Utilizing side streams of pulse protein processing: A review

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Abstract
Plant-based protein ingredients are gaining popularity among consumers for various reasons such as the increasing demand for high-protein diets, sustainability of the sources, and negative perceptions associated with animal proteins. Main source for plant proteins is pulses such as peas and beans. Pulse seeds contain up to 25% (w/w) protein, whereas nonprotein components are present in much higher proportions. Starch, fiber, and soluble material are generated as side streams of pulse protein manufacturing processes. These side streams, unless properly utilized, create both economic and environmental challenges. Therefore, the utilization of process side streams is of paramount importance for the overall sustainability of the plant protein manufacturing processes. This review summarizes the key research advances and potential opportunities in valorization of side streams from pulse protein manufacturing processes.

KEYWORDS
coproduct, legume, plant protein, pulse protein, side stream, sustainability

1 | INTRODUCTION

The continued growth of human population towards an estimated 9.5 billion, accompanied by an estimated 60% increase in food demand by 2050, has highlighted the necessity of sustainable sources for food (Aiking & de Boer, 2018; Henchion et al., 2017). It is well documented and known that protein from animal sources is less sustainable than protein from plant sources (Aiking & de Boer, 2018). Historically, meat- and plant-based protein foods have been treated as two contrasting categories especially in terms of their physical appearance and sensory characteristics. Recent advances in plant protein-based, meat-like product development successes have narrowed this gap creating a wealth of opportunities for the food industry.

Prior to the recent consumer interest in plant-based meat alternatives, legitimate concerns have been raised on the sustainability of conventional sources providing adequate protein in the diet for the growing global population (Hefferman, 2017). For example, one study revealed that to produce 1 kg of beef protein required approximately 18 times more land, 12 times more fertilizer, 10 times more pesticides, 10 times more water, and 9 times more fuel compared with producing 1 kg of protein from kidney beans (Sabaté et al., 2015). Region-specific agro-ecological, climatic, and cultural issues also contribute to the difficulties in providing adequate protein in the diet from animal sources in certain regions of the world, particularly in Asia and Africa.

The lack of palatability and low protein nutritional value of non-legume plant proteins, such as cereal proteins, has made pulse a preferred source for plant protein. For example, maize protein, although abundantly available, is not considered a preferred source of plant protein due to color, flavor, and functionality issues along with lower protein nutritional value compared to pulse proteins (Boye et al., 2012). Allergenicity of commonly used plant proteins, soy and wheat, is yet another reason for pulse protein to be a preferred source (Marchisotto et al., 2017).

The ability of legume crops in fixing atmospheric nitrogen has provided an advantage in agricultural operations in arid and developing regions in the world while playing the crucial role of providing protein in the diet. Legumes, such as soy, peas, and beans, are used by...
farmers as rotational crops in the fields, in order to improve nitrogen in soil, where cereals are grown. Studies have suggested additional benefits, such as improved soil microbial activity, in crop rotation with legumes (Venter et al., 2016).

The term “grain legume” is commonly used to identify edible seeds of plants from family Fabaceae, also known as Leguminosae. In the eastern regions of the world, the term “pulses” is also used to identify legumes (Wijeratne & Nelson, 1987). Legumes that are used to obtain oils, such as soybean and peanut, are referred to as oil seeds. Oil seed processing to obtain “vegetable oils” produce side streams (referred to as either cake or meal), which contain protein and fiber, primarily. Historically, these oil extraction process side streams have been of feed grade and not intended for food use (Wijeratne & Nelson, 1987). The introduction and development of extrusion processing technology has expanded the food uses, such as textured vegetable proteins (TVP®), of oil-seed process side streams.

Traditionally, legume seed-based products have been consumed without much further processing, yet in various forms, in different cultures. The use of minimally processed legume seeds, such as canned beans, cleaned peas, and lentils, for traditional dishes is very popular among some ethnicities even today. Legumes contribute to the balance of protein quality by providing the essential amino acid lysine to cereal-based diets in Asian countries. Cereal proteins contain sulfur-containing amino acids, along with others, but lack appreciable amounts of lysine. Thus, cereal-legume combination provides much needed good quality protein in the diet, particularly in the developing regions of the world (Wijeratne & Nelson, 1987).

Until recently, the utilization of plant-based protein ingredients in processed foods has been challenging due to the lack of appropriate quality ingredients at commercial scale. Milling of legume seeds and separation of milled “flour” to extract high-protein fractions has enabled the utilization of pulse proteins in commercial, processed food products. The consumer demand has increased for pulse protein containing products with the successful introduction of plant protein-based, meat-mimicking products to the market (Fellet, 2015; Geistlinger, 2015). Manufacturing operations of pulse proteins products, however, generate large amounts of nonprotein side streams. This review highlights ways to valorize those side streams (also referred to as byproducts or coproducts) to ensure both economic viability and environmental sustainability of plant protein manufacturing operations.

2 | IMPORTANCE OF VALORIZING SIDE STREAMS

Increasing demand for legume proteins has created great interest in valorization of side streams in order to make the overall process profitable and sustainable. As with any processing operation of an agricultural product, legume protein processing generates large amounts of process side streams. Given that the protein composition is approximately 25% of the seeds, theoretically, around 60%–75% of the raw material ends up in the side streams. In making protein ingredients, the process side streams contain primarily starch and fiber. Wet processes result in considerable amounts of soluble matter that find their way into steep and wash water. The exact proportions of these side streams depend on the both the process and the final protein product composition.

Side stream-derived products make relatively cheaper raw materials compared with conventional raw materials. However, lack of appropriate and commercially affordable processing technologies could make the valuable side streams either unutilized or under-utilized. The costs involved in separation, extraction, and purification must be considered in using side streams for ingredient manufacturing. The cost of manufacturing side stream-derived ingredients could be mitigated, at least in part, by properly integrating the side stream processes to the main product process rather than implementing the side stream process as an afterthought. Incorporating side stream valorization processes to the main operation, after the protein extraction process line is established, requires major capital investments to reconfigure the established manufacturing process.

Valorization of pulse protein process side streams provides a range of benefits to manufacturing operations. Creating an additional source of revenue from side streams, improving business viability by diversification of the processing operation, and reducing process waste while meeting government and local regulations on waste disposal are considered, as primary advantages of valorizing process side streams are among the main advantages (Tassoni et al., 2020).

2.1 | Sustainability of pulse protein production

Most conventional food and ingredient manufacturing processes, including plant proteins, focus on making a single final product while treating process side streams as lower value material or waste. This approach has led to release of large amounts of unutilized or under-utilized process by-products resulting in either unsustainable or less sustainable manufacturing processes. Waste streams generated by food manufacturing processes could create social and environmental issues while affecting the economic viability of the process. As with any other manufacturing operation, the three important aspects of sustainability—social, economic, and environmental—would need to be considered in establishing high-protein ingredients manufacturing processes. Ensuring sustainability requires all process inputs, that is, raw material, to be converted into useful products (van der Padt, 2014).

The demand for sustainable sources of food, growing concerns on animal welfare, and increasing popularity of vegetarian and vegan diets have become social trends while contributing to continuously increasing consumer preference for plant-based proteins (Estell et al., 2021; Heffernan, 2017; Pimentel & Pimentel, 2003). Plant-based protein production is known to be more sustainable compared with animal protein production in terms of both the energy requirements and environmental impact (De Boer & Alkinger, 2011; Pimentel & Pimentel, 2003). Plant proteins have lower carbon footprints and generate lower emissions compared with animal proteins (Loveday, 2019). In plant protein manufacturing processes, starch,
fiber, and soluble matter side streams are becoming serious issues for commercial operations. The environmental impact of the production process could be improved by fully utilizing the process raw materials to avoid disposal of side streams as waste. In the recent past, much research has been carried out to investigate novel ways to utilize and valorize pulse protein process side streams but with limited applicability for large scale commercial operations (Moreno-González & Ottens, 2021; Patras et al., 2011; Tassoni et al., 2020). Practical and sustainable avenues to utilize and valorize side streams from pulse protein manufacturing processes are, therefore, of paramount importance.

2.2 | General strategies for side stream utilization

When using side streams for processing value-added products, several important aspects must be taken into consideration; quality of raw material used for the process, collection of side stream as a valuable raw material for subsequent processes, and application of proper treatment or storage conditions prior to further use. The overall quality of the original raw material used in the process determines the quality and composition of the side streams. For example, initial physical cleaning or washing of the raw material (i.e., seeds) could reduce the presence of unwanted physical matter and microbes in the side streams. The first and foremost requirement for valorizing side streams is to collect them as useful and valuable raw material while preserving the desired quality traits to minimize contamination, microbial spoilage, and undesirable chemical and enzymatic reactions. In most current commercial operations, the side streams are not collected in a manner that ensures safety and quality required for them to be used in either food or other high-value applications. Identifying and utilizing appropriate processing technologies would permit preservation of desired quality and functionality of the side streams (Luzardo-Ocampo et al., 2020).

The side stream valorization process can be grouped into three categories: separation, structuring, and transformation. Separating the side stream into fractions containing the desired compounds is an important first step of the process. This could be achieved by various physical processes such as clarification, centrifugation, filtration, and chromatography (van der Padt, 2014). Structuring involves alterations to the physical structure of separated material and structuring is required to enhance the desired properties of the ingredient that is produced using separated side stream as raw material. Macroscale, microscale, submicroscale, and nanoscale physical structuring processes such as homogenization, foaming, granulation, agglomeration, crystallization, and various size reduction processes are used as structuring processes. Reactions that are carried out to convert raw material fractions into either ingredients or products are categorized as transformation. Transformation includes processes such as extrusion, cooking, drying, roasting, fermentation, hydrolysis, and chemical or enzymatic reactions (van der Padt, 2014). For example, enzymatic reactions could be used to transform the raw material into food ingredients such as syrups from side stream starch.

3 | MAJOR SIDE STREAMS OF LEGUME PROTEIN PROCESSING

Legume seeds contain starch, protein, and fiber as main compositional components and relatively smaller amounts of fat and minerals. General compositions of various legume seeds have been reported in the literature (Table 1). The variations among the reported values for a

### Table 1: Compositions (% w/w) of major components of various legume seeds

| Legume                  | Protein | Carbohydrate/starch | Fiber (crude) | Fat  | Ash   | Reference                                      |
|-------------------------|---------|---------------------|---------------|------|-------|------------------------------------------------|
| Black bean              | 22.9–23.2 | 36.9–61.6             | 6.4–23.7      | 1.6–3.4 | 4.6–5.0 | Koehler et al. (1987) and Siddiq et al. (2010) |
| Chickpea                | 24.0–33.0 | 41.9                 | 13.8          | 5.5  | 3.5   | Adamidou et al. (2011)                           |
| Cowpea/black-eyed pea   | 23.6–33.0 | 37.0–52.0             | 2.0–5.0       | 1.0–2.1 | 2.0–5.0 | Longe (1980), Moongngarm (2013), and Tyler et al. (1981) |
| Faba bean               | 26.4–39.7 | 36.9–61.6             | 6.4–23.7      | 1.5–2.1 | 2.9–4.3 | Adamidou et al. (2011), Alghamdi (2009), Bhatti (1974), and Tyler et al. (1981) |
| Great Northern bean     | 20.8–23.6 | 45.5–47.2             |                | 1.3–1.7 | 3.8–4.4 | Koehler et al. (1987) and Tyler et al. (1981)       |
| Lentil                  | 19.5–26.3 | 53.6–56.2             | 7.0–8.1       | 1.9–2.2 | 4.2–5.7 | Tyler et al. (1981) and Zia-Ul-Haq et al. (2011) |
| Lima bean               | 14.5–24.0 | 47.1–50.5             | 32.6–33.6     | 0.6–0.7 | 2.4–3.9 | Seidu et al. (2015) and Tyler et al. (1981)       |
| Mung bean               | 25.8–27.5 | 52.2–52.8             | 2.2           | 1.6   | 2.9   | Moongngarm (2013) and Tyler et al. (1981)         |
| Navy bean               | 20.4–26.5 | 44.9–47.0             | 1.7–2.0       | 4.0–4.9 | 9.0–9.7 | Koehler et al. (1987) and Tyler et al. (1981)     |
| Pinto bean              | 17.5–21.6 | 60.1                 | 1.3–3.7       | 1.4–3.5 | 3.2–5.2 | Koehler et al. (1987), Moongngarm (2013), and Siddiq et al. (2010) |
| Red kidney bean         | 20.9–28.7 | 49.3–56.6             | 11.6–18.4     | 0.80–2.1 | 1.1–2.8 | Geerts et al. (2017), Naguleswaran and Vasanthan (2010), and Tyler et al. (1981) |
| Yellow pea/field pea    | 21.4–25.9 | 49.3–56.6             |                |       |       |                                                 |

Note. A range is provided where multiple values have been reported in the literature.
given legume could be due to the variety/cultivar, agronomical factors, and the methods used for analyses. Either dry or wet processes are used to make protein-rich fractions of legumes in commercial operations; fractions containing 60%–80% protein are referred to as “protein concentrates” and >80% protein-containing products are referred to as “protein isolates.” However, these two terms are used rather vaguely in literature, and the actual proportion of protein in the product depends on a variety of factors including source, vendor, intended use, and region.

Protein concentrates could be prepared by either dry or wet fractionation processes whereas only wet fractionation is used commercially to manufacture protein isolates (Pelgrom et al., 2013; Rempel et al., 2019; Schutyser et al., 2015; Sumner et al., 1981; Swanson, 1990). Regardless of the kind of process, the general approach to produce high-protein ingredients is to preferentially remove portions of nonprotein matter, that is, primarily starch and fiber, from the raw material. An outline of basic processes generally used to make protein isolates, and side streams at commercial scale are illustrated in Figure 1.

Commercial-scale dry processes available for producing high-protein fractions involve grinding seeds into flour followed by separation of fractions by physical means such as sieving and air classification. Grinding is usually performed using either a pin mill or similar milling equipment. The milled material is then fractionated based on the size and density of the particles by air classification. Generally, in the milled material, the coarse particles would contain high levels of starch, whereas the fine particles would contain high levels of protein (Rempel et al., 2019; Sosulski & Youngs, 1979; Swanson, 1990; Wu & Nichols, 2005). Coarse particles are separated as a starch and fiber containing side stream fraction (Figure 1).

In wet processing, the seeds are dehulled, ground into flour, followed by preparing a slurry in which proteins are “solubilized” by adjusting pH to alkaline levels (Sumner et al., 1981; Swanson, 1990). Once nonsoluble, nonprotein matter (primarily starch and fiber) is removed through separation and filtration techniques, the solubilized protein is precipitated by adjusting the pH to an acidic level, ideally to the isoelectric point of the protein (Gullion & Champ, 2002). This conventional wet process of making either protein concentrates or isolates generate side streams of soluble matter containing various “solids” in suspension; soluble proteins, starch, and fiber. A concentrated soluble matter is prepared by removing moisture from solubles containing liquid side stream (Figure 1).

3.1 Starch

Starch is a major nonprotein component that makes its way to side streams of plant protein manufacturing operations. Although pulse seeds contain a high proportion of starch (up to 45% depending on the source), pulse starch is not commonly used in the food industry (Hoover et al., 2010). During both dry (e.g., milling and air classification) and wet (e.g., precipitation at isoelectric pH) processing of pulse seeds, starchy coproducts such as high starch containing flour (starch content ~70%) and starch (starch content >95%) are produced (Li et al., 2011; Ratnayake et al., 2002).

Most legume starches have been well characterized and experimented in various applications (Hoover & Ratnayake, 2002; Ratnayake et al., 2001; Ratnayake et al., 2002). Legume starches are different from most traditional food starches in both granular structure and starch polymer composition. These unique characteristics pulse starches result in a markedly different in-product functionality and poor storage stability compared to commonly used food starches such as maize, wheat, and potato (Hoover & Ratnayake, 2002; Hoover & Sosulski, 1991; Ratnayake et al., 2002; Simsek et al., 2009). High amylose content (30%–45%), in general, and a highly ordered C-type semi-crystalline granule structure of pulse starches result in restricted swelling and solubility, high gelatinization temperature, resistance to shear-thinning, increased enzyme and acid stability, fast
retrogradation, and high gel elasticity (Comer & Fry, 1978; Czuchajowska et al., 1998; Gujska et al., 1994; Gunasekera et al., 1999; Hoover, 1995; Hoover et al., 2010; Ratnayake et al., 2002; Sosulski et al., 1989; Stute, 1990; Vose, 1977).

As the supply of pulse starches is expected to increase, it would be important to investigate commercially viable processes to either modify pulse starch to make them suitable for food and other applications or exploring new applications that could exploit the unique functionalities of pulse starches.

### 3.2 Fiber

Pulse seed processing for protein provides few types of fiber side streams: (a) large quantities of insoluble fiber from testa, that is, seed coat, (b) cotyledon fiber (i.e., so-called “inner fiber”), and (c) relatively smaller quantities of soluble fiber, such as pectin, xylooligosaccharides, and galactooligosaccharides.

Pulse seed coat (or “hull”) represents approximately 8% of the mature pea seed and contains of 75%–90% fiber. The hull fibers contain varying levels of cellulose, hemicelluloses (arabinan, xylan, and glucomannan), xylose-rich pectin, and lignin (Martens et al., 2017; Renard et al., 1997). Cotyledon or “inner fiber” has distinctly different compositions and properties compared with hull fiber and consists of hemicelluloses, pectin, and gums. Cotyledon fiber contains 35%–70% fiber, depending on the source, and relatively more soluble compared with hull fiber (Dalgetty & Baik, 2003). Commercially available cotyledon fiber ingredients also contain varying amounts of protein and starch depending on the processing method and extent of purification. Both hull and cotyledon fibers could contribute to dietary fiber in food products (Carbonaro, 2011). Hulls are separated mainly by dry dehulling of legume seeds, whereas cotyledon fibers are separated during wet fractionation processes. Compositions of separated hull and cotyledon fibers from several pulse seeds are given in Table 2.

#### Table 2: Proximate composition of hull and cotyledon fibers from pea, chickpea, and lentil (adapted from Dalgetty & Baik, 2003)

| Legume   | Fiber fraction | Protein (%)<sup>a</sup> | Starch (%) | Fiber (%) | Ash (%) |
|----------|----------------|-------------------------|------------|-----------|---------|
| Pea      | Hull           | 5.2                     | 2.6        | 88.9      | 3.3     |
|          | Cotyledon      |                         |            |           |         |
|          | Insoluble      | 8.4                     | 4.3        | 82.9      | 4.4     |
|          | Soluble        | 23.6                    | –          | 64.7      | 11.7    |
| Chickpea | Hull           | 12.1                    | 7.4        | 74.8      | 5.7     |
|          | Cotyledon      |                         |            |           |         |
|          | Insoluble      | 10.1                    | 2.9        | 83.7      | 3.3     |
|          | Soluble        | 16.1                    | N/D        | 70.6      | 13.3    |
| Lentil   | Hull           | 9.7                     | 1.3        | 86.7      | 2.3     |
|          | Cotyledon      |                         |            |           |         |
|          | Insoluble      | 9.4                     | 5.1        | 81.5      | 4.0     |
|          | Soluble        | 24.0                    | –          | 64.4      | 11.6    |

<sup>a</sup>N × 6.25.

Soluble fiber recovery may not be as straightforward as insoluble (cellulosic) fiber recovery due to low molecular weight, low amounts present, and interferences from other material in the liquid side streams. Chemical and enzymatic processes are used to extract soluble fibers from pulse processing side streams. Soluble fibers primarily contain α-galactooligosaccharides (α-GOS) that contain raffinose, stachyose, verbascose, and ajugose, present in 2%–10% amounts depending on the source of pulse (Saini, 1989; Tosh & Yada, 2010). The exact composition of the oligosaccharides depends on the type of legume seed and other factors such as the maturity of the seeds at the time of harvesting and the method of processing (Saini, 1989). The compositions of α-GOS in common legumes are given in Table 3. α-GOS, in purified form, could be used as a digestive resistant soluble fiber ingredient in various food applications.

### 3.3 Liquid side streams of legume processing

#### 3.3.1 Steep water

The mature legume seeds are hard in nature primarily due to their thick seed coats and compactly packed cotyledon. These anatomical restrictions result in low water absorption by raw pulse seeds during cooking (Tiwari & Singh, 2012). Therefore, soaking or steeping pulse seeds in water is a common practice to reduce cook time prior to further processing. Soaking of pulse seeds leads to release of some water-soluble compounds such as soluble fiber, water-soluble carbohydrates (oligosaccharides and simple sugars), soluble proteins, minerals, vitamins, pigments, antioxidants, and phytochemicals such as phenolics and saponins (Borchgrevink, 2012; Huang et al., 2018). The steep water from pulse soaking has shown to possess important functional properties such as foaming, gelling, and emulsifying, and thus, it can be used in certain food preparations such as eggless meringues and gluten-free bread (Huang et al., 2018; Stantiall et al., 2018).
pulse steep water, however, could contain anti-nutritional compounds, such as phytic acid, lectins, and saponin (Borchgrevink, 2012). Accordingly, further treatments to either remove or minimize the presence of such compounds may be required to produce food ingredients from steep water.

### 3.3.2 Aquafaba

Legume seeds, such as beans and chickpea, are canned and sold in “ready-to-eat” form. In canning, the seeds are cleaned and retorted in brine. This process results in both compositional and textural alterations in legume seeds while making them easier to further process for consumption. During the canning process, the legume seeds absorb moisture, while soluble compounds, such as sugars, soluble proteins, phospholipids, saponins, soluble oligosaccharides, and pectic compounds, migrate from inside the seeds into the brine. The composition of leached compounds into the brine depends on the type of legume, brine composition, and process conditions (Rockland & Radke, 1988; Ros & Rincon, 1993).

In using canned chickpea, the brine that contains material leached from the seeds is usually discarded. This brine, commonly referred to as “aquafaba,” has been found to contain useful properties and food uses (Mustafa & Reaney, 2020). Aquafaba is known to have foaming, gelling, and emulsification properties that make it suitable to use as an egg replacer in select food products in which foaming and emulsification are required (Alsalman et al., 2020; Buhl et al., 2019; Mustafa & Reaney, 2020; Shim et al., 2018; Stantiall et al., 2018). For example, aquafaba can be used in bakery products, meringues, macaroons, mousse, mayonnaise, and cocktails (Alsalman et al., 2020; Lafarga et al., 2019; Shim et al., 2018).

The composition of aquafaba has been studied and reported in the literature (Alsalman et al., 2020; Buhl et al., 2019; Mustafa & Reaney, 2020). The compounds that are responsible for its functional properties, however, have not been clearly established yet. Given that aquafaba consists of a mixture of diverse compounds and brine salts, the functionality of aquafaba could depend on the blend of compounds including salts, saponin, phospholipids, and soluble proteins present in the mixture.

### 3.4 Phytochemicals and bioactive compounds

Legume processing by-products have been evaluated as potential sources of nutraceuticals and bioactive compounds. Most legumes contain polyphenolic compounds that possess antioxidant activity. These compounds include flavonols, flavone glycosides, flavanols, and proanthocyanidins. Extraction of bioactive compounds requires extensive processing and separation technologies depending on the compound being extracted. Some examples are milling to achieve fine particle sizes, physical treatments such as ultrasonication to assist dispersion of compounds, efficient heat treatments such as microwave, radio frequency, ultrasonication, extractions using solvents, subcritical/supercritical water or carbon dioxide processing, separation using membranes, and chromatographic systems (Altemimi et al., 2017; Carbonaro, 2011; Zhong et al., 2015; Zuluaga et al., 2020). Despite being feasible in small, laboratory scale, some of these processing technologies may not be economical for large-scale commercial processing operations. Various approaches, such as phase separation, adsorption, precipitation, and chemical and enzymatic processes, to extract bioactive compounds from side streams have been reviewed recently (Moreno-González & Ottens, 2021).

### 4 CONVENTIONAL AND CURRENT USES OF SIDE STREAMS

The side stream derived products are used in a variety of food, feed, and industrial applications depending on their quality and composition. Traditionally, side stream derived ingredients have been experimented to replace rather expensive ingredients. The end product properties, however, could depend on the proportion of side stream ingredient added (Carbonaro, 2011). Accordingly, a balance between the amount of side stream ingredient used and acceptable level of product change needs to be established prior to using such ingredients in traditional food formulations. Using a new ingredient in a conventional product formulation, without altering either the processing steps or process parameters, is usually impossible. Explained below are well-documented and currently available food, pet food, feed, and industrial uses for pulse protein process side streams.
4.1 | Food ingredients

4.1.1 | Pulse starch as a food ingredient

Historically, the lack of commercial availability and the poor functional properties of pulse starches have played key roles in less utilization of them in food applications (Hoover & Ratnayake, 2002; Ratnayake et al., 2002). Several studies have investigated how to improve the functionality of pulse starches via physical, chemical, and enzyme modifications (Hoover et al., 2010; Hoover & Sosulski, 1991; Lu, Belanger, et al., 2018; Ma et al., 2018). The properties and functionalities of legume starches vary somewhat depending on the source (Hoover & Manuel, 1996; Hoover & Ratnayake, 2002).

Pulse starch properties, such as fast retrogradation and ability to make elastic gels, are preferred in manufacturing food products such as sausages, pâté-type meat products, and gluten-free oriental noodles (Comer & Fry, 1978; Wang et al., 2014). Pea starch could replace wheat flour in the formulation of low-fat bologna with minimal change in functionality and sensory properties (Pietrasik & Janz, 2010).

For the starch noodle production, mung bean starch is preferred as it provides desired color, glossiness, transparency, and texture to the noodles. In addition, mung bean starch properties such as high amylose content and restricted granule swelling during gelatinization provide high shear resistance to its paste (Hoover et al., 1997; Li et al., 2011; Sung & Stone, 2004; Tan et al., 2009; Zou et al., 2019). Mung bean starch is now widely used as an ingredient in commercial noodle making. Some studies have evaluated other legume starches for noodle making without much success in achieving a product quality comparable to those made with mung bean starch (Lii & Chang, 1981; Singh et al., 1989; Sung & Stone, 2004).

Generally, legume starches are less digestible by α-amylase enzyme compared to most other commonly used food starches. Several studies have suggested pulse starch could be a good source of resistant starch (RS) in food products (Bravo et al., 1998; García-Alonso et al., 1998; Hoover & Zhou, 2003; Mahadevamma & Tharanathan, 2004). Increased levels of RS may enable making health claims on products fortified with pulse starches.

4.1.2 | Pulse fiber as a food ingredient

Pulse fibers, pea fiber in particular, have been evaluated and deemed suitable for production of food ingredients. In purified form, these fibers can be used in various food and pet-food applications. Desirable functional properties, such as high water-binding capacity, oil-binding ability, high swelling capability, high viscosity, and texturing ability of legume sourced fibers, allow them to be used in a variety of food applications such as bakery products, sauces, and meat products (Anderson & Berry, 2000, 2001; Novak et al., 2019; Sosulski & Sosulski, 1986; Vose, 1980).

Pea hull fiber has been accepted by Health Canada as a dietary fiber (Health Canada, 2017; Fitzpatrick, 2007). The hull fiber is used primarily to enrich the dietary fiber content of food without substantially modifying the basic product properties. The cotyledon fiber could be used as texturing or bulking agent in addition to increasing dietary fiber content (Guillon & Champ, 2002; Martens et al., 2017). Pea fibers could replace food additives which provide the desired “clean label” benefit for gluten-free, dairy-free, lactose-free, and plant-based processed products. It has been reported that pea fiber could be used in food applications such as batters and breading, pasta, meat (sausages, hamburgers, cooked hams, and meat balls), cereal-based products such as bread and baked goods particularly biscuits, crackers, snacks, cakes, waffles, pizza, and tortilla (Dalgetty & Baik, 2003; Guillon & Champ, 2002; Martens et al., 2017). Pea inner fiber could be used in ground beef to increase the fat retention and cooking yield substantially (Anderson & Berry, 2001). The traditional food usage of pulse fiber, however, has not improved corresponding to the increasing supply in recent years.

The health benefits of pulse fibers are comparable to most other, commonly consumed, dietary fibers (Elslinger et al., 2014; Hashemi et al., 2017; Lambert et al., 2017). Dietary fiber is known to protect against a range of diseases and adverse physiological conditions; constipation, diverticular disease, colon-rectal diseases, diabetes, obesity, metabolic syndrome, gall stones, and colon cancer (Tiwari & Cummins, 2011). Fiber is also known to enhance metabolic functions such as reducing plasma lipid levels and improving glucose metabolism (Martens et al., 2017). The current levels of dietary fiber consumption is deemed insufficient and has been associated with the above mentioned diseases particularly in the Western parts of the world (Statovci et al., 2017; Zinöcker & Lindseth, 2018).

4.2 | Pet food

There is a dearth of information, on utilizing pulse ingredients in pet food product processing, in the published literature. Only a few studies have suggested the potential utilization of pulse seed derived ingredients in extruded pet food products (Hoover & Sosulski, 1991; Spears & Fahey, 2004; Tyler et al., 2017). Despite the lack of published research evidence, the industry has been investigating and utilizing pulse-based ingredients in pet food products (McGrane, 2006).

Starch is used as a binder and structure forming ingredient in extruded pet foods, given that starch is not a required nutrient in pet food products, especially in products intended for cats and dogs because high caloric diets could be detrimental to animals’ health (Carciofi et al., 2008; Spears & Fahey, 2004). Pulse starch, being relatively more resistant to digestion compared with commonly used cereal starches, has been highlighted as a good source of starch for pet food products (Carciofi et al., 2008; Spears & Fahey, 2004).

Pulse starch and fiber, in combination, could be used in various pet-food formulations to obtain desired product attributes, such as texture, as well as nutritional functionalities such as low glycemic and high dietary fiber in the product. Additionally, opportunities exist in formulating new pet food products with essential nutrients added to compensate those either do not exist or are available in inadequate levels in the formulations.
The use of grains, including grain legumes, in pet foods has gained some notoriety recently because of presumed link between grain-based diets and diet-associated dilated cardiomyopathy (DCM) in animals. Grain-free diets have been associated with taurine deficiency that has been speculated to be linked to DCM (Freeman et al., 2018). This suspected link between taurine deficiency and DCM, however, is still under debate and investigation. FDA has not established grain-free pet food leads to DCM (FDA, 2019), and no scientific literature with strong evidence supporting a link between grain-free pet food and DCM is available as of today.

4.3 | Animal feed

The use of grain legumes for animal feed has been well researched and documented (D’mello, 1992; Jezierny et al., 2010; Voisin et al., 2014). The use of pulse protein process side streams for animal feed, however, has not been researched in great detail. Several published studies suggest the feasibility of using pulse side streams in non-ruminant (swine) feed. Addition of pea fiber to feed has improved the gut microbiome to improve overall health, has reduced the presence of bacterial pathogens in the gut, and had no effect in ileal amino acid losses in pigs (Che et al., 2014; Chen et al., 2014; Leterme et al., 1998; Luo et al., 2017). Supplementing traditional ruminant feed with hull fibers from several pulses have shown promising results. Pulse fiber supplementation has not affected the normal digestion patterns and has improved energy and fiber intake (Mekasha et al., 2002; Mekasha et al., 2003).

Pea starch has been experimented and compared against wheat starch for extruded aquaculture feed with successful results. Pea starch containing feed for Atlantic salmon has shown to improve feed physical quality parameters, compared with wheat starch, when used as a binder in the recipe (Sørensen et al., 2011).

More often, starch, fiber, and soluble matter side streams find their way to other applications and landfills when the collected material does not meet the required quality standards such as pathogenic microbial composition. Therefore, it is important to further evaluate the use of legume protein process side streams in animal feed. Integrating feed ingredient processing to the primary process (i.e., protein manufacturing) would be helpful in eliminating both contamination of side streams and logistical issues.

4.4 | Industrial uses

Valorizing process side streams for industrial applications is relatively easier compared with food, pet-food, and feed applications because the variety of available choices are not limited by food regulations and consumer acceptance. For example, chemical modification of industrial starch has more choices and wider ranges available for processing compared with producing a modified starch for a food application. Generally, biofuel, packing material, substrates for various enzymatic and microbial processes (such as enzyme manufacturing and fermentation adjuvants), textile applications, and bioplastics are considered conventional industrial applications for legume side streams derived products (Tassoni et al., 2020).

The unique functionality of pulse starches, such as strong gelling ability makes them suitable to be used in some industrial applications with or without modifications (Li et al., 2019; Ratnayake et al., 2002). For example, native pea starch is used in manufacturing adhesives for corrugated-boards and used as a clay depressant in potash-mining industry (Vose, 1977). The utilization of modified pulse starches, such as cationic pea starch in the paper industry to improve paper strength and phosphorylated pea starch in the production of pressure-resistant microcapsules in carbonless paper, also has been reported (Colonna et al., 1995; Tiwari & Singh, 2012; Vose, 1977). Pulse starches, for example pea starch, can be used to make biodegradable and edible films and coatings for packing fruits and vegetables (Saberi et al., 2018; Zhou et al., 2019). This is a sustainable alternative to replace petroleum or plastic based packaging materials. In addition, pulse starches could be used potentially in agrochemical and pharmaceutical applications as matrix materials for microencapsulated products (Guillon & Champ, 2002).

5 | NOVEL USES OF SIDE STREAMS

In utilizing side streams, the cost of processing is a major factor that has to be taken into consideration. Preventing microbial contamination, fractionation, drying, and appropriately temperature-controlled storage operations are required usually in the production of high-value ingredients. Such processing steps, however, increase the cost of manufacturing the product. Consequently, developing affordable processes and properly integrating them into the main process of protein ingredients manufacturing are essential to establish sustainable commercial operations. Additionally, following good manufacturing practices and meeting regulatory requirements are necessary in processing side streams for food uses. These would be better accomplished with a holistic system approach in establishing legume protein manufacturing operations rather than first establishing a process for protein ingredient production and subsequently modifying the process to valorize side streams.

5.1 | Starch for novel food applications

The pulse starch paste is resistant to shear-thinning at high temperature, which is important for canned foods and extruded snacks (Czuchajowska et al., 1998; Gujska et al., 1994; Stute, 1990; Zou et al., 2019). During low temperature storage, the cooked pulse starches undergo rapid retrogradation and water syneresis (Hoover & Sosulski, 1985; Sosulski et al., 1989). The characteristic high susceptibility to retrogradation of legume starches is beneficial for the production of pulpy products via freeze-thaw (sponge) process as the retrograded starch keeps a pulpy texture even after prolonged...
cooking (Stute, 1990). It has been reported that process coproduct combinations, such as corn gluten meal and starch–fiber from pulse protein isolation process, could be used in instant masa flour (Naguleswaran, Patel, & Ratnayake, 2019). Starch from pulses such as pea, chickpea, lentil, and various types of beans could be used to manufacture such products. In addition, the pulse starches could be used in formulation of porridge, cakes, snacks, and beverages as they tolerate a wide range of processing conditions (Li et al., 2011). Pulse flours and fractions, including starch from chickpea, green and red lentils, yellow pea, and pinto and navy beans, can be used in the development of gluten-free cracker snacks without compromising the consumer acceptability (Han et al., 2010). Studies have shown that pea, lentil, faba (broad) bean, cowpea, and bean starches could be used in the production of starch noodle as cheaper alternatives to mung bean starch (Tan et al., 2009; Wang et al., 2012; Wang et al., 2014). Chemical modifications may provide acceptable in-product functionalities to legume starches for them to be used in noodles; oxidized pea starch has been used successfully in noodle preparation (Li & Vasanthan, 2003).

Nutritionally, the pulse starches are better than cereal starches as they contain substantial amounts of slowly digestible starch (SDS) and RS (Hoover & Zhou, 2003; Lu, Donner, et al., 2018). High amylose content and high amylpectin crystallinity of pulse starches mainly cause slow digestion in the small intestine and thereby reduce the rate of glucose delivery to the blood (Guillon & Champ, 2002; Ratnayake et al., 2002; Sosulski et al., 1989). It has been reported that the addition of roasted pea starch increased both SDS and RS contents in pea bread with acceptable palatability, compared with a white bread control (Lu, Donner, et al., 2018).

Physical treatments, such as heat-moisture treatment and annealing could alter key functional properties of certain legume starches to make them suitable for specific applications in which high levels of SDS and RSs are preferred (Chung et al., 2009; Hoover & Manuel, 1996). Currently, such clean label pulse starch products are not commercially available.

### 5.2 | Starch for novel nonfood applications

Pulse starch is considered relatively a cheap source of starch compared to common commercial starches such as corn, wheat, and potato for industrial applications. Legume starches, being relatively less digestible while having good gelling properties, have been studied for nutraceutical and drug delivery systems (Farrag et al., 2018a, 2018b; Nadaf et al., 2021; Yang et al., 2017). Certain premodifications to starch may be required prior to using pulse starches in controlled delivery applications. Both native and modified pulse starches could be used in general pharmaceutical applications such as tablet making (Mahajan & Kelkar, 2017; Nadaf et al., 2021).

Legume starches have been experimented in production of aerogels. Relatively high amyllose contents and fast retrogradation properties are deemed beneficial in producing aerogels using legume starches. For example, pea starch provides higher surface area, compared with amylomaize starch, in aerogels (Baudron et al., 2020). Starch-based aerogels could be used in various applications such as insulating material, biomedical applications, nontoxic scaffolds, filtration, and purification systems and light weight structural material (Kenar et al., 2014; Zheng et al., 2020).

Pea starch could be used either as a supplement or an alternative to corn and wheat starches for bioethanol production as corn and wheat starches are primarily used in food manufacturing (Farooq & Boye, 2011; Tiwari & Singh, 2012).

### 5.3 | Novel applications for pulse fiber

Increased use of pulse fibers in foods is driven by both the demand for more fiber in processed food products and facilitated by the increased availability of pulse fiber ingredients. Several studies on the composition and detailed characterization of pulse seed fibers have been published recently (Noguchi et al., 2020; Tiwari & Cummins, 2020). This new information would be helpful in better understanding the structure–function relationships of fiber from pea and other pulse process side streams. There is increasing evidence of dietary fibers from pulse sources providing health promoting effects, such as reducing glycemic effects and improving gut microbiota (Eslinger et al., 2014; Hashemi et al., 2017; Lambert et al., 2017; Myhrstad et al., 2020).

Fibers from both hulls and cotyledon of pulse seeds could be used in food applications where water binding, oil binding, and structure improvements are required. For examples, pea fibers could be incorporated in bakery products (breads, cakes, waffles, pizza, and tortillas), batters and breading, pasta, and meat products (sausages, patties, meat balls, meat burgers, nuggets, and loaves). In meat applications, pea fiber is used as an extender, binder, and a fat replacer (Mehta et al., 2015; Pietrasik et al., 2020). Pulse fibers are preferred for meat products because of their favorable functional properties such as water retention, lubrication, lowering cooking loss, texture modification, and neutral flavor (Martens et al., 2017; Mehta et al., 2015).

The hulls and brans from pulse seeds could be used in animal feed and pet food applications (Farooq & Boye, 2011). Research has demonstrated health promoting effects, such as improved digestion and bowel function, in pets fed with pea fiber containing diets (Wernimont, Fritsch, Schiefelbein, et al., 2020). Polyphenols and other antioxidants, sometimes associated with pulse fibers, have shown additional health benefits, such as anti-inflammatory effects, in pets (Jackson et al., 2020; Wernimont, Fritsch, Jackson, et al., 2020).

Novel industrial applications have been investigated for pulse fibers; thermostable peroxide enzyme that is used for industrial (e.g., commercial catalyst for phenolic resin synthesis), analytical, and biomedical (e.g., component of medical diagnosis kits) applications can be produced from pulse hull fibers (Carbonaro, 2011; Farooq & Boye, 2011).
5.4 | Soluble proteins for novel food applications

In the production of pea protein isolate, the liquid side stream (pea “whey”) is generated as a byproduct. This byproduct contains a variety of soluble components such as albumin proteins, galacto-oligosaccharides, sugars, and salts (Barata et al., 2015a; Croy et al., 1984; Gao et al., 2001; Lu et al., 2000). Albumin, which accounts for approximately 30% of total proteins in pea seeds, is rich in sulfur containing amino acids. Globulin proteins, in contrast, lack sulfur containing amino acids (Croy et al., 1984; Lu et al., 2000). Therefore, the albumin-rich liquid side stream could be used as a sulfur and nitrogen source for yeasts in manufacturing fermented products. In addition, soluble protein side stream could be added back to pea fiber side stream in preparing feed for livestock (Barata et al., 2015a). The liquid side stream from pea protein processing and corn gluten meal (a byproduct from corn starch processing) could be processed to make a hybrid plant protein concentrate, with improved nutritional and functional properties, that could be used in meat applications (Naguleswaran, Patel, & Vaz, 2019).

Albumin proteins extracted from pea flours have shown high foaming and emulsifying properties enabling them to be used in preparation of a variety of food (ice creams, meringues, fruit cakes, bread, high-protein bars, coffee whiteners, and ready-to-drink beverages or pea milk) and industrial (cosmetic and pharmaceutical) products (Barata et al., 2015b; Lu et al., 2000; Senecot et al., 2018). The functional properties of pea albumin-based ingredients could be enhanced by removing other compounds present such as salt and small molecule carbohydrates in the extract. Microfiltration and ultrafiltration processes could be used to obtain a high purity albumin fraction for food and industrial applications (Barata et al., 2015b; Senecot et al., 2018), but the manufacturing costs of this product may not be economical with currently available processing.

5.5 | Inhibitors as dietary supplements

Various anti-nutritional factors (trypsin inhibitors, chymotrypsin inhibitors, amylase inhibitors, lectins, phytic acid, polyphenols, tannins, and saponins) are present in very small quantities in pulse seeds (Abeykoon et al., 2021). Most of these compounds either get removed along with side streams or inactivated during the process while trace amounts may end up in protein products. Generally, the levels of anti-nutritional factors in pulse-derived products should meet either established or acceptable thresholds but not necessarily nonexistent. Some of these compounds are known to possess health promoting effects and, therefore, could be used in nutraceuticals, dietary supplements, and pharmaceutical applications (Carbonaro, 2011).

The following is an example for a successful commercial application of a pulse-derived anti-nutrient. Tormo et al. prepared an α-amyrase inhibitor from white bean extract which when fed to type-2 diabetic rats exhibited reduced glycemia, that is, low postprandial plasma insulin (Tormo et al., 2006). Subsequently, a human study was carried out by Vinson et al. showing the white bean extract’s ability to control glucose absorption process and potential in inhibiting starch-induced hyperglycemia (Vinson et al., 2009). Further work by other researchers led to the commercialization of a product known as “phase-2 starch neutralizer,” which is marketed as a weight control supplement (Udani et al., 2004; Udani et al., 2009).

6 | CONCLUSIONS

Legume protein ingredients have gained popularity in the marketplace in the past decade leading to an increased production of process side streams. Valorization of these side streams is of paramount importance in ensuring both the process and economic sustainability of legume protein manufacturing operations.

Major side streams of pulse protein manufacturing process—starch, fiber, and soluble solids—are being used in a limited number of traditional food, feed, and industrial applications that are deemed inadequate to fully utilize the continuously increasing production. A variety of novel uses for side streams have been investigated and published in the literature. Lack of both commercial-scale process technologies and consumer knowledge might have contributed to the underutilization of pulse protein process side streams in non-conventional food, feed, and industrial applications.

Although finding novel food, feed, and industrial applications for legume protein process side streams has earned the attention of researchers in the recent years, the limited availability of commercially viable solutions for process side streams is an on-going challenge for the pulse protein industry. Future research efforts may focus on finding scalable, physical fractionation, and purification technologies to ensure the commercial viability of food ingredient solutions given the increasing consumer demand for non-chemically processed foods. Subcritical and supercritical extraction, radio frequency, ultrafiltration, various dry fractionation processes, and enzyme-assisted conversions have been researched, with limited success, to valorize legume protein side streams. These technologies require further refinement to ensure both the economic viability and process sustainability.

It would be critically important to evaluate the potential end uses for side streams when establishing sustainable pulse protein manufacturing processes.

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