Kidney bean (Phaseolus vulgaris) starch: A review

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Abstract
The mini review focuses on the morphology, pasting, rheological and in vitro digestibility of kidney bean starch. In legumes seeds, starch is the most abundant carbohydrate reserve in plants and have been ascribed medicinal and cultural as well as nutritional roles. The major carbohydrate of kidney bean seeds is starch, which accounts for 25–45% of the dry matter. Lower swelling and high solubility of kidney bean starches indicate their higher functional properties than cereal starches. High amount of resistant starch (RS) and slow digestible starch (SDS) and low amount of rapidly digestible starch (RDS) present in kidney bean starches provide their potentiality as a good source of RS. Starch is a macro-constituent of many foods and its properties and interactions with other constituents, particularly water and lipids, are of interest to the food industry and for human nutrition as starch properties may greatly determine the product quality.

KEYWORDS
digestibility, DSC, kidney bean starch, morphology

1INTRODUCTION

Beans are members of the Fabaceae family, which include legumes, and are important food crops both economically and nutritionally and are cultivated and consumed worldwide. In 2017, the global production of bean was 31,405,912 t under the area of 36,458,894 ha and in India, about 15,425,864 ha of land is under beans cultivation with total production of 6,390,000 t (Food and Agriculture Organization [FAO], 2017). Kidney beans (Phaseolus vulgaris) is one of the most globally important legume crops and an important component of human nutrition because of high protein content (20%–25%), complex carbohydrates (50%–60%) and a good source of vitamins, minerals, poly-unsaturated fatty acids (Rehman, Salariya, & Zafar, 2001; Reyes-Moreno & Paredes-Lopez, 1993), and appreciable amount of folate and fiber (Shi, Xue, Kakuda, Ilic, & Kim, 2007). The major kidney bean seed storage polysaccharide is starch accounting 25%–45% (Su, Lu, & Chang, 1997; Yoshida et al., 2003). Starch is the main storage carbohydrate of plants and contributes 50%–70% of the energy in the human diet, providing a direct source of glucose. It is often used as an additive ingredient in food products such as sauces, soups, confectionery, sugar syrups, ice cream, snack foods, meat products, baby foods, and fat replacers (Copeland, Blazek, Salman, & Tang, 2009). As the demand for convenience foods increases, the use of starch and its by-products increases rapidly. Among different types of starches, maize, wheat, and potato are widely used in a diverse range of applications. Finding alternative to these commercial starch sources may offer additional substitutes for meeting the rising demand in the starch industry (Ngobese et al., 2018). Legume starch exhibits better gel characteristics and resistant starch (RS) contents when compared with cereal and tuber starches. This mini-review will provide an update on chemical composition, morphology, thermal properties, and in vitro digestibility of kidney bean starch with a view to providing suggestions for needed research to improve the implementation of kidney bean starch in the food and nonfood industries.
2 | CHEMICAL COMPOSITION

Isolating starch from legumes is quite difficult because of the presence of insoluble flocculent proteins and fine fiber, which diminishes sedimentation, co-settling with starch to give a light, loose deposit (Schoch & Maywald, 1968). Wet milling method is a commonly used process for isolating starch from legumes. Wani, Sogi, Wani, Gill, and Shivhare (2010) isolated starch from kidney beans by wet milling that involves repeated filtration through screens and alkaline washing (0.5-M NaOH). The starch yield, moisture, protein, fat, and ash of kidney bean starches have been found in the range of 90%, 8.5%–14.5%, 0.03%–1.3%, 0.1%–0.6%, and 0.1%–0.7%, respectively (Reddy, Suriya, & Haripriya, 2013; Wani et al., 2010), indicating that the isolated starch were quite pure and these constituents were comparable with other legume starch studied (Abdel-Rahman, El-Fishawy, El-Geddawy, Iiya, & Haripriya, 2013; Wani et al., 2010). Isolating starch from legumes is quite difficult because of the presence of low protein content in kidney bean starches, it may be used for manufacturing high glucose syrups (Torruco-Uco & Betanucur-Ancona, 2007). Like cereal and tuber starch, kidney bean starch is also composed of amylose and amylopectin. The proportion of amylose and amylopectin depending upon the starch source. Kidney bean starch is reported to have the highest apparent amylose content and the lowest amount of long side chains of amylopectin when compared with other legume starches. The quality of starchy foods is highly correlated with their amylose content. Amylose plays an important role in the pasting and gel texture properties of starch during cooking (Srichuwong, Sunarti, Mishima, Isono, & Hisamatsu, 2005). Bajaj, Singh, Kaur, and Inouchi (2018) and Du, Jiang, Ai, and Jane (2014) reported the amylose content of 49.73% and 32.4% for kidney bean starches.

3 | MOLECULAR STRUCTURE

Amylose and amylopectin are the main α-glucan components of starch. Amylose is small, linear, or slightly branched molecules and located primarily in amorphous regions, whereas amylopectin is large, highly branched molecules and interactions of the outer branches of the polymer creating crystalline regions (Donald, 2001; Jane, Xu, Radosavljevic, & Seib, 1992; Yoshida et al., 2003). The gelatinization of a starch and the thermal properties of starch appear to be influenced by the amylopectin-amylose ratio as well as the amylopectin architecture (Copeland et al., 2009). Amylose and amylopectin both have an effect on the dough rheology and therefore on the structure of baked bread (Schirmer, Höchtötter, Jekle, Arendt, & Becker, 2013). Furthermore, Whistler and Johnson (1948) reported that the amylose content influences the nutritional and technological properties, such as susceptibility to enzymatic hydrolysis, and gelling and pasting behavior. The iodine binding capacity (IBC), limiting viscosity number (η), degree of polymerization (DP), and β-amylolysis limit for amylose from kidney bean starch was in the range of 20%, 180%, 1,300%, and 85.9%, respectively (Billaderis, Grant, & Vose, 1979). The proportions of DP 6–12, DP 13–24, DP 25–36, and DP ≥37 and average chain length of kidney bean starches were observed to be 23.65%, 51.21%, 12.65%, 12.49% and 21.20%, respectively (Demiate et al., 2016; Du et al., 2014). Amylose and amylopectin molecular weights were approximately $0.90 \times 10^5$–$2.25 \times 10^5$ and $3.58 \times 10^7$–$12.80 \times 10^2$ Da, respectively (Wang & Ratnayake, 2014). As reported by Srichuwong and Jane (2007), branch chains of DP 6–24 are located in a single cluster structure of amylopectin molecules, forming semi-crystalline structures of the starch granules. Weight-average molecular weights (Mw) of $8.31 \times 10^8$ g/mol and z-average radii of gyration (Rz) of 306.95 nm were observed for the kidney bean amylopectins (Du et al., 2014).

4 | SWELLING POWER AND SOLUBILITY

Swelling and solubility indices provide an evidence of the magnitude of interaction between starch chains within the amorphous and crystalline domains. Swelling power and solubility defines as a function of temperature, and it increased with the rise in temperature. Kidney bean starch possess single stage restricted swelling and low solubility behavior (Hoover & Sosulski, 1985) which, is indicative of the existence of strong bonding forces within the starch granule (Lineback & Ke, 1975). Hoover and Sosulski (1985) observed an increase in swelling and solubility between 70 and 80°C, thereafter the increases were gradual. They concluded that as the temperature increases, intragranaerum binding forces become weak, which facilitate less restricted swelling.

Gani et al. (2016) reported swelling power and solubility of 1.62–2.13 (g/g) and 2.11%–2.285% at 60°C for starches from different kidney beans cultivars. They reported the highest values of swelling power and solubility for kidney bean starches at 90°C over temperature range of 60°C–90°C. The swelling index and solubility of 10.4–11.6 g/g and 14.7%–17.9% has been reported in starch from kidney beans (Gani, Bashir, & Wani, S. M., & Masoodi, F. A., 2012; Wani et al., 2010). Legume starches show a lower degree of swelling and solubility index as compared with the cereal starches (Hoover, Hughes, Chung, & Liu, 2010), in spite of having a higher proportion of free amylose and lower proportion of lipid complexed amylose. As reported by Abdel-Rahman et al. (2008), legume starches are more viscous than those of cereal starches, indicating that legume starches have a higher resistance to swelling and rupture than do cereal starches.

5 | XRD PATTERN

Starch granules are densely packed with semi-crystalline structures and X-ray diffraction (XRD) is a fundamental technique used in the characterization and identification of starch granules crystalline structure. Three types of plant starch (A-, B-, and C-type) are reported according to their XRD patterns. A-type starch contains...
only A-type allomorph, and B-type starch contains only B-type allomorph (Cheetham & Tao, 1998). Compared with A- and B-type starches, the C-type starch is complex and contains both A- and B-type allomorphs. A-type characteristics from cereal starches, B-type found in tubers and C-type X-ray pattern, an intermediate between A and B type, present in legumes is reported (Hoover & Sosulski, 1985). Crystalline structure of kidney bean starch was observed to be of C-type (mixture of A- and B-type) (Hoover & Sosulski, 1985; Singh, Belton, & Georget, 2009). Typical X-ray pattern of kidney bean starch is shown in Figure 1. The A-type and B-type x-ray pattern is characterized with reflections centered at 15.3°, 17.0°, 18.0°, 20.0° and 23.4° 2θ angles and 5.5°–5.6°, 15.0°, 17.0°, 19.7°, 22.2° and 24° 2θ angles. C-type x-ray pattern reflects at 5.5°, 7.0°, 18.0°, 20.0° and 23.5° 2θ, which is believed to be a superposition of the "A" and "B" type pattern (Gani et al., 2016). A study conducted by Rupollo et al. (2011) reported that the XRD pattern of bean starches showed peaks at diffraction angles 2θ of 15°, 17°, 20°, 23° and 26°. Li et al. (2014) reported that white kidney bean starch exhibited peaks at about 15°, 17° and 23° 2θ, corresponding to d spacing of about 5.81, 5.1 and 3.8 Å, indicating that kidney bean starch showed C-type (mixture of A- and B-type) crystalline structure.
6 | MORPHOLOGICAL CHARACTERISTICS

The size and shape of starch granules are important in relation to their technological properties, including the viscosity of their pastes (Wojciechowski, Siqueira, Lacerda, Schnitzler, & Demiate, 2018). The scanning electron microscopy (SEM) micrographs of kidney bean starch granules showed round, elliptical, irregular, and oval shapes with smooth surfaces (Wani et al., 2010) with some indentations or hollows at one end (Gani et al., 2016). Scanning electron micrographs of kidney bean starch are shown in Figure 2. Wang and Ratnayake (2014) reported no evidence of starch damage or extraneous matter of kidney bean starches when examined under SEM. Starch granules of kidney beans were reported to have 6–32 μm width range and 8–42 μm length range (Wani et al., 2010; Hoover and Vose, 1980). Singh et al. (2008) reported To, Tp, and Tc of 68.3 °C, 73.4 °C, and 79.1 °C for kidney bean starch. Cook and Gidley (1992) explained that the enthalpy of gelatinization (ΔHgel) reflects primarily disrupting double helices than long-range disruption of crystallinity. Wani et al. (2010) reported ΔHgel of 8.6 to 10.2 J/g for

7 | PASTING CHARACTERISTICS

Pasting properties provide relevant information about the cooking behavior of starches during heating and cooling cycles. Brabender visco-amylograph (BVA), rheometer, and rapid visco analyzer (RVA) are commonly used to examine the pasting characteristics of starches. Pasting profile of kidney bean starches is presented in Table 1. Sharma, Singh, Virdi, and Rana (2015) reported pasting temperature (PT), peak viscosity (PV), final viscosity (FV), breakdown viscosity (BV), and setback viscosity (SV) ranged from 75.4 °C to 83 °C; 2,156 to 5,703 cP; 4,250 to 7,251 cP; 213 to 2,388 cP and 2,156 to 3,936 cP, respectively for 17 landraces of kidney bean starches. Pasting properties established that kidney bean starches had high PV in comparison with commercial corn and potato starches, making them good thickening agent (Wani et al., 2010). Kidney bean starch is reported to have high PT indicates the higher resistance of starch granules towards the swelling, which may be attributed to the higher amylose content and the tighter granular structure than other legumes starches (mung bean and lima bean; Chang et al., 2018).

8 | THERMAL CHARACTERISTICS

Differential scanning calorimetry (DSC) provides quantitative measurements of heat flow associated with gelatinization, where the endothermic peaks are indicative of melting (Rupollo et al., 2011). Thermal characteristics of kidney bean starches are shown in Table 2. For starches, the onset, peak, and conclusion temperatures of gelatinization (To, Tp, and Tc, respectively) are determined by DSC and have been reported to be influenced by the molecular architecture of the crystalline region, which corresponds to the distribution of amylopectin short chains (DP6–11; Noda et al. 1998). Kidney bean starches gave single narrow gelatinization endotherms. This phenomenon has been ascribed to the water-mediated melting of starch crystallites, initiated by the stripping of starch chains in the swollen amorphous regions of the granule (Biliaderis, Maurice, & Vose, 1980). Singh et al. (2008) reported To, Tp, and Tc of 68.3 °C, 73.4 °C, 79.1 °C for kidney bean starch. Cook and Gidley (1992) explained that the enthalpy of gelatinization (ΔHgel) reflects primarily disrupting double helices than long-range disruption of crystallinity. Wani et al. (2010) reported ΔHgel of 8.6 to 10.2 J/g for

### TABLE 2  
Thermal characteristics of kidney bean starches

| Instrument/model                                      | Temperature range  | Heating rate | To (°C) | Tp (°C) | Tc (°C) | ΔH (J/g) | Reference                  |
|------------------------------------------------------|--------------------|--------------|---------|---------|---------|----------|---------------------------|
| DSC-60A equipment (Shimadzu, Kyoto, Japan)           | 10°C to 100°C      | 2°C/min      | 68.7    | 73.8    | 79.1    | 8.1      | Wojciechowski et al. (2018) |
| Differential scanning calorimeter (DSC, New Castle, USA) | 30°C to 120°C      | 10°C/min     | 62.38   | 70.30   | 78.72   | 7.59     | Li et al. (2014)           |
| Differential scanning calorimeter (TA-Q20 DSC)       | 35°C to 200°C      | 10°C/min     | 57.5    | 98.3    | 162.4   | -        | Reddy et al. (2013)        |
| Differential Scanning Calorimeter (TA-60WS, Shimadzu, Kyoto, Japan) | 10°C to 95°C | 5°C/min | 71.73 | 74.73 | 77.34 | 1.73 | Rupollo et al. (2011) |
| Differential scanning calorimeter (Pyris-6 DSC, Perkin-Elmer, Waltham, MA) | 120°C | 5°C/min | 66.2 | 74.1 | 81.6 | 16.5 | Güzel and Sayar (2010) |
| DSC (200 PC-Phox Phoenix; Netzsch, Burlington Germany) | 20°C to 100°C | 10°C/min | 62.3–65.9 | 67–70.7 | 71–74.9 | 8.6–10.2 | Wani et al. (2010) |
| Differential Scanning Calorimeter (Caluire, France) | 25 to 110°C | 1°C | 68.3 | 73.4 | 79.1 | 3.0 | Singh, Nakaura, Inouchi, and Nishinari (2008) |

Note. To - onset temperature, Tp - peak temperature, Tc - conclusion temperature. ΔHgel - enthalpy of gelatinization.
starches from four kidney bean starches, whereas Singh et al. (2008), Hoover and Ratnayake (2002), and Su et al., 1997 observed enthalpy values of 3.0 J/g, 12.1–16.2 J/g and 8.8–12.5 J/g kidney bean starches.

9 | IN VITRO DIGESTIBILITY

Englyst, Kingman, and Cummings (1992) categorized starch into rapidly digestible starch (RDS), slowly digestible starch (SDS), completely but more slowly, digested in small intestine and attenuates postprandial plasma glucose and insulin levels. It is generally the most desirable form of dietary starch, and RS (not digested in the small intestine and passes to the colon where microbes ferment these substrates and produce short-chain fatty acids) based on the rate of glucose released during starch hydrolysis by digestive enzymes. The most desirable feature of common beans starches is that they contain appreciable amounts of resistant and SDS and reported to have low glycemic index (GI) response and positive impacts on human health (Tharanathan & Mahadevamma, 2003). Du et al. (2014) determined the amount of RS, SDS, and RDS and fractions of native red kidney bean starch as, 72.1%, 18.1%, and 9.8%. Kidney bean starches have high SDS and RS contents and low GI; therefore, they are suitable as a dietary carbohydrate alternative for the management of diseases such as diabetes and hyperglycemia (Du et al., 2014). Rehman and Salaraya (2005) reported 9% digestibility of red kidney bean as 36.8%. Kidney bean starches are reported to have low digestibility (Eyaru, Shresthab, & Aricot, 2009), which may be attributed to high amylose content, absence of pores on surface of starch granules and C-type crystalline structure (Singh, 2011).

10 | CONCLUSIONS

Starch represents the major source of available carbohydrate in the human diet. C-type XRD patterns and round, ovoid, and irregular shapes starch granules are characteristics of kidney bean starches. Kidney bean starches have been reported to demonstrate higher viscosity as compared with cereal starches on pasting, making them good thickening agent. Presence of high SDS and RS and low RDS in kidney bean starches provides their capability as a good source of RS and makes it more suitable for the diabetic patients.

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

AUTHOR CONTRIBUTIONS

Sneh Punia conceptualized the study, conducted the literature of review, and prepared the review draft. All authors contributed to the critical review and editing of the manuscript.

DATA AVAILABILITY STATEMENT

Due to technical limitations, the full dataset is unable to be published at this time. However, it is available upon request from the authors.

ETHICS STATEMENT

This article does not contain any studies with human and animal subjects.

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