are provided in Table 2, while the following studies illustrate this point.

A study on red gram (pigeon pea) genotypes reported differences in grain yield and other stability parameters such as number of pods/plant and 100-seed weight (Kodanda, Reddy, Venkateswarlu, Obaiah, & Siva Jyothi, 2011). Similarly, Joshi, Acharya, Patel, and Vaghela (2011) investigated 64 distinct pigeon pea genotypes (A lines, B lines, and varieties) at three locations and found that grain legume yields were stable for only a few genotypes.

Twenty dry bean cultivars from different locations and year of growth showed varying characteristics (seed weight, water hydration capacity, and cooking time) with deviation in protein, starch, and phytic acid (N. Wang, Hou, Santos, & Maximiuk, 2017). For example, the contribution to variance for seed weight was dominated by cultivar (greater than 90%), but protein content was dominated by year of growth, with the contribution from cultivar to protein content being less than 30%. Similarly, G × E effects have been shown to affect the properties of lentil (N. Wang & Daun, 2006) and field pea (N. Wang, Hatcher, Warkentin, & Toews, 2010).

A study of 20 cultivars of lentil grown over 5 years at several locations quantified variation in seed size and testa color and showed relationships to saponin content (Ruiz, Price, Rose, & Fenwick, 1997). Seeds with brown testa had lower saponin content than those with beige or green colored testa, but there were also differences in saponin content between lentils of a specific color.

Differences between the types of chickpea (desi and kabuli) have been credited to seed type and shape (Saini & Knights, 1984). For chickpea cultivars (8 desi and 7 kabuli) grown at two different locations that were cyclone-milled, fiber content and percentage of seed coat were significantly higher for the desi samples at both locations, but there were not significant differences in the protein and ash contents of their flours (Jambunathan & Singh, 1979). A different lab confirmed this, reporting that desi types had higher acid detergent fiber content and average seed coat weight (Saini & Knights, 1984). In other studies, statistically significant differences were found between desi and kabuli types in terms of seed density (Tikle & Mishra, 2018), chemical composition (crude fiber content, minerals, and polyphenols), *in vitro* starch digestibility (Jambunathan & Singh, 1981; M. Singh, Kherdekar, & Jambunathan, 1982), and oligosaccharide and starch components (Saini & Knights, 1984), while seed protein content and amino acid composition have been reported to be similar (U. Singh, Raju, & Jambunathan, 1981). Seed coats of kabuli cultivars had higher amounts of Ca, Zn, Cu, Fe, and Mn and these varied with location (Jambunathan & Singh, 1981). Mean values of the oligosaccharide stachyose were higher in desi cultivars (M. Singh et al., 1982).

Genetic diversity also was prominent when chickpea cultivars were milled (in a "laboratory blender" to pass through a sieve equivalent to 212 μm mesh size) to reveal differences in flour composition and pasting properties (N. Singh, Kaur, Isono, & Noda, 2010). Differences in seed size and testa (% of dry grain legume weight) of six cultivars of desi chickpea milled in a horizontal attrition-type mill led to significant differences in milling quality parameters (dehulling efficiency and splitting yield). No significant differences were found within the two seed classes

(6 to 7 and 7 to 8 mm) for either parameter. The study also revealed that dehulling efficiency is more strongly affected by genotypic differences due to the higher range of values found over the trials for both seed classes. A more recent study with fewer chickpea cultivars reported significant differences between cultivars for milling characteristics determined on an experimental mill (Tikle & Mishra, 2018). Therefore, ease of seed coat removal and splitting of chickpea is genotype-dependent. The off-flavor and aroma attributes of pea were highly variable depending on the species, market class, cultivar, crop year, location, and storage conditions (Malcolmson et al., 2014). Moreover, how well a particular processing method reduces antinutritional compounds in pulses also is highly dependent on G × E factors (Patterson, Curran, & Der, 2017).

The effect of G × E parameters on milling performance has been mostly conducted on chickpea cultivars. The small body of literature available for other pulses demonstrates a need to understand how G × E factors affect milling performance. Further investigation is essential to reveal differences (if any) based on G × E parameters to help breeding programs produce pulse genotypes with high milling efficiency and low variability in properties such as seed size. Establishing a minimal list of parameters that can be used to assess the genotype and environment factors for cultivars in pulse breeding programs would also be useful to breeders.

Drying. Drying is an integral postharvest process. There are several wetting and drying processes employed to bring grains and grain legumes to a safe storage moisture to keep them free from microbial growth, insects, and pests. Drying to attain an appropriate moisture content changes the physical properties of the grain legume (Sablani & Ramaswamy, 2003) just as it does those of other grains such as wheat (Bushuk & Hlynka, 1960).

In the process of pretreating pulses prior to milling, wetting and drying cycles may be conducted (Wood & Malcolmson, 2011). In a study of lentil, Scanlon, Cenkowski, Segall, and Arntfield (2005) dried lentil samples back to 13% moisture, either by micronization or by air-drying, following tempering to various moisture contents. Substantial increases in the rewetting capacity of the tempered and dried lentil were evident for tempering regimes above 20%, and this was more pronounced for the lentil samples that were micronized. Small increases in the porosity of the tempered and air-dried lentils were also observed (Scanlon et al., 2005). Even though porosity changes were small, based on relationships between density and hardness of wheat starch endosperm (Dobraszczyk, Whitworth, Vincent, & Khan, 2002), the wetting-drying cycles that induce porosity changes in grain legumes may significantly affect their milling behavior.

Postharvest storage. The effect of storage on the millability and milled-product quality of pulses is another important factor. Most studies on postharvest storage have linked effects to the physical properties of pulses, including the time required for cooking (Coelho et al., 2007; Wood, 2017). Variables during storage, such as temperature, relative humidity (RH), light, oxygen level, and moisture content have been related to changes in seed coat color (Pratap, Mehandi, Pandey, Malviya, & Katiyar, 2016). A significant amount of research has focused on the hard-to-cook (HTC) phenomenon associated with prolonged and suboptimal storage conditions (Wood, 2017). However, a correlation between storage parameters (viz. moisture content, RH, and temperature) and millability of pulses needs to be firmly established. For instance, since water content and water activity of the stored seed influence millability, these parameters were the focus in a storage study of common beans by Paredes-López, Barradas, and Reyes-Moreno (1989). For seeds stored at 32 °C and 75% RH for 120 days, both parameters increased prior to attaining equilibrium values.

Different water absorption characteristics were found for two genotypes of bean stored at 29 °C and 75% RH for three storage periods (45, 90, or 135 days). The difference in soaking characteristics was attributed to the phenolics or tannins present in the seed coat (where dark testa color was associated with high tannin content) (Coelho et al., 2007). Bean cultivars (Negro Qro and Canario) stored at 40 °C and 80% RH for 135 days showed a significant increase in moisture, water activity, and hardness in comparison to fresh samples (Paredes-López, Maza-Calviño, & González-Castañeda, 1989); prolonged storage also altered the color of the beans.

A study on black bean storage revealed an increase in cooked bean hardness with an increase in storage period (9 months), moisture content (8%, 10%, 12%, and 14%), and storage temperature (8.5, 25, and 40 °C) as compared to untreated beans at 10.5% moisture (Aguilera & Ballivian, 1987). Significant differences in hardness values were reported with moisture and temperature increases. Plateau values in cooked bean hardness were reached between 4.5 and 6 months and at about 6 months for 8.5 and 25 °C, respectively; however, hardness was still increasing by 9 months for beans stored at 40 °C. In another study, different color values were found for pinto bean cultivars when stored for different duration (36, 72, and 108 days), temperature (15, 21, and 27 °C), and RH (45%, 60%, and 75%) (de Almeida, Coelho, Schoeninger, & Christ, 2017).

Our thorough review of the literature reveals that storage studies on pulses have essentially focused on the HTC phenomenon that is measured on the whole seed. Since changes in parameters such as seed hardness with increasing storage duration alter the uptake of water during tempering and the friability of the seed during milling, these studies do provide insight into the expected millability of pulses. Nevertheless, research is required to explicitly quantify changes in millability parameters with respect to changes in storage conditions.

Pretreatments. Historically, pretreatments have been serendipitously applied to pulses to aid in dehulling or making other processing steps easier without fully understanding their impact on millability. However, some pretreatments have been well studied for pulse flours, with a focus entirely on improving nutritional properties or modifying functional properties. This section focuses on the treatments done prior to milling that affect the millability of various pulses. Examples are partial germination, soaking, conditioning and tempering, pitting, hydrothermal treatment, and micronization.

Premilling treatments influence the milling process by loosening the hull, reducing breakage, and improving the quality of the split products (Tiwari, JaganMohan, & Vasan, 2007). Several pretreatments have been employed depending on the pulse, the country or region, and the miller's experience. For instance, pigeon pea (*Cajanus cajan* L.) was subjected to a dry premilling (pitting) treatment (with application of oil) or a wet (soaking followed by application of red earth) premilling treatment (Tiwari, JaganMohan, & Vasan, 2008). The purpose in each case was to get liquid between hull and cotyledons to allow better separation during dehulling. Another study combined pitting, oil application (0.2%, 0.4%, 0.6%, 0.8%, or 1.0% concentration), and drying (40, 50, 60, 70, 80, or 90 °C) for 30 min to examine the dehulling efficacy of black gram using an emery roll polisher (Tiwari et al., 2007). Maximum dehulling (85.5%) was achieved with 0.8% oil concentration and drying at 90 °C.

Pitting is the introduction of dents or scratches on the surface of seeds (scarification of hulls) using an abrasive roller machine to aid in the absorption of oil and water so as to facilitate further processing (U. Singh, 1995; Sokhansanj & Patil, 2003). The specific nature of pitting varies according to pulse type (Narasimha, Ramakrishnaiah, & Pratape, 2003). An investigation of moisture effect (6%, 8%, 10%, 12%, or 14%) on pitting of pigeon pea showed that pitting of grains at 10% moisture content resulted in the maximum amount of dehulled grain (87.2%) as well as optimal dehulling efficiency (86.7%, with cottonseed oil application) (Goyal, Vishwakarma, & Wanjari, 2010).

Soaking of grain legumes is primarily done to soften the exterior matrix for easy removal of the seed coat. Soaking in sodium bicarbonate solution (1%, w/v) affected the dietary fiber components of black gram, chickpea, lentil, and red kidney bean seeds; an increase in hemicellulose, neutral detergent fiber, acid detergent fiber, and cellulose was observed in all except lentil. Soaking in sodium bicarbonate resulted in a decrease in lignin as compared to raw (no soaking) or water soaking of seeds (Rehman & Shah, 2004). Such treatments are expected to influence milling performance. Other components are altered by soaking treatments: lentil flours obtained from seeds soaked for 60 min in excess water which were then dried had an 11% to 31% decrease in starch content (Vidal-Valverde et al., 2002).

Conditioning and tempering are two terms that are often used interchangeably. Tempering is the addition of water to reach a certain moisture content to influence milling parameters (Arntfield et al., 1997), whereas conditioning typically refers to the time required to soften the grain legume matrix following water addition. Tempering with different mixtures (water and chemicals) to 26% and 28% moisture resulted in a reduction of hardness and firmness of cooked black and navy beans that had been micronized (Bellido, Arntfield, Cenkowski, & Scanlon, 2006). Tempering lentils to increasing moisture contents, which were then dried back to 13% moisture content, led to small increases in apparent elastic modulus (Scanlon et al., 2005). Bahnassey, Khan, and Harrold (1986) remarked that reduction of seed moisture content was essential for effective removal of hull from cotyledon in lentil, navy bean, and pinto bean.

In a study of hydrothermal (steam) treatment of pigeon pea, it was found that a 10-min treatment followed by drying for 3 hr at 50 °C was the optimal pretreatment for milling (Tiwari et al., 2008). The authors found that hydrothermally treated samples resulted in better quality and quantity of dehulled grains and hulling efficiency as compared to a control (only drying), a dry method (pitting, oil application, and drying), and a wet method (soaking, tempering, red earth application, and drying) (Tiwari et al., 2008). Improvements in dehulling efficiency with hydrothermal treatment of black gram also have been reported (Joyner & Yadav, 2015). Preroasting followed by milling of certain pulses (navy bean, pinto bean, and lentil) resulted in increased digestibility of protein without altering their neutral detergent fiber contents (Bahnassey et al., 1986). However, flour functionality may be affected by the temperatures and moisture contents attained. For example, Tiwari et al. (2007) found that the maximum volume of fermented batter (for 24 hours, fermented in flasks) was achieved for dehulled black gram but only for drying temperatures less than 60 °C.

Micronization utilizes high-intensity infrared radiation to process grain legume seeds (Cenkowski, Hong, Scanlon, & Arntfield, 2003; Ribéreau et al., 2017). It is typically used to improve the product quality and cooking characteristics of grains (pulses and cereals) (Deepa & Hebbar, 2016). Micronization of green lentil (var. Eston) above 130 °C and moisture tempering (16% and 23% from 8%) resulted in higher water holding capacity and oil absorption capacity of the roller-milled flours and did not affect the total protein or ash content (Pathiratne, Shand, Pickard, & Wanasundara, 2015). Micronization of lentil tempered to higher moisture contents led to slight seed darkening (reduced lightness values) as compared to lower moisture levels (Arntfield et al., 1997), and to more rapid water uptake (Scanlon et al., 2005). Micronization and tempering conditions implemented for lentil (var. Laird) at 170 °C increased the hardness of the seeds, resulted in their darkening or "browning," and caused structural damage along the cell wall (from an SEM study) (Arntfield et al., 2001). However, only slight darkening was observed for micronization at 138 °C. Micronization of tempered black beans (to 22% moisture content for 32 hours) in various solutions (including water) resulted in darker beans, with a less green hue, whereas minimal changes were observed for navy bean (Bellido et al., 2006). Micronization and pregermination of yellow pea flours increased water holding capacity with no significant effect on ash, protein, or fat content as compared to untreated flours (Ribéreau et al., 2017).

Germination results in the reduction of antinutrients, increases micronutrient bioavailability, and improves the sensory properties of pulses (Marengo et al., 2017). Commercial systems that combine partial germination with a drying process permit germinated grains to be milled into various types of flours (Bellaio, Kappeler, Rosenfeld, & Jacobs, 2013). The effect of germination on the nutritional and culinary properties and reduction of antinutrients has been well investigated, but there are few studies on the effect of pregermination on the milling performance of pulses. In one such study, Marengo et al. (2017) observed that germination of chickpea (3 days at 18 to 24 °C followed by drying at 50 °C for 10 hr) resulted in reorganization of storage proteins (increased concentrations of solubilized proteins and accessible thiols); the modified proteins produced better dough mixing properties for the sprouted chickpea flour. Furthermore, the starch and ash contents decreased in the sprouted chickpea flour (yield of 90% compared to unsprouted chickpea). In another study with black bean, germination increased the ash content (slightly), crude protein content (relative to total dry matter), and the pasting temperatures, and decreased the carbohydrate content, insoluble dietary fiber, minerals (Ca, Fe), and paste viscosities (peak and final); the soluble dietary fiber content and starch content remained unchanged (Guajardo-Flores et al., 2017).

Pretreatment of pulses historically has been employed to aid milling. However, for a fixed set of milling conditions, there is little information available on flour properties. For example, no study has established a particle size effect in the resultant flour from any one specific pretreatment. Typically, studies on roasting, germination, and micronization have focused on investigating the effects on proximate composition and functional properties with milling imprecisely defined. Water-holding capacity increased in pregerminated and micronized flours, while mixed trends have been observed for fat-holding capacity and foaming characteristics. Systematic studies are required in order to understand pretreatment effects specific to milling performance.

Pulse Milling

The milling process itself reduces the particle size of the material, but it usually includes processes such as sifting and purification (Limsangouan & Isobe, 2009). Wood and Malcolmson (2011) defined milling of pulses as a combination of decortication or dehulling, which involves removal of the seed coat; splitting that cleaves the cotyledons and produces "splits"; and flour milling, which produces ground flour. Milling methods for pulses can be broadly categorized into dry and wet milling. Wet milling typically involves immersion of the grain legume in water to facilitate absorption, thus softening the seed. The subsequent result is a dried ground powder of varying particle sizes. Dry grinding leads to a very different product compared to wet grinding, particularly with respect to physiochemical changes, and it requires more power for the grinding process itself (Brennan, Butters, Cowell, & Lilly, 1976; Solanki, Subramanian, Singh, Ali, & Manohar, 2005). In this review, we focus on dry milling that results in ground flour from grain legumes, a process that overall is substantially more energy-efficient than any wet milling process (M.E.J. Geerts, van Veghel, Zisopoulos, van der Padt, & van der Goot, 2018). Wet milling is used in wheat processing to separate starch and gluten (van Der Borght, Goesaert, Veraverbeke, & Delcour, 2005), just as wet milling is employed to obtain protein isolates and starch from grain legumes (with fiber-enriched streams obtained from both commodities). Since this review is focused on the production of whole or refined pulse flours, no details are provided on wet milling.

Defining pulse flour

The initial processing of pulse seed prior to utilization in various applications is to grind it down to a particular size. The biggest challenge faced by the millers and processors of pulses is a lack of definition for the term "pulse flour." In contrast, for wheat flour milling, flour is a well-defined word. In the United States, the Food and Drug Administration uses a particle size criterion to define flour as a powder where "not less than 98% passes through a cloth having openings not larger than 212 μm" (FDA, 2018). The absence of a similar definition for any pulse flour severely complicates valid comparison of the properties of materials from milling studies that are carried out in different laboratories. In these studies, pulse flour is loosely described as the flour produced from pulse seeds that are ground either coarsely, finely, or having medium coarseness or fineness without any definitive parameter. Elsewhere, ground pulse seeds are utilized without mentioning the particle size, or "pulse flour" is retrieved from a particular governing agency that cannot divulge the particle size. In many cases, the flours used by researchers would not be characterized as a pulse flour according to the wheat flour definition set by the U.S. Code of Federal Regulations (FDA, 2018). Therefore, the introduction of a particle size criterion becomes very important when defining pulse flour, and this is discussed in relation to various studies in the section "Size reduction".

Dehulling

Dehulling is the process of removal of hulls (seed coats) of pulses to facilitate milling. Traditionally, different pulses have been subjected to various dehulling methods and techniques depending on the history of the pulse crop in that particular geographical region. A good description of the influence of structural differences among and within given grain legumes on the efficiency of the dehulling operation has been provided by Narasimha et al. (2003). Recently, the performance and mechanism of several dehulling machines, along with the optimization of the dehulling process and its operating parameters, were reviewed by Vishwakarma et al. (2018). Specific parameters that need to be optimized for pulse dehulling include pitting, abrasion, soaking, administration of small amounts of edible oil, and drying. Because of the differences in composition between hull and cotyledons, dehulling can increase the protein and starch content and decrease the insoluble and soluble fiber content of the resulting flour (Vaz Patto et al., 2015; Wu & Nichols, 2005).

The major factors that affect the dehulling of grain legumes include seed variety, size and shape, moisture content, and seed hardness (Vishwakarma et al., 2018). The underlying mechanism that governs the dehulling process is the nature of bonding between hull and cotyledons and its effect on ease of dehulling (Wood et al., 2014a,b,c). Accordingly, pulses can be classified into 2 broad categories—those where separation of the hull and cotyledon is difficult (for example, pigeon pea, mung bean, common bean) and others where this separation is easily achievable (for example, chickpea, dry pea, lentil). The former require multiple passes to achieve separation, whereas for the latter, dehulling is readily achieved with only one or two passes (Vishwakarma et al., 2018). In their comprehensive review, Vishwakarma et al. (2018) also evaluated dehulling quality using several different methods/equations. They concluded that the coefficient of wholeness of seeds (minimal production of splits, broken pieces, and powder), apparent yield (representing dehulling effectiveness), dehulling efficiency (reflecting machine performance), and dehulling loss (a measure of machine limitations) are important parameters to optimize dehulling machines and their operating parameters for a particular pulse type.

Pretreatments prior to dehulling are a common practice in the milling industry. As cited earlier, sodium bicarbonate pretreatment can improve the dehulling efficiency of pigeon pea (Srivastava, Mishra, Chand, Gupta, & Singh, 1988). The authors reported a process that included pitting, administration of a 5% to 6% (w/w) sodium bicarbonate solution, conditioning for 4 hours, followed by drying to 9.5% moisture content, prior to abrasive mill dehulling.

Grinding machines

Grinding machines function using balls, blades, hammers, pins, or rollers as they subject the material to attrition, compression, impact, shear, abrasion/friction, or cutting actions (Hoover, Hughes, Chung, & Liu, 2010; Indira & Bhattacharya, 2006). Roller mills induce compressive stress and shear to disintegrate the particles (Scanlon & Dexter, 1986), whereas a hammer mill (a type of impact mill) processes soft, medium-hard, and hard materials to fine sizes via impact forces (Hixon, Prior, Prem, & Van Cleef, 1990). Impact mills enforce collisions between the wall and powder particles, whereas jet mills use impact forces from interparticle collisions to accomplish particle size reduction (Pelgrom et al., 2013).

The milling machines and the forces they exert on grain legumes to grind them down to smaller particle sizes are outlined in Table 3. Wheat has been grounded using almost every existing type of mill, and pulse millers also utilize these mills to reduce particle size. Impact mills (for example, hammer, pin) are widely used for pulses that have a rigid seed coat and produce very fine flour. Additionally, sieves are used in practically every mill to redirect stocks for additional grinding to produce smaller sized particles. The fineness of the flour and the changes in the microstructure of the grain legume can be an issue if the end application is not defined. There are still many unanswered questions about flour fineness, separation index, and so on, as these parameters are still largely undefined for pulse milling with respect to the open research literature. For individual commercial millers, meeting targets on specification sheets typically dictates milling strategies.

Table 3–Forces at work on grain legumes (pulses) from different milling techniques (Hixon et al., 1990; Posner & Hibbs, 2005).

Mill type	Force/function	Particle size/fineness	Commodity	Reference
Stone mill	Compression, shear, abrasion	User-defined	Wheat, rice, pulse	Gómez et al. (2008); Kumar, Malleshi, and Bhattacharya (2008); Maskus et al. (2016); Otto et al. (1997)
Roller mill	Compression, shear, friction	User-defined	Wheat, pulse	Kosson et al. (1994); Maskus et al. (2016); Ribéreau et al. (2017); Sakhare et al. (2014); Watson et al. (1975)
Impact mill (hammer or pin mill)	Impact	Medium to medium fine	Pulse	Dijkink and Langelaan (2002a,b); Gómez et al. (2008); Maskus et al. (2016); Tyler (1984)
Ball mill	Impact and compression	Coarse to fine	Pulse	Sadowska et al. (2003)
Disc mill	Shear	Fine or very fine	Wheat, pulse	Kumar et al. (2008)
Jet mill (other than impact)	Particle–particle and particle–wall collisions, centrifugal	Very fine	Pulse	Limsangouan and Isobe (2009); Pelgrom et al. (2013)
Classifier mill	Control particle size distribution	User-defined	Pulse	Pelgrom et al. (2013)

Size reduction

Size reduction is a major unit operation in various industries (food, pharmaceutical, mineral, and so on) (Vishwanathan & Subramanian, 2014). It prepares raw materials for subsequent separation processes and breaks solid materials to obtain particular particle sizes or shapes (Hixon et al., 1990). The functionality of the products of size reduction operations depends on the nature of the grinding forces applied as well as the internal structure of the materials (Scanlon & Lamb, 1993, 1995; Vishwanathan & Subramanian, 2014).

Particle size distribution. Many researchers have determined the particle size distribution using different sieve sizes and determined parameters such as the geometric mean particle diameter, volumetric diameter, or other similar metrics to define the particle size of various flours. Measures of the dispersion in the particle size distribution are also often cited (Maskus, Bourré, Fraser, Sarkar, & Malcolmson, 2016).

Under fixed milling conditions, the average volume particle diameter of the flours of bean and lentil was significantly smaller than that of pea, which was associated with the initial seed hardness of the beans and lentils (Pelgrom et al., 2015). Commercially sourced pulse flours (chickpea, green and red lentil, pinto and navy bean, and yellow pea) had substantially different particle size distributions when passed through several sieves (Tyler series of 841, 400, 250, 177, 149, and 125 μm) (Han, Janz, & Gerlat, 2010). In this study, none of the commercial pulse flours would have been characterized as flour according to the U.S. Code of Federal Regulations definition for wheat flour (FDA, 2018).

Some studies have compared the particle size with respect to different grinding machines and the reduction in particle size with several passes of grinding. Fine, pin-milled yellow pea flours had the smallest particle sizes as compared to flours that were stone-milled (largest particle size), hammer-, coarse pin-, or roller-milled (Maskus et al., 2016). In a study on milling of cowpea, Kerr, Ward, McWatters, and Resurreccion (2000) examined the effect of screen sizes (0.5, 1, and 2 mm) on the distribution of particle sizes. Not unexpectedly, when the 0.5 mm screen was used, the majority of particles were retained on the smaller sieves (less than 105 μm), but the extent of change was dramatic, with the 2-mm screen producing only 10% of particles less than 105 μm compared with more than 70% for the 0.5-mm screen (Kerr et al., 2000). A reduction in particle size from 3800 to 61 μm was observed for red gram (pigeon pea) after 16 minutes of intermittent milling in a mixer grinder (cutting and shear forces), although the greatest degree of size reduction occurred in the first 4 minutes (Vishwanathan & Subramanian, 2014). Higher energy consumption during secondary grinding of the overtails from the primary milling operation was evidence that coarser fractions were less amenable to further size reduction (Vishwanathan & Subramanian, 2014). Hammer milling (with a 1.73 mm screen) of cowpea produced finer particles (with 50% of the particles greater than 280 μm) as compared to plate milling and use of a laboratory (Wiley) mill; all mills showed smaller particle size with decreasing clearance or screen size (A. Singh et al., 2005).

Jet and impact milling of yellow pea were conducted using different classifier speeds (2500, 4000, and 8000 rpm) (Pelgrom et al., 2013). Increasing classifier speed resulted in a decrease in yield, average particle diameter, flour moisture content, and increased protein content. At 8000 rpm, the particle size of the flour ranged from 17 to 26 μm. For milling of broad and green beans, an intermediate particle size (250 μm) produced via hammer milling led to flours with better functional properties (higher antioxidant capacity, total phenolic content, and resistant starch) than screw crushing (1000 μm) or jet milling (60 μm) (Limsangouan & Isobe, 2009). Hammer milling of lentil, cowpea (black-eyed pea), black gram, green gram (mung bean), and desi chickpea using a 1.6-mm screen or a 0.2-mm screen produced coarse (860-75 μm) and fine-ground (250-45 μm) particles, respectively (Indira & Bhattacharya, 2006). Based on the relationship between seed hardness and the ease of creating new surface area in the powder, the authors commented that lentil is more amenable to size reduction in terms of increases in particle surface area and number of particles. Therefore, grinding characteristics (such as energy consumption) vary extensively and are influenced by the geometry of the seeds (size, shape, thickness, and surface area) and their mechanical properties (hardness and breaking strength) (Indira & Bhattacharya, 2006). More energy was consumed in fine grinding following coarse grinding, attesting to the outcomes reported by Vishwanathan and Subramanian (2014).

In a comparison of whole-pea flour (median particle diameter of 0.669 mm) with fractionated flours (retained on various sieves from 2.5 to 0.122 mm), no changes in density were observed, but the whole-pea flour had a higher bulk density due to its heterogeneity in particle size allowing filling of voids; specific surface increased with a decrease in particle size (Maaroufi et al., 2000). In a study of flours of pinto bean, a high-starch (air-classified) fraction was found to have lost more moisture than the whole pinto bean flour due to its increased surface area. This resulted in lower water activity compared to the whole pinto bean flour (Simons, Hall, & Biswas, 2017).

Various researchers have explored the particle size distribution of pulse flours and a wide range of values has been reported. A pronounced effect of different mills on particle size is noticeable in the literature. Jet and pin milling result in very fine flours (less than 60 μm) with hammer milling, roller, and stone mills producing various particle sizes depending on their specific configurations. It is therefore extremely difficult to compare the results of various studies that use different mill configurations and pulse types. There is a real need to investigate mill effects on the extent of size reduction and the variability of particle size distributions, particularly targeting desired distributions for specific applications.

Effect on flowability. Hard-to-mill grains typically have poor flowability characteristics and this has implications for the design of flow systems and processes required for the manufacture of flour-based products. The discernible differences between milling of hard and soft wheat flour due to poorer flowability of soft wheat flours are well documented (Neel & Hoseney, 1984). However, very little information is available in the literature on the flowability of pulse flours or their parent stocks, even though a number of research studies point to the lack of sufficient knowledge on flowability. In the absence of a complete understanding of pulse flour flowability, researchers have used arbitrary methods to alter this important parameter. For example, Pelgrom et al. (2015) added 1% fumed silica to improve the flowability of their pea flours.

Flowability characterized by the angle of repose, compressibility index, and Hausner's ratio (based on the bulk and tapped densities) showed that red kidney bean had acceptable flow characteristics as compared to mung bean (poor), black gram (very poor), and red split lentil (the least flowable) (Gani et al., 2015). Flow character of chickpea flour was poorer than that of pea, bean, and lentil of similar size, all decreasing as a function of average particle size (Pelgrom et al., 2015). The decrease in dispersibility could be associated with increased fat content, indicating that elevated fat levels impair separation. In a recent study of hammer-milled pea, Kallenbach, Kaiser, Fujiwara, Manthey, and Hall (2017) showed that a lower angle of slide (that is, easier flow) was observed for flour produced with screens of smaller size. It is worth noting that the smallest hammer mill screen size was 0.832 mm in this study.

Given that studies on flowability of pulse flours are virtually nonexistent, some studies on wheat flour are included that may have relevance to the handling characteristics of pulse stocks during milling. A study by Neel and Hoseney (1984) investigated flowability parameters (bridging threshold and bulking number) to elucidate flour cohesion effects for soft and hard wheat flours with respect to moisture content, presence/absence of fat, and particle size distribution. The most significant differences were found for the presence/absence of fat in flour systems; however, soft wheat flour showed additional sensitivity to all three parameters, which was attributed to irregular particle shape. Another study showed that chemical composition (protein, fat, and damaged starch) had a profound effect on the dynamic flowability (cohesion, flow function, and angle of internal friction) of wheat flours (Siliveru, Ambrose, & Vadlani, 2017). Moreover, a shift in flowability from easy-flowing to cohesive was recorded at 12% moisture content (w.b.) and a particle size of 45 μm.

Little information is available on the flowability of pulse flours. Studies on particle size, particle shape, and moisture and lipid contents that make powders easy or difficult to flow are required to ascertain the flowability characteristics of different pulse flours.

Separation of components

The typically available milled pulse fractions in the market are whole pulse flours, pulse fiber, pulse starch, and pulse protein flours, concentrates, and isolates. Some of the commercially available products include pulse flours of pea, chickpea, bean, and lupin, and fiber, starch and protein concentrates and isolates from pea (Farooq & Boye, 2011). Efforts have been made to compile the plethora of information on the composition, molecular structure, properties, processing methods, and applications of major pulse fractions—dietary fiber (Tosh & Yada, 2010), protein (Boye, Zare, & Pletch, 2010), and starch (Hoover et al., 2010). Milling of pulses increases the surface area so that starch granules can be separated from protein bodies (Hoover et al., 2010; Vaz Patto et al., 2015). Although milling and concomitant sieving operations can lead to fractions that are enriched in 1 or more of these components, the production of concentrates and isolates requires air classification and/or wet milling. The wet milling method is more exhaustive and encompasses several steps including soaking, homogenization, filtration, oven drying, pulverization, and sieving to produce the highly purified starch fraction compared to the dry milling method (M.E.J. Geerts et al., 2018; Hoover et al., 2010). We focus on separation of the aforementioned components as a result of changes in dry milling conditions.

How are separation goals related to particle size? The particle size distribution of flours plays a significant role in fractionation. Enrichment by differences in the particle size of starch (15 to 40 μm) and protein particles (approximately 5 μm) is well established (Pelgrom et al., 2015). Therefore, milling of seeds to an appropriate particle size is essential to obtain desired enriched fractions. Pelgrom et al. (2013) summarized important size targets for pea based on previous studies: protein bodies are between 1 and 3 μm, starch granules, 22 μm, and whole cells or parts of cells constitute particles larger than 40 μm. The average size (diameter) of starch granules of pulses varies from 5 to 104 μm (Tiwari & Singh, 2012).

Separation techniques. There are several fractionation techniques employed by industry and researchers for obtaining chemical constituents such as protein (and subsequently their isolates), starch, and dietary fiber from pulse flours. The type of milling and its extent (fineness or coarseness) affects the separated fractions (and their characteristics), which is pulse-dependent (Boye et al., 2010). Frequently, the first separation operation is dehulling. The effect of dehulling on altering the protein/starch ratio for various pulses is shown in Figure 2. It can be seen that there is a tendency for protein loss upon dehulling.

Dry fractionation involves milling (impact) and air classification to separate the protein and starch fractions (Pelgrom et al., 2013; Schutyser et al., 2015). Air classification separates the milled flour into a fine, protein-enriched fraction and a coarse, starch-enriched fraction (Boye et al., 2010). The separation of protein and starch fractions via air classification along with other methods of protein extraction has been comprehensively reviewed by Boye et al. (2010). Wet fractionation processes have been combined with dry fractionation processes. The advantage of wet fractionation methods is that they do not break starch granules (Naguleswaran & Vasanthan, 2010), whereas dry fractionation can break the starch granules into smaller fragments when they are being released from the protein matrix (Pelgrom, Boom, & Schutyser, 2014).

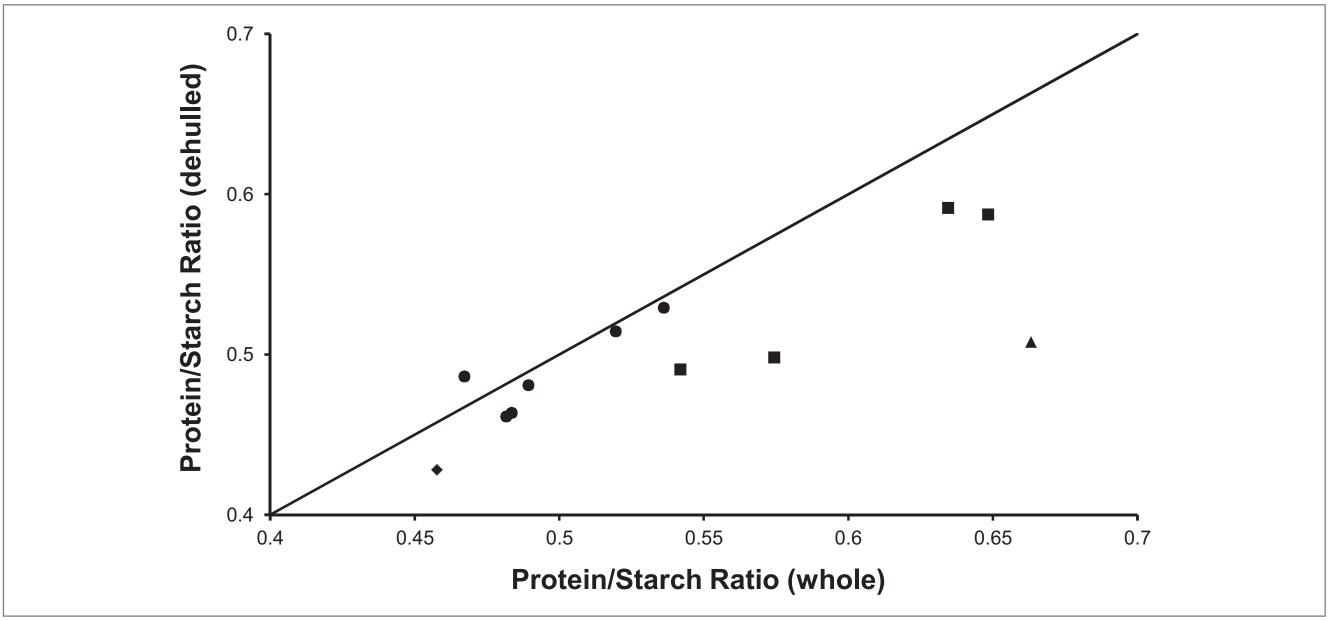

Figure 2–Relationship between protein to starch ratio in dehulled grain legumes relative to that in whole seeds for pea (●) from Wang et al. (2008), lentil (■) from Wang (2008), cowpea (◆) from Mamiro, Mbwaga, Mamiro, Mwanri, and Kinabo (2011), and black bean (▲) from Guajardo-Flores et al. (2017). Multiple points for the same grain legume represent different cultivars. The $y = x$ line represents no change in protein to starch ratio due to dehulling.

In a landmark study, several pulses (mung bean, green lentil, faba bean, field pea, navy bean, and cowpea) were subjected to pin milling coupled with air classification cycles to retrieve starch and protein concentrates (Tyler et al., 1981). The first pass yielded an enriched protein content stream (49% to 75%) with low starch content (0% to 4.6%). The starch fraction from the first pass contained 58% to 76% starch. When subjected to remilling and another air classification of the starch fraction, the starch fraction was enriched to 71% to 86% (starch) and 4% to 10.4% (protein), while the protein fraction had protein contents ranging from 38% to 68% (protein) and 0.4% to 16.6% (starch). Due to the high starch content in the protein fractions and vice-versa, this method would not be suitable for producing a protein isolate. Starch separation efficiency ranged from 96% to 99%, and PSE ranged from 78% (for cowpea) to 89% (for mung bean) following the second milling and air-classification pass (Tyler et al., 1981).

In a more recent study, air classification was coupled with an assessment of the performance of jet milling and impact milling of yellow pea to separate starch-rich and protein-rich fractions (Pelgrom et al., 2013). Both types of mills had a classifier (to separate smaller particles from those that were recirculated back into the mill to be reground). Classifier speed was seen to be a critical factor in effecting a starch–protein separation, generating a protein stream that had more than 50% protein (starting point = 23%) when operating at optimal speed (Pelgrom et al., 2013).

A further means of obtaining protein-rich streams from pulses following dry milling processes is through use of triboelectrostatic separation (Pelgrom et al., 2015). In this process, an applied electric field induces separation of protein-enriched particles (which acquire a charge) from other particles. J. Wang, Zhao, deWit, Boom, and Schutyser (2016) were able to show that a multistep electrostatic separation process could provide a protein-enriched stream that was 65% protein after size reduction of lupin (starting from 51% protein content in flour obtained by hammer milling and air classification). The authors found that greater size reduction (which was expected to liberate more protein) actually impeded electrostatic enrichment due to enhanced aggregation of small particles. The process has also been applied to obtain a protein-enriched stream from navy bean flour following pin milling (Tabtabaei, Vitelli, Rajabzadeh, & Legge, 2017). These authors found that air flow conditions during operation were a critical control parameter for enrichment, and this, in turn, was particle-size-dependent.

Starch enrichment. Several studies have shown that milling followed by air classification is a useful means of producing a starch-rich fraction. Although extensive milling leads to higher purity, adherent protein remains after repeated cycles of impact milling and air classification (Tyler, 1984). Starch isolation/enrichment typically requires wet milling to produce highly purified starch (Hoover et al., 2010). However, dehulled field peas were cyclone milled (0.25 mm screen opening) and the starch–protein separation efficacy was compared with direct wet milling of the dehulled peas (Naguleswaran & Vasanthan, 2010). The authors suggested that better separation was attained in the dry milling method because of its effective fragmentation processes.

Many studies have shown that coarse milling (larger particle size) results in higher starch content. Dry fractionation of yellow pea (flour and fine and coarse fractions) revealed that the fine fraction was rich in protein, fiber, oil and ash (Pelgrom et al., 2014; Tyler et al., 1981) and the coarse fraction had less fiber but high starch content. Moreover, grinding (coarse and fine fractions) and air classification led to a high-starch flour (55% yield, 67% starch, 16% protein) and a high-protein flour (32% yield, 41% protein). Exceptions to the general rule do occur though. A study showed that cowpea flour with smaller starch granules (<3.5 to 18 μm) produced fines with higher starch content than pigeon pea or faba bean that have larger sized starch granules (Cloutt, Walker, & Pike, 1986). A fractionation method for "commercially milled" garbonzo bean led to significantly lower protein, free lipids, and ash content in the fine fraction (less than 86 μm) and lowered the starch content of the coarse fraction (greater than 330 μm). This outcome contrasts with the more extensively reported trend seen for pea, and this was ascribed to compositional differences in the cotyledon from which these particles emanated (Otto, Baik, & Czuchajowska, 1997).

Air classification of pin-milled pinto bean (88% flour particles ≤ 44 μm) resulted in 80% of a starch-rich fraction (15 to 45 μm) and 20% of a protein fraction (≤15 μm) (Simons et al., 2017). The high-starch fraction (HSF) was whiter in color than the whole pinto bean flour, potentially due to its higher concentration of starch and lesser amount of protein. Ash content decreased with air classification and no significant change (via fractionation) in total dietary fiber content was found in either stream. Different cycles of pin milling (1, 3, 9, or 12 times at 14000 rpm) followed by air classification of both whole and dehulled field pea resulted in coarse fractions (greater than 18 μm) with a high-starch content and fine fractions (less than 18 μm) with high-protein content (Wu & Nichols, 2005).

A laboratory hammer milling investigation of cowpea flour by Kerr et al. (2000) showed an increase in starch with decreasing mill screen size (2, 1, and 0.5 mm). When the flour on the mill screens was further sieved (sieve sizes of 0.297 and 0.149 mm), more starch was located on the smaller sieve and the collecting pan, indicating the importance of the size of the screen during impact milling to achieve separation goals.

Starch- and protein-enriched samples obtained from pin milling and air classification of field pea showed no effect of seed maturity (presence of immature seeds differing in size and shape) on the starch and protein separation efficiencies (Tyler & Panchuk, 1984). However, the presence of immature (green, small, or shrunken) seeds may lead to difficulty in dehulling, and consequently there may be high fiber content in the classified fractions.

Protein enrichment. Roller milling of green and yellow pea cultivars has been used to produce various mill fractions (Kosson, Czuchajowska, & Pomeranz, 1994). On the basis of anatomical distributions of lipid and protein and which mill fractions had large or small amounts of these components, the authors concluded that the high-protein flour was retrieved from the outer layer of pea, while the coarse fraction was from the inner portion of the cotyledon. In another study (Otto et al., 1997), roller milling of the same pea cultivars led to a lower protein content in the break flours. Flour from the central (softer) part of the cotyledon had lower protein and fiber content and higher starch content than the flour from the outer layer of the cotyledon (Otto et al., 1997).

Tempering (moisture contents 3.8 to 14.3%) and drying of yellow field pea and faba bean prior to pin milling was conducted to investigate separation efficiency in an air classification process separating starch and protein fractions (Tyler & Panchuk, 1982). The yield of the protein-rich stream and the PSE increased with a reduction in moisture content, which means improved milling efficiency at lower moisture content allowed better separation of protein and starch. Furthermore, low moisture content samples had greater values for seed hardness (assessed by sample grinding time and the proportion of the pulse flour that passed a 38 μm screen after milling); the concomitant brittleness lead to better milling performance (higher yield and better starch/protein separation in the fractions). Therefore, it was suggested that seed moisture below 10% provided the most suitable conditions for impact (pin) milling of yellow field pea and faba bean, and most likely other grain legumes. With a reduction in moisture levels in the raw seeds of pea and lupin, PSE (total protein recovery, %) was enhanced and the yield of smaller particles increased in the fine fractions; both outcomes were ascribed to increased brittleness (Pelgrom et al., 2015).

Pelgrom et al. (2015) investigated a number of premilling treatments, such as adjustment of moisture and removal of hull and lipids (by organic solvent extraction) to improve the purity and yield of the protein fractions obtained from air classification of predried yellow pea. At similar milling conditions, seeds at lower moisture (4 to 13%) yielded smaller particle sizes. Presoaking and freezing cycles decreased the mean particle size and protein content in the fine fraction, while increasing the protein content of the coarse fraction with respect to the overall composition of the pea.

Fiber enrichment. Pulses have a high proportion of dietary fibers concentrated in the hull (seed coat). Dietary fiber includes a complex mixture of indigestible polysaccharides (cellulose, hemicellulose, oligosaccharides, pectins, gums), waxes, and lignin found in the plant cell wall. The total dietary fiber (TDF) content of pulse flours differs according to the grain legume (Vaz Patto et al., 2015), but it ranges from 14 to 33 g/100 g dry matter (d.m.) with soluble dietary fiber (SDF) from 1 to 9 g/100 g d.m. Several studies have shown how incorporation of the cell wall components is a way to enrich dietary fiber in the separated fractions.

As hulls separated from cotyledons contribute to the IDF in pulses, Dalgetty and Baik (2003) showed that roller milling of chickpea, lentil and pea reduced the IDF (from 10.0, 11.4, and 11.3% for raw seed to 6.5, 4.1, and 5.3% for the flour) and the TDF (ranging from 18.3 to 20.0% for raw seed to 11.5 to 15.6% for flour). However, SDF was not significantly different between the seed (6.9 to 8.7%) and the flour (7.4 to 9.1%) (Dalgetty & Baik, 2003).

Hammer milling (4-mm screen) and granulometric fractionation using mesh sieves (2.5 to 0.122 mm) also led to a flour on the smaller sieves that had lower cell wall content (crude fiber from 0.9 to 11.8% d.m.) (Maaroufi et al., 2000). In another study, several passes of roller milling produced coarse (break) and fine (reduction) green gram fractions (Sakhare et al., 2014). SEM and chemical analysis showed higher fiber content (71%) present in the coarse fractions (Sakhare et al., 2014) whereas higher protein content (30%) resided in the reduction fractions.

From the research literature it is apparent that milling must be vigorous enough that air classification can separate the milled particles into a fine, protein-rich fraction and a coarse, starch-rich fraction, but the particle size delineation between coarse and fine varies according to the pulse. Post-milling fractionation can be effectively utilized if the particle sizes of the aforementioned components of a particular pulse are controlled. Milling of the hulls results in a higher dietary fiber content in the flour. Wide ranges of particle sizes of starch, protein bodies, and dietary fiber have been found in several pulses, potentially due to G × E outcomes, component extraction, and processing effects.

Physicochemical changes

Starch. Various milling conditions and parameters have been formulated with respect to starch damage. The impact of starch damage and particle size is well known for rice flour (Araki et al., 2009; Kadan, Bryant, & Miller, 2008). Studies of starch damage in wheat flours also show the inverse relationship between particle size and starch damage (Evers & Stevens, 1985; Scanlon et al., 1988).

Many studies have reported that starch damage in pulse flours increases with fine milling when using high-speed milling. For instance, greater starch disruption resulted from smaller mill screen sizes in laboratory hammer milling of cowpea (Kerr et al., 2000). Jet milling at high classifier speeds (8000 and 12000 rpm) resulted in starch damage that was considerably higher than with impact milling (Pelgrom et al., 2013). The difficulty in assessing the effect of the milling process on starch damage per se is that different studies have analyzed starch damage in products with very different particle sizes. Roller milling of yellow pea resulted in significantly higher starch damage (2.8%) than other milling methods (stone, hammer, and pin milling) (Maskus et al., 2016), but differences in particle size and the degree of shearing can markedly influence starch damage in roller milling (Scanlon & Dexter, 1986). Another study of roller milling, but of green gram, also reported high-starch damage in the fine fractions based on microstructure analysis (Sakhare et al., 2014). Higher starch damage was reported for field pea (larger, nonsmooth with fissures on the surfaces, and irregularly-shaped starch granules) than for pinto and navy bean conducted using fixed hammer milling conditions (Gujska, D.-Reinhard, & Khan, 1994). The authors implied that higher starch damage would confer greater swelling power and this could be utilized in extruded products.

In contrast to these dry milling studies, some fractionation methods have reported little or no starch damage. For example, wet milling of navy bean resulted in minimal starch damage (0.007%) (Maaran, Hoover, Donner, & Liu, 2014). No starch damage was reported in starches isolated from faba bean, black bean, and pinto bean, even though cracking of starch granules was reported (Ambigaipalan et al., 2011). A comparison of dry milling of pea to retrieve pea starch showed 12.4% starch damage, which was higher than wet milling isolation methods (Sun, Chu, Xiong, & Si, 2015). Therefore, it can be concluded that high-starch damage results from dry milling, especially when conducted at high speeds to produce flours of small particle size.

Protein. Although mechanochemical transformations are used to produce solvent-free chemical changes in molecules (Dubinskaya, 1999), there are no consistent reports of protein structure modifications by dry milling in the way that starch granules are modified in their properties. Reporting on the thesis results of Ward (1995), Kerr, Ward, Mcwatters, and Resurreccion (2001) stated that an increase in soluble protein was found in finer flour (hammer milled to pass a 0.5 mm screen). Therefore, the possibility of protein modification by milling is worth examination.

Fiber. Many reports have focused on evaluation of hull content as a means to assess the insoluble and soluble dietary fiber components of pulses. Milling can affect the physiochemical properties of dietary fiber components (Dogan, Aslan, & Gurmeric, 2018), including hydration (water-retention and absorption), oil/fat retention, and porosity. A study by Daubenmire, Zabik, and Setser (1993) revealed high water retention capacity for navy bean hulls that were coarsely milled (425 to 850 μm) as compared to the finely milled fractions (less than 150 μm). With a decrease in particle size (950, 490, and 300 μm) arising from hammer milling of pea hulls with different screen sizes (2, 1, and 0.5 mm), there was an increase in water holding capacity (potentially due to an increase in the surface area and pore volume), and water-binding capacity (Auffret, Ralet, Guillon, Barry, & Thibault, 1994).

Effect on water absorption

It is largely believed that more finely milled (smaller particle sized) flours have higher water holding capacity (Scanlon et al., 1988; Vaz Patto et al., 2015). However, some studies with pulse flours have shown a departure from this trend. Contrary to expectations associated with increased surface area (Farooq & Boye, 2011), poor water absorption characteristics were found in fine-milled cowpea flours (Kerr et al., 2000; McWatters, 1983). Water absorption of cowpea flour decreased with decreasing mill screen size (0.5, 1, and 2 mm); however, fractions sieved from these flours had variable values for water absorption depending on the mesh size (Kerr et al., 2000).

From pulse milling studies, a trend of low water absorption with extensive milling has been observed. However, it is not clear whether this is due to differences in composition or to physicochemical changes in the components during milling. This is ably demonstrated with an analysis of the results of size reduction of pea with different mills (Maskus et al., 2016), where a negative relationship between water absorption and reduction in particle size is observed, but only for milled, dehulled samples (Figure 3).

Effect on other properties

The impact of size reduction on other properties of pulse flours, such as color, rate of hydration, oil absorption, digestibility, and palatability, needs study (Sarkar & Subramaniam, 2016) to better understand the effect of milling on the end-use performance of the flour. Food structure has important consequences for nutrient availability (Donald, 2004). Therefore, size reduction of pulses is expected to alter the manner in which nutrients are absorbed and specific physiological responses are elicited, for example, glycemic index (Jenkins et al., 1981). Indeed, one outstanding question is, "does the whole ground pulse flour have the same nutritional impact as the whole unground pulse?"

In animal feeding studies, there is indication that more effective size reduction improves nutrient availability. A study on lupin indicated that nutrient utilization in pigs increased as particle size was reduced (Pieper et al., 2016). However, the results of this study may not be extrapolated to pulse flour studies since their "fine ground" fraction was material that passed through a 1-mm sieve. A more refined particle size study of ground pea was conducted by Maaroufi, Chapoutot, Sauvant, and Giger-Reverdin (2009). After grinding peas to pass through a 4-mm screen, the comminuted product was sieved to produce nine fractions retained on sieves ranging in size from 2500 to 122 μm and the throughs of the 122 μm sieve. A clear effect of particle size on the rate of gas production in an *in vitro* rumen fluid fermentor was observed, with faster generation of gas as particle size decreased. The same research group compared the nutritive value of pea flour prepared in a hammer mill with that in a roller mill in an *in vivo* study of feeding of goats (Giger-Reverdin, Maaroufi, Peyronnet, & Sauvant, 2015). Although median particle size differed quite considerably between "flours" produced by the three types of mills, particle size had no effect on cell wall or crude protein digestibility, an outcome that the authors attributed to the chewing efficiency of dairy goats.

An *in vitro* assessment showed the importance of cell intactness on the extent of starch hydrolysis in chickpea, pea, mung bean, and red kidney bean (Dhital et al., 2016). The pulses were either partially or fully cooked and cell walls disintegrated with high-speed stirring overnight. Enhanced rates of starch hydrolysis were observed regardless of the degree of cooking, pointing to the importance of cell wall integrity for availability of nutrients contained within the cells. As a result, the authors concluded that "fine milled legume flour will not have the equivalent slow digestion property as cooked whole legumes." In a recent study, Luhovyy, Hamilton, Kathirvel, and Mustafaalsaafin (2017) conducted *in vitro* digestion of navy bean that had been ground to different sizes by pin milling. They showed that smaller particle size fractions had faster glucose release rates, an effect that persisted even when the

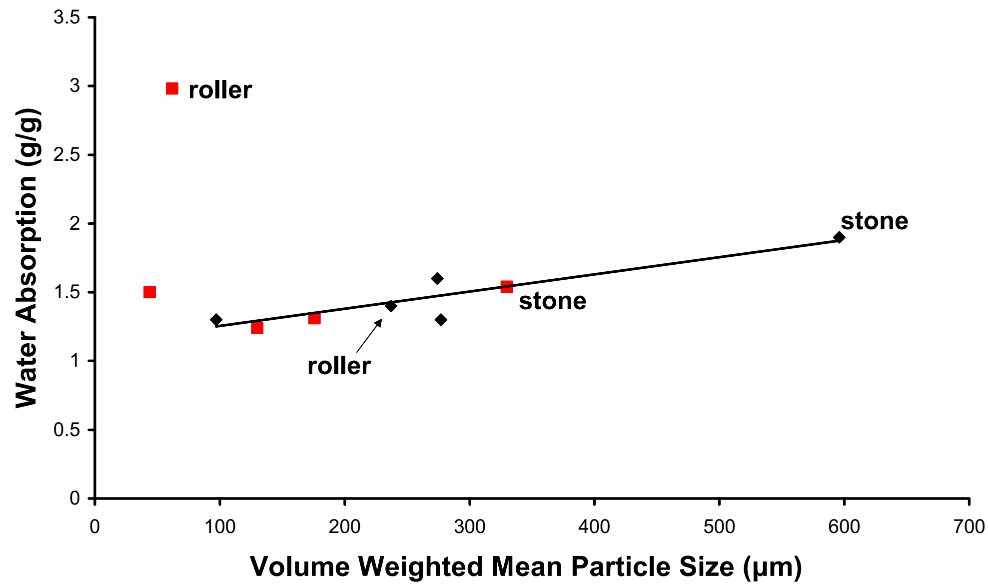

Figure 3–Relationship between water absorption and volume-weighted mean particle size for field pea samples (dehulled [◆] or whole [■]) reduced in size by various mills, data plotted from results of Maskus et al. (2016). Line is the best-fit relation for dehulled samples.

fractions were "baked" as a flour–water paste. It is worth noting that the moisture content employed for baking of the flours was low (approximately 33% flour absorption basis) (Luhovyy et al., 2017).

Wheat flour containing 10% of commercially milled flours from whole and split yellow pea, which had been subsequently fractionated on sieves, was utilized in white pan bread (Davies-Hoes, Scanlon, Girgih, & Aluko, 2017). The authors showed differences in the antioxidant potential of the fractions according to particle size fraction, just as had been demonstrated for particle size differences brought about by use of different mills (Limsangouan & Isobe, 2009).

In a recent review of flavor in pulse ingredients (Roland, Pouvreau, Curran, van de Velde, & de Kok, 2017), no mention was made of particle size effects on flavor or aroma. Nevertheless, particle size effects on aroma have been reported for wheat bran (Galliard & Gallagher, 1988) and chocolate (Afoakwa, Paterson, Fowler, & Ryan, 2009), and it has been suggested that fewer flavor issues are evident when pea flour incorporated into bread flour has been milled to smaller particle size (Dyck, 2017).

The paucity of information in a number of areas that affect the marketability of pulses means that relationships between milling conditions and other properties of pulse flours, such as nutritional quality, should be explored.

Pulse Flour Products

The pulse flour products in the market mainly comprise cold and hot extruded products (pasta, noodles, and snacks) and baked products (cakes, cookies, bread, and gluten-free [GF] products). Other forms include fried and meat-based products. The application of several pulses and their components in baked (GF, bread, cake, cookie, and so on), extruded (pasta and spaghetti), and other products (emulsions and beverages) has been reviewed recently (Foschia, Horstmann, Arendt, & Zannini, 2017; Melini, Melini, Luziatelli, & Ruzzi, 2017; Sozer, Holopainen-Mantila, & Poutanen, 2017). The effect of addition of pulse ingredients on quality aspects (for example, batter viscosity and volume, bread specific volume, cake volume index and softness, and texture profile properties) of baked and pasta products was also reviewed for several pulse flours and their components (protein isolates and starch) (Foschia et al., 2017). Moreover, the effect of functional properties such as solubility, water holding and fat absorption capacity, emulsification, foaming, and gelation on the properties of end products has also been reviewed (Foschia et al., 2017). However, in neither of these reviews was there a focus on milling or grinding as means of manipulating the functionality of the bioprocessed pulse ingredients for specific end products (M. Geerts, Strijbos, van der Padt, & van der Goot, 2017).

In this section, we strive to draw out the available information on pulse-based products in terms of the outcomes of the milling process on the quality of products where pulse flours are incorporated. For example, how do pulse flour quality parameters such as particle size, protein content, and separation index affect the quality of products into which the milled flours are incorporated? As such, effects of pulse flour quantity will be minimally addressed here and the reviews above should be consulted in that regard.

Baked products

Various studies have been undertaken to incorporate pulse flours into baked products to enhance their functional and nutritional properties. These include baked-product studies with chickpea flour, lentil flour, pea flour, and bean flour. One of the issues in comparing different studies is that not all studies use the FDA particle size definition for flour, so that potential effects of large particle size in the pulse flour (and thus poor miscibility of ingredients) may be a significant factor in quality assessments of the finished product (Table 4).

In a comparison of partial substitution of lentil, navy bean and pinto flours in the production of pita bread, Borsuk, Arntfield, Lukow, Swallow, and Malcolmson (2012) showed no quality differences between coarse (90% less than 440 μm) hammer-milled fractions and fine (90% less than 50 μm) hammer and pin-milled flours, except for crust color, where coarse flours produced pita breads that were lighter in appearance.

Table 4–Some select descriptions of milling processes for bakery applications of pulse "flours".

Grain legume	Application	Mill	Particle size	Reference
Lupin	Bread	Barley pearler (hull removal); falling number mill	<132 μm	Pollard et al. (2002)
Green gram	Bread	MLU 202, Buhler	<132 μm	Sakhare et al. (2014)
Pea, chickpea, lentil	Bread	Miag Multomat	no size given	Dalgetty and Baik (2006)
Pea	Bread	Ball mill	50 to 250 μm (by sieving)	Sadowska et al. (2003)
Lentil, bean	Bread	Laboratory mill	250 μm	Kohajdová, Karovičová, and Magala (2013)
Chickpea	Bread	Retsch laboratory hammer mill	<1.0 mm screen	Mohammed, Ahmed, and Senge (2014)
Navy bean, pinto bean, lentil	Pita bread	Lab-scale hammer mill, Hosokawa pin mill	Mean = 17 to 23 μm or 150 to 190 μm	Borsuk et al. (2012)
Chickpea	Gluten-free bread	Commercial, undefined	Undefined	Miñarro et al. (2012)
Bean (*Phaseolus vulgaris* L.)	Wheat flour tortilla	Jacobson pilot scale hammer mill	Pass a 500 μm sieve	Anton, Ross, Lukow, Fulcher, and Arntfield (2008)
Lentil	Cake	Commercial, undefined	95% of particles <150 μm	de la Hera et al. (2012)
Chickpea	Cake	Stone mill	particle size below 210 μm	Gómez et al. (2008)
Pea	Cake	Commercial pin mill	17 μm = mean particle size	Gómez et al. (2012)
Navy bean	Cookie	Jacobson lab scale hammer mill (1.5 mm screen)	90% <425 μm	Zucco et al. (2011)

In a study involving navy bean flour incorporation into cake batter, particle size affected the pH of the batter but not its density or viscosity (M. Singh, Byars, & Liu, 2015). Increasing the proportion of lentil flour reduced the density of a layered cake batter (de la Hera, Ruiz-París, Oliete, & Gómez, 2012). For sponge cakes, cakes made from fine flours (less than 140 μm) exhibited the highest cake volume; cakes made from coarse-milled flour produced cakes showing poor quality. In layered cakes, the proportion of lentil flour corresponded to increasing cake density and decreasing cake volume. Flours from different lentil cultivars affected cake color, but their particle size did not. In a study on chickpea flour incorporation, sponge cakes made with a "fine" chickpea flour (smaller particle size and less fiber) had the highest volume (Gómez et al., 2008).

Sponge and layered cakes were obtained with incorporation into wheat flour of 25%, 50%, or 100% pin-milled pea flour (mean particle diameter [D] = 17.4 μm, 8.9% protein) and their air-classified starch (D = 24.1 μm, 10.2% protein) and protein concentrates (D = 9.6 μm, 51.5% protein) (Gómez, Doyagüe, & de la Hera, 2012). An increase in protein content increased batter viscosity for both cake types and decreased cake specific volume. Cake hardening was slowed, which was surmised to be due to less starch and so less retrogradation. No color difference was visible for cakes produced with navy bean flour with respect to particle size distribution for whole (75 to 425 μm), coarse (greater than 105 μm), and fine ($\leq$ 105 μm) bean flours (M. Singh et al., 2015). These authors also observed that higher protein content (11%, 18%, and 21%) increased the viscosity of the cake batters. Particle size affected cake batter stickiness and rheology. Cake volume index was not affected by the protein content, but there were differences with respect to different bean flours and their particle sizes (cake made from fine bean flour had the lowest volume). Texture (firmness and springiness) was not affected by flour, particle size, or protein content (M. Singh et al., 2015).

For cookies, incorporation of fine and coarsely milled navy bean, pinto bean, and green lentil into wheat flours showed that smaller particle size flours (17 to 23 μm) led to a decrease in spread factor and increased cookie hardness compared to those made from coarsely milled (150 to 190 μm) flour (Zucco, Borsuk, & Arntfield, 2011). Cookie weight increased for both coarse- and fine-milled flour cookies, perhaps reflecting enhanced interactions of water and flour components. Cookie color was also affected, with incorporation of higher levels leading to darker top surfaces, except for pinto bean flour, and this effect was more evident for the finely milled flours.

An important outlet for pulses, pulse fractions, and pulse flours is in GF products. Pulse utilization in several gluten-free (GF) products (cakes, muffins, crackers, and breads) has been extensively reviewed (Foschia et al., 2017; Sozer et al., 2017). Chickpea, pea, lentil, and bean flours (particle sizes < 210 μm) were incorporated in a 1:1 ratio with rice flour to make GF-layered cakes (Gularte, Gómez, & Rosell, 2012). Bean flour had the highest batter viscosity. Lentil flour produced cakes with the highest specific volume (all pulses increased the specific volume except for chickpea). Pulses affected the texture (instrumental hardness and chewiness) and color attributes of the cake. Nutritionally, pulse-enriched cakes had higher total protein, available protein, mineral, fat, and fiber contents (except for chickpea). Lentil flour incorporation produced the best GF cakes with respect to nutritional and physicochemical properties. Not surprisingly (Scanlon & Zghal, 2001), negative correlations between hardness and loaf specific volume of chickpea-based breads have been reported (Gómez et al., 2008; Miñarro, Albanell, Aguilar, Guamis, & Capellas, 2012).

For baked products, the particle size of the flours plays a significant role. Some appreciation of the breadth of differences between particle sizes of pulse "flours" for bakery applications can be gleaned from Table 4. The best sponge cakes with the highest volume were produced from fine flours. An increase in protein content corresponded to increased batter viscosity and decreased cake volume and poorer color characteristics (producing a browning effect). A particle size effect was seen for cookie formulations where fine-milled flour increased cookie hardness. Some pulses have been extensively studied for use in baked product formulations; however, others (black bean, pigeon pea, and black-eyed pea) still require research to fully understand how to best utilize them.

Extruded products

Extrusion can be conducted as a "hot" or a "cold" process, with emphasis in the former as an expansion process for crispy snack products, and in the latter as a forming operation for shaped dense food products. The functional properties of pasta products

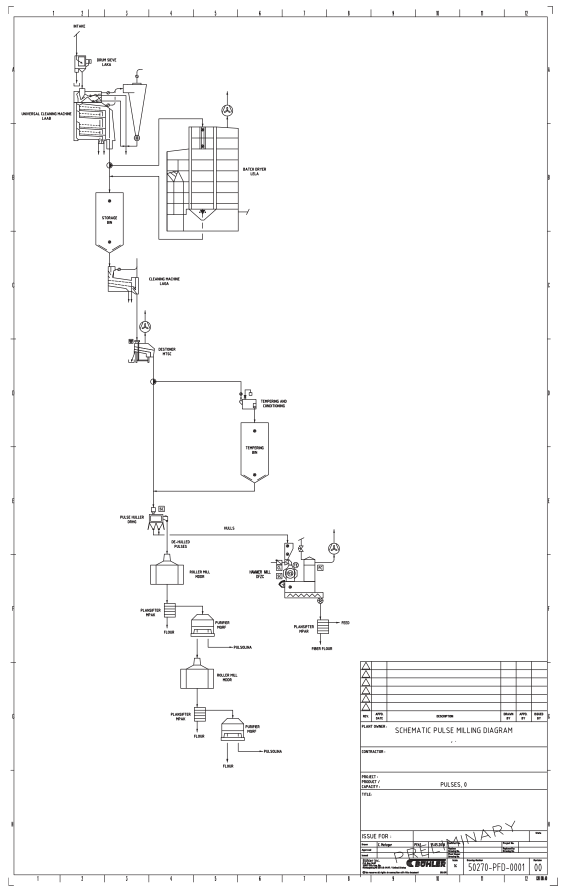

Figure 4–Potential mill flow to create semolina-sized particles from pea that would be suitable for extruded grain legume products.

can be altered by extrusion with resistant starch content changed, proteins denatured, and pasta swelling during cooking restricted (Vaz Patto et al., 2015). Hot extrusion has been shown to be effective at reducing antinutritional factors (Nikmaram et al., 2017) and enhancing protein digestibility scores (Nosworthy et al., 2018). In producing ground particles suitable for extruders, larger particle size is often preferred (Carvalho, Takeiti, Onwulata, & Pordesimo, 2010). Roller milling is one effective means of producing such particulates. A hypothetical mill-flow diagram is shown in Figure 4 that produces coarse and fine "semolina" fractions, that we denote as pulsolina (ground pulse particulates with sizes between 180 and 600 μm). A certain amount of break pulse flour is also produced in this mill flow.

Faba bean flour inclusion significantly increased pasta hardness (Petitot, Boyer, Minier, & Micard, 2010; Rosa-Sibakov et al., 2016), an effect attributed to increased protein content. This protein enhancement of pasta firmness has been observed for incorporation of split pea (Petitot et al., 2010) and lupin (Doxastakis et al., 2007) flours in spaghetti formulations. A reduction in firmness was observed when black gram was roller-milled to semolina-sized particles (approximately 550 μm) to create protein-enriched vermicelli (Rajiv, Milind, Inamdar, Sakhare, & Venkateswara Rao, 2015). A decrease in water absorption was reported with increasing faba bean flour incorporation into spaghetti (Petitot et al., 2010; Rosa-Sibakov et al., 2016), which was attributed to higher propensity for aggregation of dough pieces that led to difficulties in extrusion.

Much research has been conducted on noodles. Mung bean and yellow pea have been commonly used to produce starch-enriched noodles (Lu & Collado, 2010). Faba bean flour was substituted in a noodle formulation up to a maximum of 40% incorporation, as higher amounts were not extrudable (Lorenz, Dilsaver, & Wolt, 1979). The quality of noodles made from isolated starches of whole seeds and split pulses (pigeon pea and mung bean) was evaluated based on sensory assessment of appearance and texture (U. Singh, Voraputhaporn, Rao, & Jambunathan, 1989). Noodles containing whole pigeon pea starch scored low on clarity, color, and general acceptability compared to mung bean starch noodles. However, the noodles from starch derived from decorticated pigeon pea had comparable color and quality (except for texture) to noodles made from mung bean starch. Microscopic examination showed the irregular shapes of the starch granules of pigeon pea and mung bean starches, which ranged from oval to round to bean-shaped (U. Singh et al., 1989), and this was though to explain variation in the starch-based noodle behavior.

Many researchers have manufactured extruded snacks from pulses. For hot extruded products, the expansion index (ratio) (EI) is a measure of the porosity of the extruded product (Nyombaire, Siddiq, & Dolan, 2011). A porridge extrudate made from coarsely ground red kidney bean flour (hammer mill, 300 μm screen) produced a low EI (Nyombaire et al., 2011). For extrudates made from hammer-milled pea flour, EI varied according to individual cultivars used to prepare the flours, but this was not correlated to the protein or starch content of the pea (Li, Kowalski, Li, & Ganjyal, 2017). Extrudates made from navy, black, and pinto bean flour had significantly lower resistant starch and lower total starch content than the raw bean flours, but extrusion did not influence protein content (Simons et al., 2015). Significantly higher hardness values of navy bean extrudates were found, which could be due to the high protein content in the navy bean extrudates that limited expansion potential.

To utilize pea flour in expanded snack and breakfast foods, pea flour extrudates were obtained by blending air-classified pea starch and field pea flour (Hood-Niefer & Tyler, 2010). The investigation revealed that extrusion quality declined with an increase in protein (6%, 12%, or 18%, d.b.) or moisture (15%, 18%, or 21%, w.b.) content as a result of reduced EI, with the bulk and particle densities increased, and the hardness of the extrudates increased. A minimum starch content of 60% to 70% has been recommended for preparation of expanded cereal products (Conway, 1971); however, only a blend of pea flour containing 85% starch had satisfactory expansion characteristics. Extrudates manufactured from a HSF and a high-protein fraction (HPF) made from navy and pinto bean were prepared (Gujska & Khan, 1991). The EI decreased with protein content, but starch (the primary agent for expansion) increased the EI. An SEM study showed that the protein had a profound effect on the microstructure, size of air cells, and smoothness of cell walls. A blend of HPF and HSF flours decreased the expansion of the extrudates, but somewhat surprisingly, the extrudates were characterized as "softer" (Gujska & Khan, 1991). Snacks produced from 56% hammer-milled cowpea flour (coarse [2 mm screen], medium [1 mm], and fine [0.5 mm]) had different bending test responses: a larger peak force was observed for snacks made from the fine flour (Kerr et al., 2001).

Pretreated (via roasting, fermentation, and germination) and whole seed pulse flours have produced acceptable extruded products, but only at lower protein contents in the flours. Many different pretreatments have produced various noncomparable extruded and baked products in terms of varying milling conditions. Nevertheless, some relationships arising from pulse properties can be advantageous. For instance, low-hydration properties of extrudates can be utilized; high protein produces good texture in pasta products; high fiber and high water absorption can be utilized in minced meat formulations (Simons et al., 2017; Sozer et al., 2017).

Other products

Many studies have analyzed various parameters for cowpea flour-based products: akara (fried cowpea product) and moin-moin (steamed cowpea paste). Moin-moin showed better texture profile measurements (firmer product) for flours of a smaller particle size (Jarrard, Hung, McWatters, & Phillips, 2007). Finer cowpea flour produced from decorticated cotyledons contributed to significantly higher cohesiveness, elasticity, and chewiness of akara as compared to akara produced from coarse particles, but it also increased the hardness values (Kethireddipalli, Hung, McWatters, & Phillips, 2002). The most suitable particle size for akara preparation is the intermediate particle range (200 to 400 μm) between flour and grits (Barimalaa & Okoroji, 2009). To mitigate the problem of poor particle size in ground products to be made into akara, it was recommended that cowpea seeds should be dried (at temperatures less than 60 °C) and milled so that 65% to 75% of the particles reside in the range of 45 to 150 μm (Kerr et al., 2000; Ngoddy, Enwere, & Onvorah, 1986).

Pin milling and hammer milling (1.73 and 2.54 mm screens) of cowpea have been found to produce akara with no significant difference in cohesiveness and chewiness; finely milled flour (1.73 mm screen) yielded the highest hardness values (A. Singh, Hung, Phillips, Chinnan, & McWatters, 2004). Moreover, instrumental color assessment showed that akara made from the product milled through the 1.73-mm screen was the darkest in color. Sensory evaluation showed that the product produced from pin milling and hammer milling were acceptable in terms of many quality attributes compared to the traditional wet milling method; akara produced from the coarser flour (2.54 mm screen) was the best in terms of overall acceptability as assessed by a set of panelists.

Yellow pea flour prepared by cyclone-milling with three screens (0.4, 0.5, or 1 mm) was used to produce batter flours with slightly different particle size distribution (87% of flour particles ranging between 150 and 75 μm) (Osei-Yaw & Powers, 1986). It was found that dehulling increased the specific gravity of yellow pea batters.

Research Gaps

This review has outlined a variety of factors responsible for the millability of pulses and the characteristics of the flours produced. Research is required to convincingly attribute certain parameters to a particular pulse type or a specific mode of milling. Therefore, there are multiple research gaps that potentially hinder better utilization of pulses because flour attributes should be better defined.

First, extensive milling studies on wheat have clearly established a large number of millability parameters. However, these have not been well defined for pulse milling. Establishment of the effects of grain legume seed size, seed weathering, moisture content, hull content, cell wall content and thickness, seed composition, and seed hardness with respect to milling behavior is a good starting point. Differences in grain legume characteristics due to G × E factors have been fairly well established for certain pulses, but further investigation is essential to help breeding programs develop pulses with low variability and high milling efficiency. Several researchers have investigated drying and storage parameters for their effect on nutritional, culinary, and other factors. However, there is a lack of studies relating these parameters to pulse millability. For instance, do prolonged storage and different drying conditions affect milling characteristics in any way? To accomplish better milling, optimization of the process is necessary. Pretreatment processes such as partial germination and micronization are established for altering the functional properties of pulses. However, a change in physical properties affects the primary outcomes of the milling process. Thus, there is a need to systematically link specific pretreatments conducted on specific pulse types to milling behavior. Moreover, pretreatments that have shown promising characteristics need to be further studied to improve milling efficiency.

Conventional cereal grain milling machines are used for pulse milling, frequently with modifications. Some researchers have optimized milling parameters for a certain pulse type. As pulses vary in shape, size, and hardness, it is difficult to employ a single machine or a given set of machine parameters for better milling efficiency. Moreover, information on grain legume properties, especially physical properties such as weight, dimensions, density, and angle of repose, would help advance pulse flour milling technologies (Tiwari & Singh, 2012). Therefore, fundamental grain properties should be determined to optimize the milling behavior of pulses and to improve milling machines for better mill efficiency.

Understanding the microstructure of the pulse grain is essential to establish processing techniques for pulse flours that will produce the most desirable end products (Tiwari & Singh, 2012). Some microstructural studies related to starch damage and protein separation do exist. They provide a sense of how milling works at a microstructural level, which is essential to the formulation of extensive relationships and dependencies. However, a general consensus from the research studies is that the microstructure of pulse-based ingredients and pulse–cereal blends needs thorough investigation to better understand particle size and component separation in pulse flour production.

Starch digestibility and chemical composition are important parameters that impact the pulse-fortified products produced from different processing methods (Fujiwara, Hall, & Jenkins, 2017). Research needs to be conducted on the starch–protein matrix and its effect on the properties of various pulse products, especially with respect to the processing method. Since pulse incorporation is increasing in GF product development (Melini, Melini, Luziatelli, & Ruzzi, 2017), the interactions between the pulse proteins and charged/neutral hydrocolloids that are used in GF formulations need to be studied (Foschia et al., 2017). The influence of interactions between protein, fiber, or bound polyphenols on the functional properties of composite pulse–wheat products also requires understanding.

Conclusions

Utilization of pulses in the western world is still limited due to various challenges such as limited end-use flour applications, poorly characterized functionality, and off flavor/aroma issues. Despite such hurdles, protein-enriched pulse flours have found their way into several products that blend with wheat, rice, and other cereals to improve nutritional profiles. Moreover, due to their GF nature, pulses on their own provide optional food formulations for people who are gluten intolerant or sensitive.

Several factors such as genotype and environment (G × E), storage, and premilling treatments lead to variability in properties for different grain legumes. This means there are confounding factors impeding definition of the millability of pulses for producing a suite of desired end products. Therefore, understanding and establishing pulse millability parameters are essential to overcome this problem.

Numerous studies on pulse flours have conducted milling in such a way that pronounced effects on particle size distribution from different mills have been found. However, the requirement of particle size specifications in the flour for various applications is a critical issue to be addressed. Investigations on the fineness or coarseness of pulse flours for specific end-use applications need to be established. The wide ranges in the starch, protein, and dietary fiber contents of pulses also allow for their component enrichment via sieving and dry fractionation or fine milling and air classification. Milling also brings a physicochemical change in terms of starch damage that complicates assessment of the effects of particle size and composition on the functional properties of pulse flours.

Recent reviews of available literature on pulses and their fractions being formulated into different kinds of products have enriched our understanding of their nutritional, functional, and physicochemical properties. The effect of several milling outcomes, such as particle size and protein content, color, and flavor, have been noted in the creation of extruded and baked products with changes in the proportion of pulse flour. However, the effect of various protein–starch matrix entanglements within pulse–cereal or other pulse-based products is not well understood and requires further research if pulses are to be effectively utilized as ingredients. Additionally, microstructure analysis of the raw seeds in comparison to the pretreated seeds to formulate general trends at the molecular and microstructural levels would be beneficial for defining millability characteristics, which would ultimately lead to well-defined flour applications.

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Authors Contributions

All authors planned the review. S.T. conducted the literature review in consultation with J.P. and M.G.S., and wrote the first draft of 70% of the review; M.G.S. and J.P. wrote the first draft of the other 30%. R.T. Tyler supervised editing of the various drafts, and A.M. designed mill flows and contributed new insights to the literature based on current pulse milling and wheat milling perspectives.

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