Seed coats of pulses as a food ingredient: characterization, processing, and applications

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Abstract

Background: In recognition of their multiple benefits on environment, food security, and human health, pulses are attracting worldwide attention. The seed coat is a major by-product of pulse processing, and its only markets are as low value ruminant feed and very limited use in high fibre foods. Recently, accumulating studies have suggested that this underutilised by-product has greater potential as a novel natural “nutritious dietary fibre” which can be used as a functional food ingredient.

Scope and approach: This review discusses biochemical and physicochemical functionalities of seed coats of six globally important pulses: chickpea, field pea, faba/broad bean, lentil and mung bean with a special emphasis on the emerging food pulse lupin. Food process modification and recent human food applications of the seed coats are summarized. Bio-availability of the seed coat compounds, and phomopsins contaminated lupin seed coats as a typical example of safety issue are discussed.

Key findings and conclusions: High levels of dietary fibre, minerals and potential health-promoting phytochemicals in the seed coats indicate their great potential to be used as a natural “nutritious dietary fibre”. However, further in-depth studies are required to improve their desirable nutritional, physiological and techno-functional properties whilst minimizing any undesirable ones.
Keywords

Pulses; seed coat; dietary fibre; minerals; by-product; food ingredient

1. Introduction

“Pulses” refers to those low-fat content leguminous seeds which are harvested for dry grain (FAO, 1994). So, oilseeds (e.g. soybean and peanut), leguminous green vegetables (e.g. green peas and green beans) and leguminous fodder plants (e.g. clover and alfalfa) are traditionally excluded. Pulses are historically important in both the human diet and cropping systems as crop rotations, due to their rich-protein and biological nitrogen fixation ability. Although most pulses are not traditionally typical Western-style foodstuffs, international events like “International Year of Pulses 2016” and “Global Pulses Day” suggest that they are being promoted to be important human food world widely (Foyer, et al., 2016).

As shown in Table 1, six of the 11 pulses which are covered in the FAO list, chickpea (Cicer arietinum), lupin (Lupinus), field pea (Pisum sativum), faba/broad bean (Vicia fabae), lentil (Lens culinaris) and mung bean (Vigna radiate), are the most important pulses globally, totally accounting for 79.89% of the world pulse production (81.8 million tonne) in 2016 (FAOSTAT, 2018). India is the largest pulse producer globally, followed by Canada, Myanmar and China. However, Australia is the largest lupin producer in the world, contributing an average of 58.22% of the world production in
2012-2016 (ABARES, 2018). Australian sweet lupin (ASL, *L. angustifolius*), which is also named “narrow-leaved lupin”, is the most important lupin specie, constituting 93% of Australian lupin production and 52% of the world production (Pulse Australia, 2016). However, chickpea has overtaken lupin as Australia’s largest pulse crop since 2011-12, with a production estimated at over 2 million tonne in 2016-17 (ABARES, 2018). As a leading pulse exporter, Australia exports over 90% of its chickpeas, faba beans, lentils and mung beans, and 60% of field peas were exported, being the largest exporter of *desi* chickpea and faba bean in the world. Notably, although Australia exported only 50% of its lupin, this accounted for 90% of world lupin export in 2013.

Pulse seed has three distinctive parts, namely the seed coat, embryonic axe and cotyledon, which generally accounts for 8-16%, 1-3% and 80-90% of the whole seed respectively (Dueñas, Hernandez, & Estrella, 2006). However, the proportions of seed coat show great genetic and environmental variability both between and within species (Table 2). For example, lupin uniquely contains a much higher percentage of seed coat than others, with up to 24% in Australian sweet lupin and around 18% in white lupin (Clements, et al., 2014). Removal of pulse seed coat (dehulling) is a primary process to produce dehulled splits, ground flours and other fractionated pulse ingredients like pulse protein and fibre. In practice, by-product generated from the dehulling process is a mixture of seed coats, embryonic axes and brokens of cotyledons (Oomah, Caspar, Malcolmson, & Bellido, 2011; Sherasia, Garg, & Bhandari, 2017). As a consequence,
dehulling loss which is the main waste stream of pulse processing represents as much
as 31% for sweet lupin in Australia (Sipsas, 2008), and up to 28% for lentil and chickpea in India (Tiwari & Singh, 2011). Currently the primary markets for pulse seed coats are low value animal feed and only very limited use in human foods such as that added to make high fibre breads and meat products (like sausage and nuggets). This by-product not only leads to a tough disposal problem for the millers, but also wastes a potential source of novel, nutritious and health-promoting food ingredient (Sherasia, et al., 2017).

Growing evidence suggests that pulse seed coats have considerable amount of dietary fibre which is associated with diverse types of minerals and phytochemicals (bioactive secondary metabolites in plants e.g., polyphenolic antioxidants). Therefore, besides the well-documented physiological benefits of dietary fibre, seed coats provide potential for various physiological benefits, such as those related to antioxidant and anti-inflammatory activities. Available studies on pulse seed coats mainly focus on proximate compositions and anatomical structures, with little attention paid to their phytochemical properties and physiological functionalities. The present review brings together the current research on the characterization, processing and applications of seed coats from six selected pulses, i.e., chickpea, lupin, field pea, faba/broad bean, lentil and mung bean. This information should encourage strategies which might enable the more extended use of pulses and their seed coats in human foods.
2. Seed coat morphology and physical properties

The pulse seed coat (often referred as hull or testa) is a protective outer layer of the pulse seed. Structures of pulse seed coats have been overviewed by Moïse, Han, Gudynaitė-Savitch, Johnson, and Miki (2005) and Smykal, Vernoud, Blair, Soukup, and Thompson (2014). Anatomical structures of seed coats of field pea (Van Dongen, 2003), faba/broad bean (Youssef & Bushuk, 1984), chickpea (Wood, Knights, & Choct, 2011), lentil (Hughes & Swanson, 1986), lupin (Clements, Dracup, Buirchell, & Smith, 2005) and mung bean (Joseph & Swanson, 1993) have been extensively examined and show great similarities. Largely, there are three specialized cross-sectional layers in typical pulse seed coats: palisade cells (macro sclereids) layer, thick-walled hourglass cells (osteosclereids) layer, and a few layers of parenchyma (Fig 1.) (Moïse, et al., 2005; Tiwari & Singh, 2011).

The seed coats significantly affect chemical exchange (e.g. water and gas), biochemistry, mechanical properties (e.g. permeability, hardness and porosity) and physiological activities (e.g. germination and metabolism) of the pulse seeds (Moïse, et al., 2005). In addition, their chemical and physical characteristics, including composition, shape, mass, smooth or rough surface, thickness, colour, density and thermal properties (e.g. thermal conductivity and thermal diffusivity) strongly affect the whole seed properties (such as density, dehulling efficiency, and cooking quality),
further determine post-harvest processing, end application and market price of the seeds (Souza & Marcos-Jilho, 2001). In this review, the most essential physical properties of the seed coats (i.e. colour, thickness and permeability) are discussed.

2.1. Colour

As a key quality indicator, colour of the pulse seeds is crucial to consumer acceptance. Seed coat colour varies significantly across different varieties (Table 2). In Australia for example, over 90% of field pea is *dun* coloured type, and principally light brown *desi* chickpea, beige or light brown faba bean, white with/without spots lupin, red lentil and green mung bean. It has been revealed that the pigmentations of seed coats are mainly attributed to chlorophyll and polyphenols (mainly flavonoids) (Hossain, Panozzo, Pittock, & Ford, 2011), which mainly are located in the external palisade layer (Wood, et al., 2011). The colours are associated with levels of those compounds, and thus their physiological properties like antioxidant capacity. For example, dark coloured pulses are reported to contain higher levels of polyphenols, mainly anthocyanins and condensed tannins, and correspondingly higher antioxidant activities than those of pale ones (Xu, Yuan, & Chang, 2007).

Colours of pulse seed coats are unstable during post-harvest processing and strongly affected by processing conditions. For example, the extremely high temperature (>40 °C) may accelerate undesirable colour darkening process in faba bean seed coat. This
is accompanied by a significant loss, ranging up to 86% of total polyphenols, which may be explained by the polymerization of polyphenols into insoluble, un-extractable high molecular weight polymers (Nasar-Abbas, et al., 2009). Similar browning was found in lentils (Nozzolillo & Debezada, 1984) and chickpea (Reyes-Moreno, Okamura-Esparza, Armienta-Rodelo, Gomez-Garza, & Milan-Carrillo, 2000) when stored at high temperature. Moreover, the unpigmented varieties are supposed to be more vulnerable to seed deterioration during storage (Souza & Marcos-Jilho, 2001). However, the exact principles which are responsible for the darkening of pulse seed coats are still unclear.

2.2. Thickness and permeability

In general, the palisade cell layer mainly decides the thickness of the seed coat. Domesticated pulse varieties have thinner, softer, more permeable seed coats than wild counterparts mainly due to decreases in thickness of the palisade layer. Moreover, the proportion and thickness of the seed coat are negatively correlated with seed size. The seed coat characteristics should be carefully considered during food processing (especially dehulling) and application. For example, kabuli chickpea has a larger seed size and thinner seed coat than the desi type (Table 2). As a result, cultivars of kabuli are normally used as whole seeds without dehulling for paste, salads, roasted or fried to make snacks (Wood, Knights, Campbell, & Choct, 2014). By contrast, cultivars of the desi type are often dehulled to dahl (split) which are directly cooked or milled to
flour. Another example to show the associations between processing properties and seed coat thickness is that lentils have thinner seed coats and thus shorter cooking times than do other pulse seeds. Additionally, thicker seed coats result in longer cooking-times in field peas (Wang, Daun, & Malcolmson, 2003) and faba beans than those which have thin seed coats (Youssef & Bushuk, 1984).

The permeability of pulse seed coats change as the seed matures and are related to their structure and chemistry (Ma, Cholewa, Mohamed, Peterson, & Gijzen, 2004). Although impermeability of pulse seed coats is important to seed vitality, it is undesirable during food processing. The impermeability will contribute to lower whole-seed cookability (“hard-to-cook” phenomenon) and customer acceptability. For example, during soaking, the thick and impermeable seed coat will slow water imbibition by the seed, restrict its expansion and thus decrease the wet dehulling efficiency. The hydrophobic waxy cuticle and condensed palisade cells layer of the seed coat are major contributors to seed impermeability (Ma, et al., 2004).

3. Pulse seed coat composition

The nutritional composition of whole pulse seeds have been reviewed in the FAO/INFOODS global food composition database for pulses (uPulses 1.0) (FAO, 2017). The composition of seed coats of the selected six pulses are summarized (Table 3). Generally, pulse seed coats have about 8-10% moisture, 3% ash, 1-3% lipids and
2-8% protein, with a major carbohydrate components (60-90%), mainly insoluble non-starch polysaccharides (NSPs) (Tiwari & Singh, 2011). Of the macronutrients, we focus on carbohydrates and minerals since they make up the majority and provide a basis for the usage of the seed coat as a food ingredient.

In general, pulse seed coats have a neutral to slightly nutty flavour, although their volatile profiles are largely unknown (Pfoertner & Fischer, 2001). Pulse seed coats are the major contributors to the phytochemical content of the whole seeds (Dueñas, et al., 2006; Luo, Cai, Wu, & Xu, 2016). Some of the phytochemicals are, historically, referred to as “anti-nutritional factors (ANFs)”, as with polyphenols, phytic acid and alkaloids. However, numerous epidemiological studies now indicate their potential benefits for human health (Rochfort & Panozzo, 2007). Investigation of the micronutrients (vitamins and minerals) and other bioactive compounds in the six pulse seed coats is embryonic.

3.1. Carbohydrates

As mentioned above, pulse seed coats have negligible amounts of starch and oligosaccharides. Instead, they are predominantly composed of structural polysaccharides (non-starch polysaccharides, NSPs), which are mainly cellulose, hemicellulose, pectin (Table 3). As such, over 50 percent of the monosaccharides in seed coat are glucose from the cellulose. The other principal sugars vary between
species. For example, the high concentrations of xylose (21.6%), uronic acids (10.0%) and arabinose (8.4%) in lupin seed coat indicate relatively high contents of arabinoxylan hemicellulose and pectin (Evans & Cheung, 1993). On the contrary, uronic acids (22.3%), xylose (10.8%) and arabinose (5.2%) are the main sugars in field pea seed coat cell walls (except glucose), indicating a high content of pectin (Guillon & Champ, 2002). It is worthwhile to note that there are also significant differences between NSPs in cotyledons and seed coats. For instance, the major constituent NSPs of lupin seed coat are cellulose (from 45 to 56 g/100g dry matter (DM)), arabinoxylan hemicelluloses (~13 g/100g DM) and pectins, whereas pectic substances and hemicellulose are the predominant parts in cotyledon (Brillouet & Riochet, 1983).

Non-starch polysaccharides are classified as the principal components of the plant dietary fibre (DF) (Lovegrove, et al., 2015). In principle, seed coat contributes a significant proportion of the DF level of pulse because of their high content of NSPs, ranging from 75 to 91 g/100g DM (Table 3). In addition, most of the DF in pulse seed coats are insoluble dietary fibre (IDF), only 3.5% of total dietary fibre (TDF) in lupin seed coat is soluble for example (Evans & Cheung, 1993). IDF levels of dehulled lentils, peas and chickpeas decreased by 64%, 53% and 35% respectively compared to raw seeds, but no significant reduction in SDF was found (Dalgetty & Baik, 2003). However, regarding the newly proposed DF definition and analytic method (i.e. AOAC 2011.25),
3.2. Minerals and trace elements

Pulses provide substantial amounts of minerals. Pulse seed coats are rich in several minerals, e.g. Ca, Mg, Mn, Cu, Zn, B, Al and Na etc. (Tiwari & Singh, 2011). Notably, 67.5% of total Ca, and 41.3% of total Al of the whole lupin seed were reported to concentrate in its seed coat (Hung, Handson, Amenta, Kyle, & Yu, 1988). Likewise, over 70% of Ca and 50% of iron in mung bean (Singh, Singh, & Sikka, 1968), lentil (Tiwari, et al., 2012) and chickpea (Jambunathan & Singh, 1981) are found in their seed coats. Besides the inter-species variations, minerals in seed coats vary widely inner-species. For instance, contents of most of the minerals, especially Ca, Zn, Cu, and Mn, in kabuli chickpea seed coat are higher than desi type (Jambunathan & Singh, 1981). Consequently, differences in the seed coats (like thickness and proportion) between pulses are used to explain the variations in mineral levels of the whole seeds.

3.3. Phytochemicals

The major phytochemicals in different pulses vary significantly. For instance, chickpea was found to be one of the major sources of dietary saponins (Oakenfull, 1981), but alkaloids are characteristically present in lupin. Although, carotenoids (a group of lipid-
soluble natural plant pigments) contents of field pea (Marles, Warkentin, & Bett, 2013) and chickpea (Ashokkumar, Tar’an, Diapari, Arganosa, & Warkentin, 2014) are suggested to be associated with seed coat colours, pulse seed coats are generally known as a poor source of carotenoids since they have low level of fat. In some cases, phytochemicals may cause toxic effects (e.g. favism caused by vicine and convicine in faba beans) (Klupšaitė & Juodeikienė, 2015). However, this review will discuss polyphenols and phytic acid in the six pulse seed coats, and alkaloids in lupins since they are more relevant to the potential positive physiological properties of the seed coats.

3.3.1. Polyphenols

Polyphenols are a wide range of secondary plant metabolites, which typically have one or more aromatic rings bearing several hydroxyl groups. The major polyphenols in whole pulse seeds are phenolic acids (e.g., benzoic/cinnamic acids and their derivatives), flavonoids (e.g., flavone and flavonol glycosides) and condensed tannins (Oomah, Patras, Rawson, Singh, & Compos-Vega, 2011). Recently, a few studies have investigated polyphenols in pulse seed coats, including chickpea (Sreerama, Neelam, Sashikala, & Pratape, 2010), faba bean (Boudjou, Oomah, Zaidi, & Hosseinian, 2013), field pea (Marles, et al., 2013), lentil (Dueñas, et al., 2006; Oomah, Caspar, et al., 2011), and mung bean (Luo, et al., 2016; Muhammed, Manohar, & Junna, 2010).
In general, these studies confirmed that polyphenols of whole pulses seeds are essentially concentrated in the seed coats, and hence they are the predominant in vitro antioxidant capacity contributors. For example, 80.3-84.2% of the total polyphenol and over 83.9% of total flavonoid content of whole mung bean seed were reported to be present in the seed coat (Luo, et al., 2016; Muhammed, et al., 2010). The proportions of total polyphenol and total flavonoid content in faba bean seed coat are up to 80.0% and 89.3% of the whole seed respectively (Boudjou, et al., 2013). Similarly, total polyphenol content of chickpea seed coat (75.94 mg GAE /g DM) was relatively higher than that of cotyledon (15.24 mg GAE /g DM) (Sreerama, et al., 2010). Condensed tannins in faba bean (Boudjou, et al., 2013), mung bean (Xu, et al., 2007), and lentil (Dueñas, Hernández, & Estrella, 2002) seed coats were report to represent over 75%, 50% and 54% respectively of the total tannins in the whole seeds. Notably, Xu, et al. (2007) found that polyphenols levels and in vitro antioxidant activities of dark coloured (like red, bronze, and black) lentil and chickpea seeds were significantly higher than those of light coloured (like white, yellow, and green) varieties. Total free phenolic acids and condensed tannins in coloured pea seed coat reached to 78.53 g/g DM and 1560 mg CE/g DM comparing to 17.17 g/g DM and not detected for those in white seed coat (Troszyńska & Ciska, 2002).

In the case of lupins, total polyphenol content in seed coats of *L. mutabilis, L. albus,* and *L. angustifolius* which grown in Brazilia were reported to be 1.15-4.49 mg catechin
equivalents (CE)/g DM which were much lower than cotyledons (7.38-12.42 mg CE/g DM) (Ranilla, Genovese, & Lajolo, 2009). The results accord with findings from Lampart-Szczapa, et al. (2003), who found that polyphenols in seed coats of *L. luteus*, *L. albus* and *L. angustifolius* grown in Poland (ranging from 0.16 to 0.42 mg caffeic acid equivalents/g DM), were 1.30-6.52 times lower than those in cotyledons (0.32 to 1.88 mg caffeic acid equivalents/g DM). Additionally, these authors revealed that free phenolic acids, primarily procatechuic acid and *p*-hydroxybenzoic acid, were mainly present in the seed coats. Likewise, they found that concentrations of tannins in the cotyledons were 4.33-31.00 times higher than that in the seed coat. On contrast, Petterson (1998) reported that most tannins (include proanthocyanidins) of lupin occurred in the seed coat, however, the initial data are unavailable.

These different and sometimes conflicting results of studies on polyphenols in pulse seed coat are difficult to interpret and compare since the lack of consensus on extraction methods and express ways (i.e., equivalents). Nonetheless, most of previous published studies have only extracted polyphenols with organic solvents in which case appreciable amounts of “bound” polyphenols in the seed coat matrix may remain un-extracted and thus the total polyphenol levels and antioxidant capacity may be underestimated (Saura-Calixto, 2012).
3.3.2. Phytic acid

Phytic acid (PA), its lower substituted homologues and its salts are referred as phytates which are commonly present in pulse seeds. Phytic acid have been implicated in the “hard-to-cook” phenomenon in pulse seeds. In addition, they are considered as the main anti-nutritional factor due to their capacity to chelate cations (in particular calcium, iron and zinc) to form insoluble complexes and therefore reduce their bio-availability (Sanchez-Chino, Jimenez-Martinez, Davila-Ortiz, Alvarez-Gonzalez, & Madrigal-Bujaidar, 2015). The content of phytic acid can be affected significantly by genetic and environmental factors, alone and in combination. However, phytic acid in mung bean (1.8-5.8 mg/g DM), pea (3.1-7.1 mg/g DM), lentil (2.5-12.2 mg/g DM), chickpea (2.8-13.6 mg/g DM), lupin (6.0-8.9 mg/g) and faba bean (5.9-15.0 mg/g DM) are generally lower than soybean (4.8-20.1 mg/g DM) (Campos-Vega, Loarca-Piña, & Oomah, 2010). Moreover, the majority of phytic acid is demonstrated to present in “the proteins bodies” in cotyledon (Campos-Vega, et al., 2010). Phytic acid of chickpea is presented in a low level (0.79 mg/g DM) in seed coat but high in cotyledon (9.82 mg/g DM) (Sreerama, et al., 2010). Beal and Mehta (1985) indicated that little (1 mg/g) or no phytic acid was found in pea seed coats.

3.3.3. Alkaloids

Alkaloids are mainly present in lupins. Quinolizidine alkaloids, mainly lupanine, 13-hydroxylupanine and angustifoline, are major contributors to the bitter taste of some
331 varieties of lupin seeds and are potentially toxic (Petterson, 1998). Bitter lupin varieties
332 have alkaloid contents ranging between 0.5-6%, in contrast the sweet varieties have
333 less than 0.02% (Resta, Boschin, D'Agostina, & Arnoldi, 2008). Moreover, alkaloids
334 can be removed by washing with water. A maximum legal limit on alkaloid
335 concentration in lupin flours and lupin products has been set at 0.02% by authorities of
336 France, UK, Australia and New Zealand (Resta, et al., 2008). Little is known on
337 distributions of alkaloids in lupin seeds, though Sipsas (2008) reported that no alkaloids
338 were found in Australian sweet lupin seed coat, but no detailed data was found.
339
340 4. Mycotoxins contamination
341 Pulses are vulnerable to be contaminated by fungus and the resulting mycotoxins (e.g.,
342 alfatoxins, ochratoxins and phomopsins) during pre- or post-harvest (CAST, 2003). A
343 further increase in human exposure of them by consuming products containing
344 contaminated pulses may occur. However, recent systematic surveys on mycotoxins in
345 pulses based human food are lacking. Here, phomopsins in contaminated lupin seeds,
346 a highly representative example of mycotoxins contamination of pulses, will be
347 discussed as a detailed case study.
348
349 Phomopsins are toxins produced by the fungus Diaporthe toxic (EFSA, 2012). The
350 fungus mainly infects lupin stems but also the seeds under high humidity storage
351 conditions (>13%). Lupin seed coat, being the outermost layer of the seed, is the most
vulnerable part of seed to be invaded by the fungus and thus may contain the highest level of phomopsins (EFSA, 2012). Phomopsins are suspected as the cause of lupinosis in grazing animals. A maximum legal limit (5 µg/kg) of phomopsins in lupin seeds and lupin foods has been established in Australian, New Zealand, UK and FAO (Schloss, Koch, Rohn, & Maul, 2015). As other mycotoxins, phomopsins are stable to food processing including soaking, cooking, and fermentation. However, seeds contaminated by phomopsins can be easily removed by seeds grading and screening since phomopsins is “almost entirely limited to dis-coloured seeds” (EFSA, 2012). In addition, resistant varieties have been developed. Extrusion which combines high pressure, high temperature and severe shear has showed the capacity to reduce other mycotoxins (e.g. alfatoxins and zearalenone) (Bullerman & Bianchini, 2007), but no studies on detoxifying phomopsins in lupin by extrusion cooking have been reported.

5. Bio-availability of nutrients in pulse seed coats

Bio-availability refers to the extent that nutrients can be released from food matrix into digestive fluid, and thereby available for intestinal transport, biotransformation, absorption and metabolism (Versantvoort, Van de Kamp, & Rompelberg, 2004). There is strong evidence that structure and composition of a food matrix will govern the bio-availability of many nutrients in the gastrointestinal tract (Wahlqvist, 2016).
A few published clinical studies have suggested that pea seed coat consumption may benefit cardiovascular and gastrointestinal biomarkers in humans, that may be due to multiple mechanisms caused by the high dietary fibre in the seed coat (Dahl, Whiting, Healey, Zello, & Hildebrandt, 2003; Flogan & Dahl, 2010; Mollard, Luhovyy, Smith, & Anderson, 2014). However, dietary fibre has been shown to significantly reduce bioavailability of several nutrients. For example, lupin seed coat in the diet decreased protein digestibility in rats (Bailey, Mills, & Hove, 1974). In contrast, removal of lentil seed coat significantly improved lentil iron bio-availability (DellaValle, Vandenberg, & Glaahn, 2013). The compact inert insoluble fibre matrix of the seed coat may be a physical barrier to block the release of nutrients, give increased viscosity of digesta and therefore impair absorption. Besides, dietary fibre, polyphenols and alkaloids can also inhibit enzymes, and chemically bind some nutrients thus lowering their bio-availability (Khattab & Arntfield, 2009).

The fermentability of cellulose and hemicellulose in the colon was surprisingly reported to be high, 70% and 72% respectively, mainly degraded by some specialized series of gut bacteria (Flint, Scott, Duncan, Louis, & Forano, 2012). It suggests that “trapped” compounds (e.g., minerals and polyphenols) in pulse seed coats could be released in colon. In this context, dietary fibre could also modulate pH of human gastrointestinal tract, especially lower pH level in colon, to enhance release and absorption of minerals (Baye, Guyot, & Mouquet-Rivier, 2017). A large proportion of polyphenols are
reported to be not bioavailable in the upper part of the human gastrointestinal tract. Instead, they will reach colon and be metabolized at a large extent by gut microbiota (Saura-Calixto, 2012). However, more studies are needed to investigate digestibility of pulse seed coats in human, as well as their physiological effects on human health (including effects on colon and gut bacteria).

6. Effect of processing on pulse seed coats

Generally, pulses are dried in the field to achieve the target moisture of 9-20% for threshing (i.e. removal of pods), then cleaned, graded and further dried to approximate 13% for storage. Storage conditions (e.g. seed moisture, relative humidity, duration and temperature) significantly affect the seed coat characteristics. For example, the seed coat colour of faba bean has been observed to darken from beige to dark brown depending upon the storage conditions (Nasar-Abbas, et al., 2009). Although pulses can be consumed either whole or dehulled splits, they require processing before consumption to (1) reduce or eliminate anti-nutritional factors, (2) improve consumer acceptability (e.g. texture, flavor), and (3) enhance nutritional properties like nutrient bio-availability. There are several conventional whole seeds processing methods, including soaking, dehulling, milling, cooking, puffing, germination (or sprouting) and fermentation (Patterson, Curran, & Der, 2017). But only few studies are found to treat isolated pulse seed coat using milling, boiling, and more recently extrusion cooking.
All have shown to affect composition, and physicochemical and nutritional properties of the seed coats.

6.1. Conventional processing

Seed coat bulk density (weight of seed coat per unit volume) is low such that further processing (like grinding) is required to increase their density to reduce its storage and transport fees after dehulling (Table 4). Grinding was reported to increase solubility of pea seed coat, from 4.1% to 8.6%, accompanying by reduction in water binding capacity (WBC) and swelling capacity by 35.2% and 21.7% respectively (Ralet, Valle, & Thibaut, 1993a). Similarly, water solubility of mung bean seed coat was 0.97% with particle size of <50 mesh (<300 μm), whereas a much lower water solubility (0.79%) was found with particle size of >35 mesh (>500 μm) (Huang, 2009). The authors also found that mung bean seed coat with smaller particle size had a significantly higher swelling capacity, WBC, and oil binding capacity but lower bulk density compared with those with bigger particle size.

Soaking followed by cooking of whole pulse seeds is the traditional domestic operation to produce edible pulse products. During soaking, pulses imbibe water to expand the seed coats, and activate endogenous enzymes (cell wall polysaccharidases which can disrupt the cell wall, and phytase which can reduce phytic acid content, for example) (Wang, et al., 2003). Moreover, water soluble compounds like minerals, soluble tannins,
phytic acid, alkaloids and polyphenols may leach into soaking, cooking and canning water (Tajoddin, Manohar, & Lalitha, 2013). As the outer layer, the seed coat plays a crucial role in controlling these exchanges during soaking and cooking. Additionally, Güzel (2012) found that atmospheric pressure cooking (APC) and high-pressure cooking (HPC) caused darkening of chickpea and faba bean seed coats, with greater effect for HPC. The colour changes may be the results of pigment degradation. Hashemi, et al. (2015) found that starch in pea seed coat increased from 0.16% to 0.59% in dry basis after boiling for 30 min, what may be due to the increase of starch bioavailability and losses of soluble compounds during boiling.

Mung bean (Tajoddin, et al., 2013), lentil and field pea (López-Amorós, Hernández, & Estrella, 2006), chickpea (Ghavidel & Prakash, 2007), and lupins (Dueñas, Hernandez, Estrella, & Fernandez, 2009) have been used to germinate sprouts. Most of these studies confirmed that germination will increase polyphenols (prominently flavonoids) and vitamins, whereas decrease anti-nutritional factors (e.g. α-galactosides, trypsin inhibitors and phytic acid). As a result, germination can improve antioxidant capacity and bio-availability of the nutrients. Seed coat impermeability is the main regulator for pulse germination. Moreover, the structure and composition of the seed coat will change significantly just before and during germination, possibly by enzymes (Finch-Savage & Leubner-Metzger, 2006). Although, so far, no study on the effect of
germination on pulse separated seed coat has been found, it can be hypothesised that changes in composition and physico-chemical properties of pulse seed coat may occur.

6.2. Extrusion

Extrusion cooking is a high temperature short time unit operation in which food will be melted in a sealed cylinder by high pressure, high temperature and high mechanical shear, then passed through a die (Alam, Kaur, Khaira, & Gupta, 2016). Depending on extrusion conditions (such as material particle size, feed rate, moisture, screw speed and configuration, barrel temperature and die geometry), the process results in disruption of cell wall structures, chemical reactions (such as polysaccharides depolymerization, Maillard reaction and starch gelatinization), and physical changes (e.g. solubility, morphological and rheological properties) (Singh, Gamlath, & Wakeling, 2007; Wolf, 2010). Moreover, extrusion has been used to incorporate seed coats of field pea (Schmidt, 1987), lupin (Tucek, 2009) into breakfast, pasta and snacks to increase their dietary fibre levels. But they are beyond the scope of this review.

Extrusion cooking, mainly twin-screw extrusion, is the most used technology to modify the functional properties of high fibre materials (Rashid, Rakha, Anjum, Ahmed, & Sohail, 2015; Wolf, 2010; Yan, Ye, & Chen, 2015). Water solubility of pea seed coat was reported to increase by 3.6-15.3% after extruded using twin screw extruder, accompanied by a dramatic increase (up to 220%) in soluble dietary fibre (Ralet, Valle,
Similarly, single screw extruder increased soluble dietary fibre in pea seed coat from 5.3% to 6.7% (Arrigoni, Caprez, Amadò, & Neukom, 1986). Correspondingly, technical properties of pea seed coat, like water binding capacity and swelling capacity, were increased by extrusion cooking. On the contrary, extrusion has shown no or slightly increased effects on the technical properties of yellow pea seed coats (Arrigoni, et al., 1986). Except the conflicting results mentioned above, data from extruded wheat bran (Rashid, et al., 2015; Yan, et al., 2015), sugar beet pulp (Rouilly, Jorda, & Rigal, 2006), onion waste (Ng, Lecain, Parker, Smith, & Waldron, 1999) support the increase in the solubility of dietary fiber, as well as the improvements on their physicochemical characteristics.

Extrusion cooking has been revealed to reduce the levels of heat sensitive extractable polyphenols, which can be extracted by aqueous/organic solvents (Singh, et al., 2007). However, it can release non-extractable polyphenols, which remain in the resulting residues of the aqueous/organic extraction, from food matrix. Depolymerization of high molecular weight polyphenols (such as condensed tannins) was also reported (Awika, Dykes, Gu, Rooney, & Prior, 2003). Additionally, extrusion cooking can increase bio-availability of minerals, mainly by reducing the chelating properties of dietary fibre and the contents of other chelating compounds such as phytic acid and condensed tannins (Singh, et al., 2007). Taken together, extrusion cooking could be an applicable technology to improve the properties of pulse seed coats. However, more
comprehensive studies are required to investigate its effects on compositional and physicochemical properties of the pulse seed coats.

7. Application of pulse seed coats in human food

Pulses have been historically important sources of energy, protein and dietary fibre in human diet. Currently, pulse seed coats have only limited use in human food such as in high fibre breads and meat products. However, the high content of dietary fibre in pulse seed coats, along with considerable amounts of minerals, phytochemicals (e.g. polyphenols) suggests they could be more widely utilized as novel functional dietary fibre ingredients (Macagnan, da Silva, & Hecktheuer, 2016). There are several commercial dietary fibre ingredients manufactured from pea seed coat and lupin seed coat, both of them have been classified as GRAS (Generally Recognized as Safe). However, lupin has been listed as a food allergen what requires mandatory labelling in Europe since 2007, and most recently in Australia and New Zealand (March 2017) (FSANZ, 2017). Moreover, there are several specific regulations on contaminants and natural toxins levels of the six pulses and their derived food products, phomopsins and lupin alkaloids in lupin seed coat for example.

Like other dietary fibre ingredients, pulse seed coats have been incorporated into baked goods, in which they have shown to change physical, nutritional, and sensory properties of the products. Dalgetty and Baik (2006) found that incorporations of pea, lentil, and
chickpea seed coats significantly increased dough mixing time, water absorption, and 
loaf weight but decreased loaf volume. The observations are in accordance with the 
results of Sosulski and Wu (1988) who added up to 7.7% of pea seed coat into dough. 
The authors of these studies concluded that breads with 5% pulse seed coat addition 
was comparable to whole wheat breads in sensory quality but had desirable higher 
dietary fibre content.

In terms of adding pulse seed coats into meat products, Verma, Banerjee, and Sharma 
(2012, 2015) used pea hull flour (PHF) and chickpea hull flour (CHF) as dietary fibre 
sources to improve qualities of chicken nuggets. The studies found that incorporation 
of the two hull flours significantly increased product yield and dietary fibre content. 
However, both reduced emulsion stability of the product, and lowered its hardness, 
gumminess and chewiness dramatically. Product colour was also affected by initial 
colours of the two hull flours and formulation differences. Sensory evaluation 
suggested that an 8% PHF addition in low salt (40% reduction) chicken nuggets were 
acceptable to consumers.

8. Conclusions

To date, pulse seed coats are little utilised in human food. However, there is potential 
for the seed coat to be used as a natural “nutritious dietary fibre” which could (1) fill 
the “fibre intake gap”, (2) provide considerable levels of minerals and antioxidants, and
achieve greater safe and sustainable utilization of pulses by exploiting value-added applications of their by-products (Saura-Calixto, 2012; Sharma, et al., 2016). However, in-depth studies on biochemical, and nutritional properties of pulse seed coats are still lacking. In addition, physicochemical properties (e.g. solubility, swelling capacity, water and oil binding capacities, and viscosity) of pulse seed coats will significantly associate with physiological functionalities (Wahlqvist, 2016), but the impacts of processing on physicochemical properties are also still unclear. Moreover, to minimize the negative impacts of dietary fibre and other anti-nutritional factors, while improving their desirable physiological properties, further work is needed to optimize the processing. Finally, parallel to the study of pulse seed coats incorporation into food products, more nutritional and safety studies on the products are needed. These will add to what are likely to be favourable cost and sustainability profiles.

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scientific search for an ideal definition and methodology of analysis, and its
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Tables

Table 1. Names and major types of the selected six pulses

Table 2. Morphological and physical properties of the selected six pulse seed coats

Table 3. Main carbohydrates and dietary fibre of three selected pulses seed coats

Table 4. Selected physico-chemical properties of pulse seed coats
Table 1. Names and major types of the selected six pulses

<table>
<thead>
<tr>
<th>Botanical name</th>
<th>FAO commodity class</th>
<th>Common/Alternative names</th>
<th>2016 World production (million tonne)</th>
<th>Main market types in Australia (• most common)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Pisum sativum</em></td>
<td>Peas, dry</td>
<td>Field pea; Protein pea; Austrian winter peas (black peas); Canadian field peas (spring peas)</td>
<td>14.36</td>
<td>• Dun (including Kaspa type)</td>
</tr>
<tr>
<td><em>Vicia fabae</em></td>
<td>Broad beans, dry</td>
<td>Faba bean /Tickbean</td>
<td>4.46</td>
<td>• <em>V. faba</em> var. minor (faba bean)</td>
</tr>
<tr>
<td><em>Cicer arietinum</em></td>
<td>Chickpeas</td>
<td>Garbanzo beans (US); Bengal gram (India)</td>
<td>12.09</td>
<td>• Desi</td>
</tr>
<tr>
<td><em>Lens culinaris</em></td>
<td>Lentils</td>
<td>Masurdahl, adas</td>
<td>6.32</td>
<td>• Red</td>
</tr>
<tr>
<td><em>Lupinus spp.</em></td>
<td>Lupins</td>
<td>Blue lupin; narrow-leaved lupin European white lupin</td>
<td>1.28</td>
<td>• <em>L. angustifolius</em></td>
</tr>
<tr>
<td><em>Vigna radiate</em></td>
<td>Beans, dry</td>
<td>Mung bean (Australia) Green/golden gram (India)</td>
<td>~3.0</td>
<td>• <em>Vigna radiata</em> (green)</td>
</tr>
</tbody>
</table>

Ref: FAO (1994); FAOSTAT (2018); Sherasia, et al. (2017); Tiwari, et al. (2011); Pulse Australia (2016).
Table 2. Morphological and physical properties of the selected six pulse seed coats

<table>
<thead>
<tr>
<th>Pulses</th>
<th>Colour</th>
<th>Seed weight (g/100 seeds)</th>
<th>Hull percentage (%)*</th>
<th>Hull thickness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lupin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. angustifoliu</td>
<td>speckled</td>
<td>3.1-23.8</td>
<td>19.4-38.8</td>
<td>257.0-335.0</td>
</tr>
<tr>
<td>L. albus</td>
<td>white</td>
<td>12.0-86.9</td>
<td>12.2-27.5</td>
<td>nd</td>
</tr>
<tr>
<td>Field pea</td>
<td>green/yellow</td>
<td>18.7-25.6</td>
<td>7.2-14.0</td>
<td>55.9-72.0</td>
</tr>
<tr>
<td>Vicia fabae</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faba bean</td>
<td>beige</td>
<td>40.0-95.0</td>
<td>11.0-15.4</td>
<td>141.0-248.0</td>
</tr>
<tr>
<td>Broad bean</td>
<td>beige</td>
<td>110.0-145.0</td>
<td>nd</td>
<td>141.0-248.0</td>
</tr>
<tr>
<td>Chickpea</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>desi</td>
<td>dark/brown</td>
<td>12.0-27.0</td>
<td>10.1-22.0</td>
<td>343.0-423.0</td>
</tr>
<tr>
<td>kabuli</td>
<td>beige/yellow</td>
<td>20.0-65.0</td>
<td>4.5-9.5</td>
<td>251.0</td>
</tr>
<tr>
<td>Lentil</td>
<td>red/green</td>
<td>4.5-7.5</td>
<td>7.0-11.0</td>
<td>25.0-65.0</td>
</tr>
<tr>
<td>Mung bean</td>
<td>green</td>
<td>2.5-4.7</td>
<td>8.6-23.5</td>
<td>30.0-330.0</td>
</tr>
</tbody>
</table>

* Data are dry basis; nd: no data were found;

Table 3. Main carbohydrates and dietary fibre of three selected pulses seed coats

<table>
<thead>
<tr>
<th></th>
<th>Pulses</th>
<th>L. angustifolius</th>
<th>Field pea</th>
<th>Chickpea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch (g/100g)</td>
<td></td>
<td>0.4-0.9</td>
<td>0.16-1.8</td>
<td>0.2-0.5</td>
</tr>
<tr>
<td>Oligosaccharides (g/100g)</td>
<td>0.4</td>
<td>nd</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>NSP (g/100g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>79.8-89.1</td>
<td>68.0</td>
<td>45.9-72.4*</td>
<td></td>
</tr>
<tr>
<td>Soluble</td>
<td>5.0</td>
<td>3.0-4.0</td>
<td>1.9-2.5</td>
<td></td>
</tr>
<tr>
<td>Insoluble</td>
<td>80.6-84.1</td>
<td>64.0-65.0</td>
<td>49.1-52.9*</td>
<td></td>
</tr>
<tr>
<td>Cellulose (g/100g)</td>
<td>44.5-51.7</td>
<td>62.3</td>
<td>18.2-29.0</td>
<td></td>
</tr>
<tr>
<td>Hemicellulose (g/100g)</td>
<td>12.7-14.4</td>
<td>8.2</td>
<td>30.4</td>
<td></td>
</tr>
<tr>
<td>Pectins (g/100g)</td>
<td>15.6-27.7</td>
<td>nd</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Lignin (g/100g)</td>
<td>0.3-2.1</td>
<td>3.5</td>
<td>1.4-4.1</td>
<td></td>
</tr>
<tr>
<td>Dietary fibre (g/100g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>88-90.5</td>
<td>81.0-91.5</td>
<td>74.9-84.2</td>
<td></td>
</tr>
<tr>
<td>Soluble</td>
<td>3.1-3.8</td>
<td>4.1-11.0</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>Insoluble</td>
<td>84.2-87.4</td>
<td>70.0-87.4</td>
<td>nd</td>
<td></td>
</tr>
</tbody>
</table>

Data are in dry basis.

NSP: Non-starch polysaccharides; nd: no data were found.

*: A remaining 15% was not hydrolysed by the NSP analyses which was supposed to be “highly bound ligno-cellulosic compounds” (Wood, et al. 2014).

Table 4. Selected physico-chemical properties of pulse seed coats

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>L. angustifoliu</th>
<th>Field pea</th>
<th>Chickpea</th>
<th>Lentil</th>
<th>Mung bean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Density (g/mL)</td>
<td>nd</td>
<td>0.6</td>
<td>0.4</td>
<td>0.7</td>
<td>nd</td>
</tr>
<tr>
<td>Bulk Density (g/mL)</td>
<td>nd</td>
<td>0.8</td>
<td>0.7</td>
<td>0.8</td>
<td>0.45-0.64</td>
</tr>
<tr>
<td>Swelling capacity (mL/g)</td>
<td>nd</td>
<td>1.9-6.0</td>
<td>3.6</td>
<td>2.4</td>
<td>5.51-9.20</td>
</tr>
<tr>
<td>Water binding (mL/g)</td>
<td>7.0-8.0</td>
<td>4.0-7.1</td>
<td>6.2</td>
<td>3.6</td>
<td>3.13-4.44</td>
</tr>
<tr>
<td>Oil binding (mL/g)</td>
<td>1.6-1.7</td>
<td>1.5-2.0</td>
<td>1.8</td>
<td>1.6</td>
<td>1.49-1.83</td>
</tr>
</tbody>
</table>

nd: no data were found.

Ref.: Guillon & Champ (2002); Dalgetty, et al. (2003); Pfoertner (2001); Turnbull, Baxter, and Johnson (2005); Ralet, et al. (1993b); Huang, et al. (2009).