Abstract

Legumes have gained increased dietary importance in recent years due to their recognized health benefits. Recent plant protein revolution has elevated legumes to the forefront from consumers' and food industry's perspective. Unlike cereal proteins and starches, there is a scarcity of information on the structural properties of legume starches. Consumption of legume-derived dietary fibers have a positive impact on the human health, in particular, gut health, which is a current research focus for nutrition and health professionals. Knowledge of legume ingredients properties (e.g., protein denaturation, starch gelatinization, pasting, and thermal properties) could aid in understanding functionality and potential uses of these materials. The physicochemical, thermal, and the functional properties of legume proteins, starches, and dietary fibers are elucidated. Both the food ingredient manufacturers and research and development professionals in the food industry can benefit from the information provided in this review article.

KEYWORDS
amylose content, flour properties, food protein, food rheology

1 | INTRODUCTION

Legumes (Fabaceae family) are dicotyledonous seeds, rich in proteins, carbohydrates, and dietary fibers (DFs). In recent years, legume-based ingredients have steadily increased in use in various food applications. Legumes have significantly higher protein content than cereal grains, making legumes among the richest food sources of proteins and amino acids for human nutrition. In addition to offering a source of essential amino acids and bioactive peptides, legume proteins influence many functional properties, which could help expand their potential use in the development of a wide variety of food products (Boyce et al., 2010; Dhull, Punia, Sandhu, et al., 2020). The carbohydrate fraction of legumes is primarily composed of starch (65%–72%) and DF (10%–20%) (Haytowitz et al., 2011). Legume starches are characterized by a higher percentage of slowly digestible resistant starch (RS), resulting in low glycemic index, and act as functional foods. The hypoglycemic effects of legumes have been further supported by high contents of DF (Trinidad et al., 2010).

In comparison to wheat, the predominant flour/ingredient used for many food products, legumes offer improved nutritional quality. Legumes have higher proteins and higher total DF content, and lower carbohydrates (Dhull, Punia, Kidwai, et al., 2020; Siddiq & Uebersax, 2012). In addition, legume-based ingredients can be used to develop gluten-free products, which has been a growing segment of food industry in recent years. Furthermore, legume-extracted proteins are emerging as a major source of continued global demand for plant proteins as meat alternative. However, despite many nutritional...
benefits, the per capita consumption of legumes is very low in the developed countries. The superior functionality of legume-based ingredients can play an important role in expanding legumes consumption beyond traditional products and uses, as shown in Figure 1. There is considerable variation in legume ingredients by pulse type; therefore, an understanding of species-specific functional properties is important. Our objective is to provide a review of research on the physico-chemical and functional properties of legume ingredients (starch, protein, and DFs) and their functional role in food product development.

![Figure 1](image)

**FIGURE 1** Diverse application of legume protein, starch and fiber ingredients

| Amino acids (g/100g seed) | Common beans | Chickpea | Cowpea | Lentil | Pea |
|---------------------------|--------------|----------|--------|--------|-----|
| Alanine                   | 0.84-0.89    | -        | 0.94   | 1.35-1.44 | 0.99-1.09 |
| Arginine                  | 0.57-1.43    | 1.57     | 1.82   | 1.98-2.56 | 1.98-2.18 |
| Asparagine                | -            | -        | -      | -      | -   |
| Aspartic Acid             | 2.59-2.67    | 0.48     | 2.56   | 2.90-3.15 | 2.77-3.28 |
| Cystine                   | 0.14†        | 0.23     | 0.14†  | -      | -   |
| Glutamine                 | -            | -        | -      | -      | -   |
| Glutamic acid             | 3.13-3.55    | -        | 4.14   | 4.60-5.00 | 3.58-4.66 |
| Glycine                   | 0.78-0.93    | 0.55     | 1.03   | 0.86-1.07 | 0.87-1.14 |
| Histidine                 | 0.58-0.77    | 0.44     | 0.85   | -      | -   |
| Isoleucine                | 0.89-1.04    | 0.85     | 0.87   | 0.91-1.05 | 1.01-1.12 |
| Leucine                   | 1.62-1.70    | 1.60     | 1.70   | 1.59-2.14 | 1.66-1.86 |
| Lysine                    | 1.24-2.57    | 1.27     | 1.26   | 1.82-2.03 | 1.70-1.83 |
| Methionine                | 0.24-0.27    | 0.09     | 0.37   | 0.67-0.79h | 0.56-0.69h |
| Phenylalanine             | 1.21-1.36    | 0.97     | 1.46   | 1.07-1.52 | 1.06-1.26 |
| Proline                   | 0.80-0.87    | 0.05     | 0.94   | -      | -   |
| Serine                    | 1.16-1.36    | 1.22     | 1.22   | 1.06-1.49 | 1.11-1.45 |
| Threonine                 | 0.79-0.95    | 0.60     | 0.88   | 1.02-1.18 | 1.00-1.09 |
| Tryptophan                | 0.18-0.20    | 1.32     | 0.22   | -      | -   |
| Tyrosine                  | 0.70-0.90    | 0.49     | 0.87   | 0.62-0.72 | 0.62-0.75 |
| Valine                    | 1.00-1.05    | 0.84     | 1.01   | 1.06-1.31 | 1.03-1.21 |

*Baptista et al. (2017): data are mean of 15 samples; Kose et al. (2019): data are from 2 genotypes—Yenice and Pirnarı.

Thakur et al. (2017).

Baptista et al. (2017): data are mean values of 9 samples.

Ciurescu et al. (2018): data are from 4 cultivars—Eston, Georgy, Berglinse, and Black.

Ciurescu et al. (2018): data are from 5 cultivars—Nicoleta, Vedea, Specter, Windham, and Biathlon.

Cysteine.

Essential amino acids.

Methionine + cystine.
Legumes are low-cost protein source, used as flours, concentrates, or protein isolates (PIs), which make them valuable and nutritious ingredients in various food systems (Barać, Pešić, Stanojević, Kostić, & Čabril, 2015). Protein contents of legumes vary according to legume species, with average contents in pea, lentil, and beans of 23.3%–26%, 25.6%–28.9%, and 19.3%–23.9%, respectively, dry-weight basis (Baptista et al., 2017). The seed proteins can be classified as structural, storage, and biologically active. The main biologically active proteins are enzymes, lectins, and enzyme inhibitors. Globulins (35%–80%) and albumins (2%–37%) are the major protein fractions in legume seeds (Hall et al., 2017). Legumin (11S) and vicilin (7S) are the major globulins, whereas enzymes, enzyme inhibitors, and lectins belong to albums (Boye et al., 2010; Venkidasamy et al., 2019). Albumins (rich in lysine and sulfur-containing amino acids) are the most abundant amino acids in the selected legumes except chickpea, whereas limiting amino acids vary according to legume species (Table 1).

Recent research has shown the significance of bioactive peptides from legume proteins, especially, in the context of diabetes mitigation and anti-gastrointestinal cancer potential. The generation of bioactive peptides is considered either from the point of view of regular and anti-gastrointestinal cancer potential. The generation of bioactive peptides is considered either from the point of view of regular and anti-gastrointestinal cancer potential. The generation of bioactive peptides is considered either from the point of view of regular and anti-gastrointestinal cancer potential. The generation of bioactive peptides is considered either from the point of view of regular and anti-gastrointestinal cancer potential. The generation of bioactive peptides is considered either from the point of view of regular and anti-gastrointestinal cancer potential. The generation of bioactive peptides is considered either from the point of view of regular and anti-gastrointestinal cancer potential. The generation of bioactive peptides is considered either from the point of view of regular and anti-gastrointestinal cancer potential.
gastric and intestinal fluids (Gharibzahedi & Smith, 2021). Lentil and red kidney bean PIs are used to encapsulate the vegetable oils and flaxseed and soybean oils, respectively (Joshi et al., 2012; Liu et al., 2014). Probiotic bacteria are encapsulated with native and modified soy PI, soy and pea protein concentrates, resulting in improved survivability, storage stability, and tolerance in the in vitro gastrointestinal tract conditions (Gharibzahedi & Smith, 2021). Various legume protein concentrates (faba bean, pea, lupin, lentil, and soy) have been used for the edible film formulations by blending with the plasticizer, glycerol (Hopkins et al., 2019), with the developed films exhibiting good mechanical and barrier properties (Bamdad et al., 2006). Saremnejad et al. (2011) prepared flexible edible films from faba bean PI and recommended those edible films to be used for packaging of light sensitive foodstuffs.

Besides traditional cooking/processing, the functionality of legume proteins can be improved using emerging technologies, for example, high hydrostatic pressure (HP), ultrasound, enzymatic hydrolysis, and combination of these technologies (Ahmed et al., 2018, 2019; Al-Ruwaih et al., 2019; Wang et al., 2020; Xu et al., 2021). The solubility and emulsifying activity index of kidney bean, lentil PI, and protein hydrolysates were increased by HP treatment. Emulsion stability of kidney bean protein hydrolysate and lentil PI decreased, as shown by notable changes in the secondary structure with a shift of amide I and amide II after HP treatment (Ahmed et al., 2019; Al-Ruwaih et al., 2019). The thixotropic behavior of the kidney bean PI was reduced by enzymatic hydrolysis, and the resultant hydrolysates behaved like a Newtonian fluid at the higher shear rate (Figure 2). HP-assisted enzymatic hydrolysis of legume proteins has potential to produce desired bioactive peptides with higher functionality and antioxidant activities (Al-Ruwaih et al., 2019). High-intensity ultrasound treatment of chickpea PIs significantly improved their solubility, emulsifying, foaming and heat-induced gel properties (Wang et al., 2020). Enzyme hydrolysis is another technique to modify legume proteins properties. Alcalase and bromelain hydrolysis improved antioxidant and anti-inflammatory properties of legume proteins modified by different techniques have potential for use in food and nutraceutical applications because of their improved nutritional/functional characteristics (Al-Ruwaih et al., 2019; Wang et al., 2020; Xu et al., 2021).

**TABLE 2** Percent amylose content and molecular weights ($\text{M}_w$) of amylose and amyllopectin in selected legume starches

| Starch source | Amylose content (%) | $\text{M}_w$ of amylose (Da) | $\text{M}_w$ of amyllopectin (Da) | References |
|---------------|---------------------|----------------------------|---------------------------------|------------|
| Adzuki bean   | 27.9–30.61          | -                          | -                               | Su et al. (1998); Zhang et al. (2019) |
| Baby lima bean| 32.7–40.24          | $4.68 \times 10^8$         | Betancur et al. (2001); Ma et al., 2017 |
| Black bean    | 23.13–45.4          | $4.36 \times 10^6$–4.03 $\times 10^6$ | Ambigaipalan et al. (2011); Byars and Singh (2016); Du et al. (2014); Hoover and Ratnayake (2002); Ovando-Martinez et al. (2011); Simsek et al. (2012); Zhou et al. (2004) |
| Carioca bean  | 40.91               | -                          | -                               | do Evangelho et al. (2020) |
| Chickpea      | 23.0–35.24          | $1.02 \times 10^8$–$2.94 \times 10^8$ | Byars and Singh (2016); Hoover and Ratnayake (2002); Huang et al. (2007); Ma et al. (2017); Miao et al. (2009); Sandhu and Lim (2008); Yniestra Marure et al. (2019); Zhang et al. (2016) |
| Cowpea        | 18.7–49.5           | $8.16 \times 10^6$–$7.84 \times 10^6$ | Adebooye and Singh (2008); Huang et al. (2007); Kim et al. (2018) |
| Dolichos bean | 21.8                | -                          | -                               | Acevedo et al. (2020) |
| Faba bean     | 24.4–39.9           | $1.0 \times 10^6$–$2.0 \times 10^5$ | Doublier (1987); Haase and Shi (1991); Sharma et al. (2020); Zhang et al. (2019) |
| Lentil        | 23.5–38.0           | $3.33 \times 10^6$–$3.81 \times 10^5$ | Byars and Singh (2016); Hoover and Ratnayake (2002); Ma et al. (2017); Sandhu and Lim (2008); Zhou et al. (2004) |
| Mung bean     | 31.6–45.3           | $2.64 \times 10^6$–$3.54 \times 10^5$ | Hoover et al. (1997); Ma et al. (2017); Sandhu and Lim (2008); Su et al. (1998) |
| Navy bean     | 28.2–43.4           | $3.27 \times 10^6$         | Byars and Singh (2016); Du et al. (2014); Gujska et al. (1994); Hoover and Ratnayake (2002); Su et al. (1998) |
| Pigeon pea    | 25.95–46.9          | $3.54 \times 10^6$–$3.96 \times 10^6$ | Acevedo et al. (2020); Kaur and Sandhu (2010); Olagunju et al. (2020); Sandhu and Lim (2008); Singh et al. (1989); Yadav et al. (2011) |
| Pinto bean    | 25.21–37.4          | $4.34 \times 10^6$–$5.28 \times 10^6$ | Du et al. (2014); Gujska et al. (1994); Hoover and Ratnayake (2002); Ovando-Martinez et al. (2011); Simsek et al. (2012); Su et al. (1998); Zhou et al. (2004) |
| Red kidney bean| 25.33–49.7          | $8.31 \times 10^6$         | Bajaj et al. (2018); Du et al. (2014); Punia et al. (2020); Reddy et al. (2013); Su et al. (1998) |
| Smooth pea    | 23.9–35.09          | $5.38 \times 10^7$         | Aberle et al. (1994); Doublier (1987); Hoover and Ratnayake (2002); Zhou et al. (2004) |
TABLE 3 Percentages of amyllopectin (AMP) chain length distribution in starches from different legumes

| Starch source          | AMP chain length | References                           |
|------------------------|------------------|--------------------------------------|
|                        | 6–12             | 13–24                                | ≥37       |
| Baby lima bean         | 21.63            | 59.45                                | 10.61     | 8.31          | Ma et al. (2017) |
| Black bean             | 18.05–30.05      | 51.02–56.24                         | 12.19–18.18 | 0.48–13.49 | Ambigaipalan et al. (2011); Du et al. (2014); Ovando-Martinez et al. (2011) |
| Chickpea               | 38.1–42.65       | 44.71–47.6                           | 7.35–8.8   | 4.2–6.5      | Ma et al. (2017); Phruwiwatthanakul et al. (2014) |
| Cowpea                 | 25.0–39.81       | 39.6–46.7                            | 13.8–16.1  | 13.9–16.3    | Kim et al. (2018); Ma et al. (2017) |
| Faba bean              | 19.33–21.69      | 53.07–53.39                          | 13.74–15.50 | 10.41–12.10 | Ambigaipalan et al. (2011) |
| Lentil                 | 26.0–26.9        | 56.2–58.4                            | 10.4–15.6  | 7.22          | Chung, Liu, Donner, et al. (2008); Chung, Liu, Pauls, et al. (2008); Ma et al. (2017) |
| Mung bean              | 24.31–29.5       | 41.6–52.56                           | 11.15–17.21 | 8.27–15.4    | Kim et al. (2018); Ma et al. (2017); Phruwiwatthanakul et al. (2014); Yao et al. (2019) |
| Navy bean              | 24.3–31.09       | 53.3–59.8                            | 8.99–16.0  | 6.39          | Chung, Liu, Donner, et al. (2008); Chung, Liu, Pauls, et al. (2008); Du et al. (2014) |
| Pea                    | 20.4–21.1        | 54.2–54.7                            | 16.0–16.2  | 8.4–8.9      | Chung and Liu (2012) |
| Pinto bean             | 20.06–35.21      | 47.79–55.77                          | 9.63–15.48 | 0.52–10.44   | Ambigaipalan et al. (2011); Du et al. (2014); Ovando-Martinez et al. (2011) |
| Red kidney bean        | 23.65–27.81      | 51.21–59.7                           | 9.90–16.6  | 7.05–12.49   | Chung, Liu, Donner, et al. (2008); Chung, Liu, Pauls, et al. (2008); Du et al. (2014); Ma et al. (2017) |

### 3 | LEGUME STARCH

Starch is the most prominent carbohydrate in legumes. In general, legume starch granules are oval-shaped, although spherical, round, elliptical, and irregularly shaped granules are also reported (Hoover et al., 2010). Starch, present as semicrystalline granules in amyloplasts (as alternating crystalline and amorphous layers), consist of two principal polysaccharides—amyllopectin and amylose, which are α-D-glucoses linked together in two different configurations. Structural and functional characteristics of these glucan polymers influence the functionality and the end use of starch.

In comparison with cereal grains, legumes predominantly possess slowly digestible starch (SDS), which is the most desirable form of dietary starch because it elicits slow glycemic response and attenuates plasma insulin levels (Chung et al., 2009). This functional property of legume starch makes it a perfect ingredient for use in healthy food products.

#### 3.1  Starch structure: Amylose and amyllopectin

The proportion of amylose (AM) to amyllopectin (AMP) in legume starches depends upon the starch source, that is, variety, growing condition, and origin; however, amyllopectin remains the significant component (Punia et al., 2020). The accepted structure of amyllopectin comprises short amyllopectin chains forming double helices and combining into clusters (Aberle et al., 1994). These clusters yield a structure that consists of alternating crystalline and amorphous lamellae. The amylose content of legume starches varies from 18.7% to 49.7% (Table 2), which differs widely due to genotypic variation, growth conditions, enzymatic activity during biosynthesis of starch, procedures of starch isolation, and so forth (Kossmann & Lloyd, 2000; Ovando-Martinez et al., 2011; Zhou et al., 2004). A range of molecular weights (M_w) have been reported for amylose (1.0 × 10^5 to 5.45 × 10^6 Da) and amyllopectin (4.34 × 10^6 to 8.31 × 10^8 Da) (Table 2). The average chain length of amyllopectin (13–24 DP, degree of polymerization) is responsible for the crystallinity for legume starches (Hoover et al., 2010; Ma et al., 2017). The chain lengths affect the enzymatic susceptibility and functional properties of starches (Du et al., 2014). The percent amyllopectin chain length distribution in legume starches (presented in Table 3) followed the order of DP 13–24 > DP 6–12 > DP 25–36 > DP ≥ 37. Chickpea starches, however, are found to be exceptional as it contained very high amount of shorter amyllopectin chains DP (6–12) compared with other legumes.

#### 3.2  Gelatinization and rheological properties of legume starches

Starch rheology is a vast area of research as it has significant impact on food product development. Starch granules gelatinize in the presence of water at the appropriate temperature followed by gel formation (Ahmed, 2012). The gel rigidity depends on the concentration of the starch and many other factors. The gelatinization and the glass transition temperature of starch have been described in another review article (Ahmed et al., 2021). Table 4 summarizes the DSC peak gelatinization temperature (T_g) of legume starches. T_g and the gel rigidity, as measured during the rheological tests, vary significantly from the macroscopic (e.g., viscoamylograph) to the microscopic measurements (e.g., rheometry). The starch gels are
subjected to small/large amplitude oscillatory shear, steady flow, or creep measurements during rheological measurements (Acevedo et al., 2020; Ahmed et al., 2016; Doublier, 1987; Phrukwiwattanakul et al., 2014). Ahmed (2012) employed the small amplitude oscillatory shear (SAOS) measurement for evaluating the gelatinization kinetics of mung bean starch by a non-isothermal technique as function of $G_0$ and $G_00$ against heating time ($t$) and found a first-order reaction kinetics. Results showed that legume starches displayed predominant elastic modulus ($G_0$) over the viscous modulus ($G_00$) resulting in a solid-like behavior ($G_0 > G_00$) (Ahmed, 2012).

| Starch source | $T_p$ (°C) | $\Delta H_{gel}$ (J/g) | $\Delta H_r$ (J/g) | RS (%) | GI | References |
|---------------|------------|------------------------|-------------------|--------|----|------------|
| Adzuki bean   | 63.85–69.84 | 2.39–17.66             | 3.86–6.36          | 11.7–55.23 | -  | Gong et al. (2017); Wang et al. (2017); Xu et al. (2018); Yadav et al. (2019); Zhang et al. (2019) |
| Black bean    | 69.9–76.64  | 12.1–14.70             | 6.70–7.48          | 33.46–74.89 | 36.40–46 | Ambigaipalan et al. (2011, 2014); Sharma et al. (2020); Zhang et al. (2019) |
| Chickpea      | 63.5–77.3   | 4.46–17.6              | 4.6               | 8.4–73.1 | 47.05–71.7 | Chung, Liu, Donner, et al. (2008); Chung, Liu, Pauls, et al. (2008); Huang et al. (2007); Miao et al. (2009); Sandhu and Lim (2008); Yniestra Marure et al. (2019) |
| Cowpea        | 73.2–81.82  | 9.41–15.40             | -                 | 3.2–76.15 | 41.4–48.14 | Herath et al. (2018); Kaptso et al. (2016); Kim et al. (2018); Ratnaningsih et al. (2017) |
| Dolichos bean | 67.92–75.44 | 8.44–12.47             | 7.41              | 57.7    | -  | Acevedo et al. (2020); Liu et al. (2020) |
| Faba bean     | 66.38–68.4  | 6.68–12.34             | -                 | 10.00–49.8 | 61.30–66.20 | Ambigaipalan et al. (2011, 2014); Sharma et al. (2020); Zhang et al. (2019) |
| Lima bean     | 75.3–79.89  | 8.34–15.2              | 5.45              | 3.8–4.5 | 34.2–39.1 | Bello-Pérez et al. (2007); Ma et al. (2017); Oladebeye et al. (2013); Segura-Campos et al. (2010) |
| Lentil        | 66.1–70.6   | 11.2–14.3              | 6.0               | 9.1–13.2 | 60.0–66.3 | Chung et al. (2009); Chung, Liu, Donner, et al. (2008); Chung, Liu, Pauls, et al. (2008); Hoover et al. (2010); Ma et al. (2017); Sandhu and Lim (2008); Zhou et al. (2004) |
| Mung bean     | 67.0–72.83  | 5.1–21.30              | -                 | 4.04–80.78 | 41.5–50.7 | Herath et al. (2018); Kim et al. (2018); Li et al. (2019); Phrukwiwattanakul et al. (2014); Sandhu and Lim (2008); Yao et al. (2019) |
| Navy bean     | 71.9–75.1   | 13.2–16.1              | -                 | 17.2–77.4 | 67.4 | Chung, Liu, Donner, et al. (2008); Chung, Liu, Pauls, et al. (2008); Du et al. (2014); Hoover et al. (2010); Ma et al. (2017); Maaran et al. (2014) |
| Pigeon pea    | 67.56–80.74 | 2.6–10.7              | 5.1–8.07          | 60.9–76.87 | 46.8–78.82 | Acevedo et al. (2020); Kaur and Sandhu (2010); Narina et al. (2012); Olagunju et al. (2020) |
| Pinto bean    | 70.14–76.5  | 13.87–16.2             | 5.09–5.89         | 36.57–75.00 | 29.79–41.10 | Ambigaipalan et al. (2011, 2014); Hoover et al. (2010); Ovando-Martínez et al. (2011); Simsek et al. (2012); Zhou et al. (2004) |
| Pea           | 60.8–67.7   | 3.6–14.2              | -                 | 67.6–70.7 | 8.7–12.6 | Chung and Liu (2012); Chung, Liu, Donner, et al. (2008); Chung, Liu, Pauls, et al. (2008); Ratnayake et al. (2002) |
| Red kidney bean | 67.0–82.1 | 3.0–14.9              | 65.8–68.4         | 17.2–35.0 | 17.2–35.0 | Chung, Liu, Donner, et al. (2008); Chung, Liu, Pauls, et al. (2008); Eyaru et al. (2009); Ma et al. (2017); Reddy et al. (2013); Wani et al. (2010) |

Abbreviations: GI, glycemic index; $\Delta H_{gel}$, gelatinization enthalpy; $\Delta H_r$, retrogradation enthalpy after 7 days’ storage at 4°C; RS, resistant starch; $T_p$, peak gelatinization temperature of starches.
Steady flow measurements of starch dispersions/gels are characterized by non-Newtonian behavior and described by a power law or the Herschel–Bulkley models. Most of the starches demonstrate shear-thinning behavior (flow index, \( n < 1 \)), with yield stresses and thixotropy (Ahuja et al., 2020). The \( n \) values for a pool of legume starches range from 0.37 to 0.76 (Byars & Singh, 2016). Thixotropic breakdown of navy bean starch has been reported at 10% and 12% concentrations during shearing at 85°C and 95°C (Lee et al., 1995). Other legume starches (faba bean and pea) also showed a lower thixotropy (i.e., shear dependence) than the cereal starches under similar conditions (Doublier, 1987).

### 3.3 | Retrogradation of legume starches

The gelatinized starches retrograde during storage and shorten the shelf life and acceptability of food products. Retrogradation in pulse starches have been studied extensively using various techniques (Betancur-Ancona et al., 2002; Hoover et al., 2010). However, syneresis is the most extensively studied method for pulse starches with a significant variation of data due to variations in measuring conditions. Syneresis is directly related to amylose content of starches, which reassociates rapidly to form a hard gel and expels out water present between the adjacent chains (Betancur-Ancona et al., 2002).

Syneresis is a concentration-dependent phenomenon and the syneresis index decreases with increasing the starch concentration for many cultivars of black bean, chickpea, lentils, and navy bean starches (Byars & Singh, 2016). Thermal analysis reflects reduction in enthalpy \( \Delta H_f \) of stored starches after gelatinization, which ranged from 3.86 to 8.07 J/g (Table 4). The \( \Delta H_f \) corresponds to melting of crystals formed through recrystallization of outer branch chains of amylopectin, which fail to regain the same degree of order as present in native starch resulted in \( \Delta H_f < \Delta H_{gel} \) (Gunaratne & Corke, 2007). Retrograded starches show reduced mobility compared to gelatinized starches due to formation of crystallites caused by AM-AM, AM-AMP, and AMP-AMP interactions.

### 3.4 | Pasting properties of legume starches

Pasting measures the starch behavior during the heating in excess water over time. The starch slurry undergoes a series of heating/cooling/holding phases during the measurements and the change in viscosity with temperature–time records during the experiment. It provides the information about the suitability of the starch for its industrial application. The most common equipment employed for the pasting properties of starch measurements are Brabender visco-amylograph (BVA), rapid viscosity analyzer (RVA), and paste cell attached to rheometer. However, Tsutsui et al. (2005) and Ahmed (2012) recommended that a precise rheometric measurement has more advantages than BVA/RVA to investigate starch characteristics by not rupturing the gel structure during the measurement.
TABLE 5  Pasting properties of selected legume starches measured using Brabender viscoamylograph and rapid viscoanalyzer

| Starch source          | Condition/unit   | Viscosity (different units) | Reference |
|------------------------|------------------|-----------------------------|-----------|
|                        |                  | Peak viscosity | Hot paste | Breakdown | Cold paste/final | Setback | Peak time (min) | Pasting temperature (°C) |
| Pigeon pea             | RVU              | 45.42          | 43.75     | 1.67      | 58.86          | 15.11    | 6.94             | 86.54                   | Oladebeye et al. (2018) |
| Lima bean              | RVU              | 84.67          | 63.63     | 21.03     | 74.28          | 10.64    | 5.01             | 86.54                   | Oladebeye et al. (2018) |
| Jack bean              | RVU              | 32.52          | 29.50     | 3.03      | 38.92          | 9.42     | 5.65             | 86.31                   | Oladebeye et al. (2018) |
| Mung bean              | mPa·s            | 7149           | 3937      | 4342      | 1130           | 4.10     | 70.7             | Li et al. (2011)         |
| Triangular pea         | mPa·s            | 3261           | 850       | 5051      | 2641           | 4.80     | 52.60            | Li et al. (2014)         |
| White pea              | mPa·s            | 3331           | 935       | 4476      | 2081           | 4.47     | 54.30            | Li et al. (2014)         |
| Spotted colored pea    | mPa·s            | 3196           | 846       | 4041      | 1691           | 4.70     | 50.45            | Li et al. (2014)         |
| Small white kidney bean| mPa·s            | 4794           | 2156      | 5122      | 2529           | 4.06     | 50.25            | Li et al. (2014)         |
| Lentil                  | Control; BU      | 958            | 586       | 372       | 1462           | 1080     | 9.00             | 77.7                    | Ahmed et al. (2016)      |
|                        | 400 MPa; BU      | 981            | 651       | 330       | 1548           | 937      | 10.2             | 80.2                    | Ahmed et al. (2016)      |
|                        | 600 MPa; BU      | 520            | 517       | 3         | 635            | 171      | 44.4             | 95                      | Ahmed et al. (2016)      |
| Pigeon pea             | Native; mPa·s    | 5892           | -         | 2091      | 7950           | 4149     | -                | 81.6                    | Acevedo et al. (2017)    |
|                        | Germination; mPa·s| 3997          | -         | 1542      | 4431           | 1976     | -                | 82.8                    | Acevedo et al. (2017)    |
|                        | Soaking-cooking (6 h–60 min); mPa·s | 6372      | -         | 1167      | 6493           | 1288     | -                | 74.1                    | Acevedo et al. (2017)    |
|                        | Microwave 100%; mPa·s | 6324      | -         | 2058      | 7492           | 3675     | -                | 82.5                    | Acevedo et al. (2017)    |
| Dolichos bean          | Native; mPa·s    | 6134           | -         | 2601      | 7672           | 4139     | -                | 75.7                    | Acevedo et al. (2017)    |
|                        | Germination; mPa·s| 1505          | -         | 551       | 1362           | 408      | -                | 76.6                    | Acevedo et al. (2017)    |
|                        | Soaking-cooking (6 h–60 min); mPa·s | 5350      | -         | 2425      | 3550           | 625      | -                | 65.4                    | Acevedo et al. (2017)    |
|                        | Microwave 100%; mPa·s | 6403      | -         | 1812      | 8308           | 3717     | -                | 77.2                    | Acevedo et al. (2017)    |
| Jack bean              | Native; mPa·s    | 1722           | -         | 948       | 1407           | 642      | -                | 85.5                    | Acevedo et al. (2017)    |
|                        | Germination; mPa·s| 1340          | -         | 763       | 989            | 352      | -                | 86.1                    | Acevedo et al. (2017)    |
|                        |                  | 4292           | -         | 752       | 5444           | 1904     | -                | 88.9                    | Acevedo et al. (2017)    |
SBV decreased systematically as a function of pressure. The decrease in BDV break-down indicates that pressure-modified gel network is more heat-stable compared with control sample.

### 3.5 RS content and glycemic index (GI)

Legumes are frequently incorporated in food products to reduce postprandial plasma glucose response after ingestion, which is the key element for dietary management of people suffering from diabetes mellitus and cardiovascular diseases. Both in vitro and in vivo studies indicate that the legume starches are capable of lowering the GI because of the presence of higher RS and SDS content (Hoover & Zhou, 2003; Zhang et al., 2016). Legume flours have lower GI compared with extracted/isolated starches (Chung & Liu, 2012; Chung, Liu, Donner, et al., 2008; Chung, Liu, Pauls, et al., 2008) as the former contain both RS-1 (physically inaccessible starch due to presence of proteins) and RS-2 (un-gelatinized/semicrystalline form of starch) whereas the latter only contains RS-2 form. For native legume starches, RS ranges between 3.2% and 80.78% (Table 4).

The differences in RS content among legumes occur due to variation in amylose contents, amylopectin chain length distribution, surface morphology, ratio of A/B polymorphic content, degree of molecular order on granular surface, and packing of double helices in crystalline region (Ambigaipalan et al., 2014; Hoover et al., 2010). The size of the starch granule also influences the enzyme accessibility. Legumes with large granular diameters compared with cereals exhibit lower GI due to reduced surface area (Acevedo et al., 2020). The GI values for legumes are listed in Table 4. Extrusion has been found to decrease the RS content of all legume starches due to gelatinization, which unveils the whole structure of starch making it susceptible to enzymes. However, the RS content in legume starches was still found to be higher compared with corn starch after extrusion (Zhang et al., 2016). A higher RS-3 content is achieved after 24 h in cold storage for chickpea and lentil starches (Tovar et al., 2002).

### 4 LEGUME FIBERS

#### 4.1 Dietary fiber (DF)

DF, a bioactive component of legumes, has proven health benefits. Legume fibers have ability to change textural, rheological, and sensorial characteristics of foods related to their physicochemical properties (Tosh & Yada, 2010). DFs are classified into soluble dietary fiber (SDF) and insoluble dietary fiber (IDF). The concentration of DF fractions differs in the hull (seed coat) and the cotyledons, which affects the physicochemical properties of legumes (Table 6). Legume hulls mainly consist of IDF, cellulose and hemicelluloses, and smaller amounts of lignin (Tiwari & Cummins, 2011). Legume cotyledons include mainly pectic substances, soluble fraction (~55%), and lower amounts of cellulose and nonstarchy noncellulosic glucans (Guillon & Champ, 2002; Tiwari & Cummins, 2011).
### Physicochemical and functional properties of DFs

Major physicochemical properties of legume fibers/hull are summarized in Table 7. The solubility indexes of legume hulls vary widely. The highest and the lowest swelling capacity were observed in black gram and green gram, respectively. Black gram and dolichos hulls have the highest WHC, whereas soybean showed the highest OHC (Mannuramath & Jamuna, 2012). The amount of SDF and IDF fractions influences the physicochemical properties of legume ingredients. SDF has a significantly higher WHC than the IDF because of its hydrophilic character (Capuano, 2017). Pectic substances (soluble fractions) are known to be the major fraction responsible for legumes fiber’s water binding. Conversely, the insoluble fractions (pectic polysaccharides, lignin, cellulose, and hemicellulose) have the ability to enhance the oil-binding capacity of legume fibers (Huang et al., 2009; Vaz Patto et al., 2015).

DFs have the ability to change physical, rheological/textural, and sensorial properties of food systems according to their physicochemical properties (Martens et al., 2017). Pea fiber addition to meat products increased cooking yield without affecting sensorial properties of the products (Anderson & Berry, 2001; Besbes et al., 2008). Chickpea and soybean hull addition to white bread formulation reduced weight loss and firmness during storage and improved shelf life, and rheological, physical, and sensorial properties of white bread (Niño-Medina et al., 2019).

Human health is also influenced by the physicochemical properties of legume DFs. For instance, high WHC of legume DFs aids bowel movement through the colon. High-viscosity DFs (e.g., pectic substances), acting as a cation exchanger, help to absorb and remove toxic substances and decrease serum glucose and lipid levels through their ability to bind heavy metal ions (Tiwari & Cummins, 2011). Furthermore, cholesterol binding ability of legume DFs change according to the amount of SDF/IDF fractions, particle size of DFs,

### Table 6: Dietary fiber contents of selected legume seeds and hulls (g/100 g dry basis)

| Legume       | Legume based ingredient | IDF  | SDF  | TDF   | References                                                                 |
|--------------|-------------------------|------|------|-------|---------------------------------------------------------------------------|
| Common beans | Seed                    | 9.90 | 2.10 | 12.20 | Veena et al. (1995); Marconi et al. (2000); Kutoš et al. (2003);          |
|              | Hull                     | 71.7a| 5.6a | 77.3a | Mahadevamma and Tharanathan (2004); Martín-Cabrejas et al. (2004);        |
| Chickpea     | Seed                    | 8.76 | 2.82 | 11.58 | Veena et al. (1995); Marconi et al. (2000); Dalgetty and Baik (2003);   |
|              | Hull                     | 77.6a| 6.50a| 84.18a| Mannuramath and Jamuna (2012)                                             |
| Cowpea       | Seed                    | 14.80| 3.10 | 18.20 | Veena et al. (1995); Carvalho et al. (2012); Benitez et al. (2013)       |
|              | Hull                     | 69.78| 1.08 | 70.86a| Mannuramath and Jamuna (2012)                                             |
| Lentil       | Seed                    | 11.40| 1.83 | 16.70 | Perez-Hidalgo et al. (1997); Dalgetty and Baik (2003); Silva-Cristobal et |
|              | Hull                     | 9.07 | 1.05 | 10.97 | Dalgetty and Baik (2003); Stoughton-Ens et al. (2010); Chen et al. (2016) |

Abbreviations: IDF, insoluble dietary fiber; SDF, soluble dietary fiber; TDF, total dietary fiber.

### Table 7: Physicochemical properties of seed coat (hull) of selected raw legumes

| Legume seed coat | Solubility index (%) | Swelling power (%) | Water absorption capacity (g/g) | Oil absorption capacity (g/g) |
|------------------|----------------------|--------------------|--------------------------------|-------------------------------|
| Green gram       | 10.39                | 5.26               | 3.4                            | 3.60                          |
| Bengal gram      | 10.32                | 5.57               | 3.7                            | 4.30                          |
| Black gram       | 13.02                | 6.74               | 3.8                            | 3.90                          |
| Red gram         | 13.04                | 5.31               | 3.7                            | 4.20                          |
| Soybean          | 12.99                | 6.51               | 3.6                            | 4.80                          |
| Dolichos         | 8.81                 | 6.24               | 3.8                            | 3.40                          |
| Pea              | 1.88                 | 5.58               | 1.51                          |
| Chickpea         | 3.61                 | 6.24               | 1.76                          |
| Lentil           | 2.38                 | 3.64               | 1.63                          |

- Mannuramath and Jamuna (2012).
- Dalgetty and Baik (2003).
- Swelling capacity (ml/g).
- Water holding (ml/g).
- Oil binding (ml/g).
pH, and temperature of the environment, and the bile acid type (Górecka et al., 2003).

5 | CONCLUSIONS

Development and commercialization of legume ingredients, especially novel starches, PIs/fractions, and dietary fibers can offer economic benefits to the food industry and boost legume growers’ revenues as well. The bioactive properties of legume-derived proteins and peptides have gained interest in recent years. Further, being a low glycemic index product, legume starch contributes to a slow release of glucose. Legume dietary fibers are effective in normalizing bowel function and gastrointestinal health. Given the current trends, the demand for various legume ingredients will continue to grow in the future. The superior functionality of legume-based products will contribute to these trends since legume ingredients not only provide the daily nutritional requirements but are also capable of producing specialty food products. In summary, legumes will continue to play a key role in human nutrition, health, and increasingly recognized potential for enhanced crop environmental sustainability.

AUTHOR CONTRIBUTIONS

S.O. Keskin: Writing - original draft; T.M. Ali: Writing - original draft; J. Ahmed: conceptualization & Writing - original draft and editing; M. Shaikh: Writing - original draft, M. Siddiq: Conceptualization & Editing; M.A. Uebersax: Technical guidance & Editing.

CONFLICT OF INTEREST

No conflict of interest exists.

DATA AVAILABILITY STATEMENT

NA

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