Food Chemistry **13** (1984) 25–68

Chemical, Nutritional and Physiological Aspects of Dry Bean Carbohydrates—A Review

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(Received: 1 February, 1983)

ABSTRACT

The current knowledge of dry bean carbohydrates related to their composition, nutritional value and physiological attributes in humans is reviewed. Dry bean carbohydrates represent up to 60% of the total seed weight and starch is the major constituent. Molecular and physico-chemical properties of legume starches are also discussed. Data to indicate the possible involvement of the raffinose family of oligosaccharides in flatulence production are given.

Food Chemistry 0308-8146/84/$03·00

INTRODUCTION

Dry beans are a major part of the traditional foods in the diet of many countries including India, Mexico, Africa and those of Central and South America. Food legume availability figures (Hellendoorn, 1979) show per capita per day to range from 3 to 8 g in countries such as Sweden, Argentina, Saudi Arabia and Australia; from 50 to 100 g in India, Brazil, Mexico and Japan and 136·5 g in Burundi. In the USA, annual per capita consumption of dry beans is about 5·4 kg (USDA, 1979*a*). Nationwide food consumption surveys (USDA, 1979*b*) show that low income groups consume more beans than do the other socio-economic groups (Cronin, 1979). Although food legumes comprise a large number of species, dry beans such as navy and pinto beans (*Phaseolus vulgaris* L.), bean sprouts, and frozen peas are popular in the USA and in Europe (USDA, 1979*b*).

Dry beans are a good source of proteins of reasonable quality and they contain up to 60 % carbohydrates (mainly starch). Dry beans are consumed in different ways; whole-cooked, whole-fried, soaked and fried, soaked and cooked and germinated and cooked. They are also canned with meats and a variety of vegetables. Such preparations require different degrees of heating, which affect the nutritional quality and digestibility of the proteins, as well as the carbohydrates. Bean proteins and the anti-nutritional factors of beans have received considerable study. However, the carbohydrates, although a major component of dry beans, have been somewhat neglected. This review summarizes the current knowledge available on legume carbohydrates to assist in identifying research needs.

COMPOSITION

The total carbohydrates of dry legumes (Table 1) range from 24·0 % in winged beans to 68·0 % in cowpeas. These carbohydrates include mono- and oligosaccharides, starch and other polysaccharides. Starch is the most abundant legume carbohydrate and varies from 24·0 % in wrinkled peas to 56·5 % in pinto beans. Soybeans and lupine seeds have the lowest starch contents (0·2 to 3·5 %). The variations observed are due to different cultivars and analytical procedures (Pritchard *et al.*, 1973; Cerning *et al.*, 1975).

Total sugars (mono- and oligosaccharides) represent only a small

TABLE 1
Carbohydrate Content of Dry Beans[a]

Composition[b]	*Winged bean seeds*	*Smooth peas*	*Wrinkled peas*	*Great Northern beans*	*California Small White beans*
Total carbohydrates (%)	24·0–42·2	56·6	—	61·2–61·5	—
Starch (%)	—	36·9–48·6	24·0–36·6	44·0	57·8
Amylose (%)	—	23·5–33·1	62·8–65·8	10·2–30·3	29·1–32·6
Total soluble sugars[c] (%)	3·4	5·3–8·7	10·2–15·1	9·9	7·7
Oligosaccharides:					
Sucrose (%)	0·3–8·2	2·3–2·4	2·3–4·2	2·0–3·8	3·0
Raffinose (%)	0·2–2·0	0·3–0·9	1·2–1·6	0·3–0·7	0·3–0·7
Stachyose (%)	0·1–3·6	2·2–2·9	2·9–5·5	2·3–3·8	2·9–3·7
Verbascose (%)	0·04–0·9	1·7–2·3	2·2–4·2	ND	0·1
Ajugose (%)	—	0·06	0·13	—	—
Crude fiber (%)	3·4–12·5	4·6–7·0	7·6	4·5–6·7	—
Lignin (%)	0·7–1·0	0·5–0·9	0·3–1·0	—	—
Cellulose (%)	—	0·9–4·9	1·2–4·2	—	—
Hemicelluloses (%)	1·36	1·0–5·1	0·9–6·6	—	—

(*continued*)

TABLE 1—*contd.*

Composition[b]	*Red kidney beans*	*Navy beans*	*Pinto beans*	*Pink beans*	*Black eye beans*
Total carbohydrates (%)	56·3–60·5	58·4	54·6–63·7	—	—
Starch (%)	31·9–47·0	27·0–52·7	51·0–56·5	42·3	41·2
Amylose (%)	17·5–37·2	22·1–36·0	25·8	14·9–35·3	15·8–38·3
Total soluble sugars[c] (%)	8·0	5·6–6·2	6·7	—	—
Oligosaccharides:					
Sucrose (%)	1·6	2·2–3·5	2·8	1·4	2·6
Raffinose (%)	0·3–0·9	0·4–0·7	0·4–0·6	0·2–0·4	0·4–1·0
Stachyose (%)	2·4–4·0	2·6–3·5	2·9–3·0	0·2–0·4	0·4–0·9
Verbascose (%)	0·1–0·5	0·1–0·4	0·1–0·2	—	—
Ajugose (%)	—	—	—	—	—
Crude fiber (%)	3·7	3·4–6·6	4·3–7·2	—	3·1
Lignin (%)	2·7–3·1	0·1	1·8–3·0	0·2	0·1
Cellulose (%)	2·5–5·9	3·2	9·0	6·0	4·9
Hemicelluloses (%)	0·3	0·5–4·9	4·0	—	—

TABLE 1—*contd.*

Composition[b]	*Black gram*	*Bengal gram*	*Mung bean*	*Red gram*	*Soybean*
Total carbohydrates (%)	56·5–63·7	60·1–61·2	53·3–61·2	57·3–58·7	25·4–33·5
Starch (%)	32·2–47·9	37·2–50·0	37·0–53·6	40·4–48·2	0·2–0·9
Amylose (%)	43·9	31·8–45·8	13·8–35·0	38·6	15·0–20·0
Total soluble sugars[c] (%)	3·0–7·1	3·5–9·0	3·9–7·2	3·5–10·2	5·3
Oligosaccharides:					
Sucrose (%)	0·7–1·5	0·7–2·9	0·3–2·0	2·7	—
Raffinose (%)	0·0–1·3	0·7–2·4	0·3–2·6	1·0–1·1	0·7–1·3
Stachyose (%)	0·9–3·0	2·1–2·6	1·2–2·8	2·7–3·0	2·2–4·2
Verbascose (%)	3·4–3·5	0·4–4·5	1·7–3·8	4·0–4·1	0·0–0·3
Ajugose (%)	—	—	—	—	—
Crude fiber (%)	1·2–7·1	1·2–13·5	1·2–12·8	1·2–8·1	2·4–5·5
Lignin (%)	3·8	2·9–7·1	2·2–7·2	2·9	—
Cellulose (%)	5·0	1·1–13·7	2·5–4·6	7·3	—
Hemicelluloses (%)	10·7	0·6–8·4	0·3–9·1	10·1	7·6

(continued)

TABLE 1—*contd.*

Composition[b]	*Broad beans*	*Lentil*	*Cowpea*	*Lupine seeds*
Total carbohydrates (%)	57·3	59·7	56·0–68·0	—
Starch (%)	41·2–52·7	34·7–52·8	31·5–48·0	0·3–3·5
Amylose (%)	22·0–35·0	20·7–45·5	—	—
Total soluble sugars[c] (%)	3·1–7·1	4·2–6·1	6·0–13·0	7·4–9·5
Oligosaccharides:				
Sucrose (%)	1·4–2·7	1·8–2·5	1·8–3·1	1·0–2·6
Raffinose (%)	0·1–0·5	0·4–1·0	0·4–1·2	0·5–1·1
Stachyose (%)	0·5–2·4	1·9–2·7	2·0–3·6	0·9–7·1
Verbascose (%)	1·6–2·1	1·0–3·1	0·6–3·1	0·6–3·4
Ajugose (%)	—	—	—	0·3–2·0
Crude fiber (%)	8·0	3·8–4·6	1·7–4·0	3·0
Lignin (%)	0·7–1·1	2·6	0·6–1·8	0·7–0·8
Cellulose (%)	1·0	4·1	—	—
Hemicelluloses (%)	4·0–4·6	6·0	—	9·3–9·9

[a] Data compiled from the following references:

Winged bean seeds: Claydon (1978); Sajjan & Wankhede (1981); Garcia (1979); Watson (1977); Ekpenyong & Borchers (1980); Blaise & Okezie (1980); Spata (1980); Rockland *et al.* (1979); Okezie & Martin (1980); Pospisil *et al.* (1971).

Smooth and Wrinkled peas: Fleming (1981); Colonna *et al.* (1980); Biliaderis *et al.* (1979); Cerning-Beroard & Filiatre (1976); Bramsnaes & Olsen (1979); Patwardhan (1962); Morad *et al.* (1980); Vose (1980).

Great Northern and CSW beans: Kon (1979); Sathe & Salunkhe (1981*a*, *b*, *c*); Iyer *et al.* (1980); Olson *et al.* (1975); Sosulski & Youngs (1979); Satterlee *et al.* (1975); Becker *et al.* (1974); Sosulski *et al.* (1976); Mieners *et al.* (1976).

Red kidney and Navy beans: Fleming (1981); Sosulski *et al.* (1982); Snauwaert & Markakis (1976); Sosulski & Youngs (1979); Kawamura (1969); Schoch & Maywald (1968); Labaneiah & Luh (1981); Naivikul (1977); Naivikul & D'Appolonia (1978); Boloorferooshan & Markakis (1979); Iyer *et al.* (1980).

Pink and Black eye beans: Labaneiah & Luh (1981); Silva & Luh (1979); Rockland *et al.* (1979).

Broad beans and Lentils: Lorenz (1979); Colonna *et al.* (1980); Biliaderis *et al.* (1979); Bhatty & Slinkard (1979); Naivikul & D'Appolonia (1979*a*, *b*); Shahen *et al.* (1978); Awadalla *et al.* (1978); Eskin *et al.* (1980); Iyengar & Kulkarni (1977); Sosulski & Youngs (1979); Patwardhan (1962); Morad *et al.* (1980); Vose (1980); Chen & Anderson (1981); Nigam & Giri (1961); Goel & Verma (1980).

Cowpea and Pinto beans: Akpapunam & Markakis (1979); Longe (1981); Monte & Maga (1980); Chen & Anderson (1981); Kumar & Venkataraman (1976); Halaby *et al.* (1981); Naivikul (1977); Iyer *et al.* (1980); Cristofaro *et al.* (1974); Sosulski *et al.* (1982); Mieners *et al.* (1976).

Soybeans: Wilson *et al.* (1978); Ekpenyong & Borchers (1980); Hellendoorn (1973); Eskin *et al.* (1980); Hymowitz *et al.* (1972); Tanaka *et al.* (1975); Rockland *et al.* (1979).

Lupine seeds: Cerning-Beroard & Filiatre (1976); Sosulski & Youngs (1979); Eskin *et al.* (1980); Sosulski *et al.* (1982).

Black gram, Bengal gram, Mung bean, and Red gram: Geervani & Theophilus (1981); Kamath & Belavady (1980); Rao (1976); Nene *et al.* (1975); Patwardhan (1962); Olson *et al.* (1975); Nigam & Giri (1961); Iyengar & Kulkarni (1977); Reddy & Salunkhe (1980); Watson (1977); Fleming (1981); Morton (1976); Deosthale (1978); Jaya & Venkataraman (1981); Goel & Verma (1980); Singh *et al.* (1982); Sosulski *et al.* (1982); Sathe *et al.* (1982); Aman (1979); Kylen & McCready (1975); Kumar & Venkataraman (1976).

[b] Per cent based on dry weight.

[c] Includes mono- and oligosaccharides.

ND = Not detected.

percentage of total carbohydrates in dry legume seeds. Among the sugars, oligosaccharides of the raffinose family of sugars (raffinose, stachyose, verbascose and ajugose) predominate in most legumes and account for a significant percentage (31·1–76·0 %) of the total sugars in several others (Nene *et al.*, 1975; Hymowitz *et al.*, 1972; Cerning-Beroard & Filiatre, 1976; Naivikul & D'Appolonia, 1978; Becker *et al.*, 1974; Kon, 1979; Rockland *et al.*, 1979; Akpapunam & Markakis, 1979; Ekpenyong & Borchers, 1980; Reddy & Salunkhe, 1980; Fleming, 1981; Sathe & Salunkhe, 1981*a*). Certain legumes such as smooth peas, wrinkled peas, black gram and red gram contain higher amounts of total oligosaccharides than others. The predominance of a particular oligosaccharide seems to depend on the type of legume. For example, verbascose is the major oligosaccharide in black gram, Bengal gram, red gram, mung bean and broad beans (faba beans), whereas stachyose is the major oligosaccharide in smooth and wrinkled peas, Great Northern beans, California Small White beans, red kidney beans, navy beans, pinto beans, pink beans, black eye beans, Bengal gram, soybeans, lentils, cowpeas and lupine seeds. Ajugose is the other higher molecular weight oligosaccharide of the raffinose family of sugar, which is present in small amounts in smooth and wrinkled peas and lupine seeds. Raffinose is present in moderate to low amounts in most legumes.

Crude fiber, also considered as roughage, consists of cellulose, hemicellulose (a heterogeneous group in which pentosans usually predominate), lignin (an aromatic polymer), pectic and cutin substances. Legumes contain appreciable amounts of crude fiber (1·2 to 13·5 %). Rather large variations in crude fiber content were observed in black, Bengal gram, mung bean and red gram. Cellulose is the major component of crude fiber in smooth and wrinkled peas, red kidney beans, navy beans, pinto beans, pink beans and black eye beans, while in other legumes (lupine seeds, lentil, broad beans, red gram, black gram), hemicellulose is the major component of fiber. Several researchers reported that glucose is the major sugar in hemicelluloses of *Vicia faba* (Pritchard *et al.*, 1973; Cerning *et al.*, 1975), cowpeas (Longe, 1981), mung beans (Buchala & Franz, 1974), wrinkled peas (Cerning-Beroard & Filiatre, 1976) and winged beans (Sajjan & Wankhede, 1981). Hemicelluloses of horse beans contain essentially xylose, small amounts of arabinose and traces of galactose and rhamnose (Cerning *et al.*, 1975). Sajjan & Wankhede (1981) hydrolyzed hemicellulose A and B fractions (extracted with alkaline solution and precipitated with acetic acid and ethanol to isolate A and B fractions) of winged beans in order to establish the proportion of hexose to pentose. They found that hemicellulose A consists of glucose, xylose and arabinose in ratios of 15·5:9:1 and hemicellulose B contained glucose and xylose in the proportion 15:1. Pritchard *et al.* (1973) suggested that the hemicellulose of *Vicia faba* is largely a glucose polymer.

Labaneiah & Luh (1981) investigated the changes in crude fiber, cellulose and lignin content of red kidney beans, black eye beans, and pink beans during a 6-day germination period. They found no significant changes in those contents.

PROPERTIES OF BEAN STARCHES

Only in recent years has there been detailed investigations on the functional properties of legume starch. One of the inherent difficulties in studies on starch is its microheterogeneity. This problem has been recognized and needs extensive investigation in order to improve understanding of starch molecules. Recently, Greenwood (1979) re-emphasized the importance of starch microheterogeneity as follows: '...The inherent complication in this whole subject is that it is not possible to make many generalizations about starch. The starch granule possesses *individuality*, for not only is its external appearance sufficiently characteristic to allow its botanical source to be identified by optical microscopy, but each granule in a population may differ from its neighbours in both its fine structure and properties.'

Physico-chemical properties of legume starches

Granule size, shape and microscopic appearance

Granule size of bean starches has been investigated by several researchers. Data on certain bean starch granule sizes are presented in Table 2. The granule size is quite variable and the granule dimensions range from about 1 to 80 μm depending on the source. Most bean starch granules are slender (greater length than width), although spherical, ovoid, elliptical and irregular granules are also found. This wide variation in granule size and shape could be due to genetic control and seed maturity.

Usually the size and shape of starch granules is characteristic of their source (Manners, 1974). For dry beans, however, a wide variability in shape is found in starch granules from the same source. If the need for

TABLE 2
Granule Size of Legume Starches[a]

Legume	*Granule dimension (μm)*			
	Width	*Length*	*Diameter*	*Unspecified*
Bengal gram	6–7, 17–29	—	—	—
Black bean	—	—	8–55[b]	—
Black gram	7·5–27·0	7·5–28·5	—	—
Broad bean	—	—	26·5[c]	—
Faba bean	12–24	20–48	—	—
Field pea	—	—	20–40[c]	—
Great Northern bean	12–20	12–58	—	—
Horse bean	—	—	20–40[c]	—
Kidney bean	23–34	—	—	—
Lentil	16–28	16–36	—	—
Mung bean	8–16	12–32	—	—
Navy bean	12–36	12–40	—	—
Pinto bean	16–28	16–48	—	—
Red bean				25–67[e]
Smooth pea	24–41	—	23·75[c]	—
Soybean	—	1–7	—	—
Wrinkled pea			18·00[c] (6–80)[d]	

[a] Compiled from Kawamura (1969); Lineback & Ke (1975); Colonna *et al.* (1980); Lai & Variano-Marston (1979); Lii & Chang (1981); Naivikul & D'Appolonia (1979*b*); Sathe & Salunkhe (1981*a*); Sathe *et al.* (1982); Vose (1980).
[b] Lengthwise diameters.
[c] Unspecified diameter.
[d] Figure in parenthesis indicates the range.
[e] Dimension not specified.

identification of starches from various legume sources should arise, this problem could possibly be overcome by separating the fraction of starch which constitutes a major portion of the total starch, and then studying that fraction microscopically to establish whether the shape and size truly represent the source.

Light microscopic studies of legume starches clearly reveal two distinct starch granule characteristics, the presence of a hylum, and the presence of lamellae. The hyla have been described in the literature as furrows or grooves, cracks and stria (Naivikul & D'Appolonia, 1979*a*), cracking dark bands (Hall & Sayre, 1971) and microfibrils (Donovan, 1979). The origin of this topographic characteristic is not known. It must be noted that the presence and length of the hylum are both variable. The hylum is not discernible on all the starch granules and its length ranges from 0 to 100 % of the length of the starch granule on which it is present. Lamellae (concentric rings), on the other hand, seem to be present on all the starch granules. The origin and nature of lamellae are also not yet known.

The hylum and lamellae observed under the light microscope are, however, not seen when legume starch granules are observed under a scanning electron microscope. Instead, the starch granule surface appears to be smooth with some occasional scar-like features. These latter structures could arise from adhering cell wall materials or proteins, or both. Starch granules in the seeds are enveloped by the cell wall. Also, starch granules may be packed in compartments with a sac-like structure. The mechanism by which amylose and amylopectin are packed within the starch granule, as well as how granules are packed together, is not yet known. The cell walls are difficult structures to rupture and intact cells containing granules usually remain, at least partially, in isolated starches.

Molecular weights

Starches are high molecular weight compounds since they are polymeric monosaccharides. Data on legume carbohydrate molecular weights are scanty. Biliaderis *et al.* (1979) reported that the major portion of legume starches have molecular weights higher than 2×10^6 (Table 3). They studied the molecular weight distribution profile of several legume starches and found that over 90 % of the starch has a molecular weight above 4×10^4. Since molecular weight has a direct bearing on starch functionality, more research is needed to improve understanding of this relationship.

Amylose and amylopectin

In legumes in general amylose may constitute a significant portion of the starch, the range being from 10 to 66 % (Table 1). The amount of amylose in the starch influences starch solubility, lipid binding and other functional properties. Amylopectin is thought to be responsible for the solubility of starch granules. Amylose and amylopectin are also responsible for the structural form of starch granules.

Recently, Biliaderis *et al.* (1981*a*,*b*) reported on a systematic investigation of the structural characteristics of legume starches. They fractionated legume starches into amylose and amylopectin and determined certain molecular properties. The data are summarized in Table 4. The data imply that the variability between amyloses from different legumes

TABLE 3
Per Cent Distribution of Molecular Weights of Legume Starches[a]

Legume	*Molecular weight*				
	$<4 \times 10^4$	4×10^4 to $>1{\cdot}5 \times 10^5$	$1{\cdot}5 \times 10^5$ to $>5 \times 10^5$	5×10^5 to $<2 \times 10^6$	$>2 \times 10^6$
Adzuki bean	7·5	7·7	9·3	8·8	66·7
Garbanzo bean	6·5	5·8	7·2	6·5	74·0
Smooth pea	4·7	4·8	6·9	7·2	76·4
Red kidney bean	7·6	7·8	8·2	6·7	69·7
Wrinkled pea	8·7	7·7	10·7	13·2	59·7
Lentil	9·9	12·5	12·0	6·3	59·3
Mung bean	3·3	8·2	10·5	9·1	68·9
Navy bean	4·8	6·6	10·0	6·9	71·7
Faba bean	1·3	6·2	10·2	8·1	74·2

[a] From Biliaderis *et al.* (1979).

may be due to (a) maturity of seed, (b) genetic control of amylose synthesis, (c) cultivar differences and (d) seed history. Iodine affinity, however, seems to be in the narrow range (18–20). Molecular weights generally are greater than 100 000. The range for degree of polymerization is quite variable (540–4000). A high degree of amylose polymerization may confer structural stability on the granule and also may be partially responsible for its resistance towards *in vitro* α-amylolysis.

Granule crystallinity
Starch granules contain both crystalline (ordered) and amorphous (unordered) regions. This crystallinity gives rise to the birefringent property of starch granules (Elbert, 1965), i.e. optical anisotropy. Birefringent material diffracts a single light beam into two beams, which can be readily observed by use of a polarized light. As a result, when legume starches are observed under a polarized light microscope they appear as four lobes divided by two dark crossed bands.

Functional properties

Swelling and solubility
Swelling of the starch granule is the first stage of hydration-related

TABLE 4
Characteristics of Legume Amyloses

Amylose source	*Iodine affinity*	*Yield*[d] *(%)*	*Degree of polymerization*	*Molecular weight*	η *(ml/g)*
Adzuki bean[a]	19·49	64·2	1 600	—	220
Garbanzo bean[a]	18·88	60·3	1 300	—	174
Smooth pea[a]	18·84	62·8	1 400	—	194
Red kidney bean[a]	20·00	—	1 300	—	180
Wrinkled pea[a]	19·82	55·4	1 000	—	136
Lentil[a]	19·62	65·1	1 400	—	188
Navy bean[a]	18·48	—	1 300	—	174
Mung bean[a]	19·43	—	1 900	—	251
Faba bean[a]	19·61	61·4	1 400	—	188
Navy bean[b]	—	—	—	165 000	0·74[e]
Pinto bean[b]	—	—	—	123 000	0·54[e]
Faba bean[b]	—	—	—	191 000	1·75[e]
Lentil[b]	—	—	—	312 000	1·85[e]
Mung bean[b]	—	—	—	245 00	2·42[e]
Bengal gram[c]	—	—	1 667	—	—
Green gram[c]	—	—	667	—	—
Red gram[c]	—	—	540	—	—
Black gram[c]	—	—	4 000	—	—

[a] Biliaderis *et al.* (1981*a*).
[b] Naivikul & D'Appolonia (1979*a*).
[c] Rao (1976).
[d] Expressed as per cent of the apparent amylose content of starch.
[e] Intrinsic viscosity values.
η = Limiting viscosity number.

properties. Legume starches usually have restricted swelling behavior. The swelling may proceed in one stage as in the case of mung bean starch, or in two stages as in case of navy bean starch (Schoch & Maywald, 1968). The number of stages in swelling has been suggested to represent the severance of weak and strong bonds. It is possible that these swelling stages originate from the crystalline and amorphous regions of starch granules.

Data on swelling and solubility of legume starches are scanty. The available literature indicates that swelling and solubility depend on starch source (botanical as well as regional), temperature and pH. Solubility of legume starches is less than 30% (Lai & Variano-Marston, 1979; Comer & Fry, 1978; Sathe *et al.*, 1981); whereas swelling of unmodified legume starches has a wide range depending on experimental conditions. For example, swelling of black gram starch increases from less than 500% to over 2600% when the temperature is increased from 21 to 95°C (Deshpande *et al.*, 1982). In the case of Great Northern bean starch swelling increases from about 400 to about 900% when the temperature is raised from 60 to 90°C. These data and other studies (Lai & Variano-Marston, 1979) suggest that while increasing the temperature increases starch swelling, inherent swelling ability depends primarily upon the starch source.

Water absorption

Water absorption of legume starches is inversely related to solubility and directly related to swelling. Preliminary investigations indicate that legume starches have a lower water absorption capacity than cereal starch (Halbrook & Kurtzman, 1975). Water absorption by legume starches has been reported to be generally less than 10 g/g starch (Comer & Fry, 1978; Sathe & Salunkhe, 1981*a*; Deshpande *et al.*, 1982; Sathe *et al.*, 1981). This property can be manipulated by several different types of treatment (Deshpande *et al.*, 1982). It appears, therefore, that legume starches have a good water absorption capacity, which could be 'tailored' by suitable modification(s) of the starch.

Gelatinization and pasting

When starch granules are heated in the presence of water, several changes occur. The most important change is the order–disorder phase transition (loss of crystallinity), as indicated by loss of birefringence and near solubilization of starch. Other phenomena that occur simultaneously include alteration in starch granule shape conformation, uptake of heat and hydration of the starch granule accompanied by granule swelling (Donovan, 1979). Often, starch gelatinization results in increased viscosity and translucency. Usually the gelatinization temperature range of legume starches is determined with a Kofler hot stage mounted polarizing microscope. The criterion is loss of birefringence. Data on gelatinization temperature of several legume starches (Table 5) indicate that most legume starches have a gelatinization temperature of 60–90°C, an exception is wrinkled peas. The fact that there is a range for gelatinization temperature is due to the heterogeneity of starch granules. Biliaderis *et al.* (1981*a*,*b*) noted that the gelatinization phenomenon is complex and depends not only on starch granule structure but also on

TABLE 5
Gelatinization Temperature of Legume Starches

Starch source	*Gelatinization temperature range (°C)*	*Reference(s)*
Lima bean	70–85	Schoch & Maywald (1968)
Lentil	64–74	Schoch & Maywald (1968)
	58–61	Biliaderis *et al.* (1979)
Yellow pea	63–73·5	Schoch & Mauwald (1968)
Navy bean	66–77	Schoch & Maywald (1968)
	68–74	Biliaderis *et al.* (1979)
Garbanzo bean	62·5–72	Schoch & Maywald (1968)
	65–71	Biliaderis *et al.* (1979)
Mung bean	60–78	Schoch & Maywald (1968)
	63–69	Biliaderis *et al.* (1979)
Wrinkled pea	69–83	Schoch & Maywald (1968)
	>99	Biliaderis *et al.* (1979)
Black gram	71·5–74	Sathe *et al.* (1982)
Black bean	63·8–76	Lai & Variano-Marston (1979)
Smooth pea	65–69	Biliaderis *et al.* (1979)
Red kidney bean	64–68	Biliaderis *et al.* (1979)
Faba bean	61–66	Biliaderis *et al.* (1979)
	61–69	Lorenz (1979)
Soybean (Amsoy 71)	73–81	Wilson *et al.* (1978)
Pea	54–66	Comer & Fry (1978)
Red bean	63–70	Lii & Chang (1981)
Adzuki bean	83–89	Biliaderis *et al.* (1979)

factors such as granule size, phosphorus content, bound lipids and protein. Several investigators have studied the starch structure–gelatinization temperature relationship (Leach, 1965; French, 1972; Robin *et al.*, 1974; Watanabe & French, 1980; Biliaderis *et al.*, 1981*a*, *b*). The relationships found are as follows. (i) In starches containing appreciable amounts of amylopectin, the associated amylopectin chain clusters constitute the crystalline entity which affects the gelatinization temperature range. (ii) Gelatinization temperature is affected by degree of amylopectin branching to the extent that excessive branching diminishes rigidity of the starch granule. (iii) High amylose content resists the gelatinization process due to its insolubility in aqueous solutions.

The exact nature of such relationships remains unclear. Factors other than the microheterogeneity and impurities usually associated with starch (such as lipids and protein) also need to be considered in understanding starch gelatinization. Phase transition of starch granules is also influenced by the amount of water in a particular system and the mechanism of transition differs depending on the water content of the system. Based on calorimetric studies of potato starch–water systems, Donovan (1979) suggested: (i) in the presence of a small amount of water (molar ratio of water to glucopyranosyl unit <5), the transition is the 'melting of crystallany' in the starch granule and the transition temperature is determined by the water content of the system, (ii) in the presence of excess water (molar ratio of water to glucopyranosyl unit >14) the phase transition is due to disordering of individual starch chains being separated ('stripped') from ordered regions of granules by the swelling action of water, (iii) in the intermediate moisture range both phenomena may occur due to localized high water concentration (thus giving rise to excess water in that region). These observations emphasize the microheterogeneity of starch.

Factors other than intrinsic microheterogeneity and impurities which may affect starch gelatinization temperature include the method of drying the starch after isolation, induced chemical modification and intentional additives.

Hot paste viscosity of starches is important in starch food applications. The Brabender–Visco–Amylograph technique is commonly used to characterize the hot paste viscosity of starches. Factors which control starch hot paste viscosity include: (i) the ease and extent of starch granule swelling and (ii) the resistance of swollen granules to dissolution by heat or fragmentation by shear (Schoch & Maywald, 1968). Kawamura & Fukuba (1957) classified legume starches into two categories based on hot paste characteristics: (i) those which do not have a substantial rise in viscosity during heating (25–92·5 °C) and cooling (92·5–25 °C) cycles (heating and cooling uniform at 1·5 °C min^{-1}) and (ii) those which show a distinct rise in viscosity during heating and cooling cycles. Kidney and broad bean starches are representative of the first category, whereas mung bean starch has characteristics of the second category. Later, Schoch & Maywald (1968) attempted to classify starches, on the basis of ease of swelling, into four groups: (i) high swelling, (ii) moderate swelling, (iii) restricted swelling and (iv) highly restricted swelling. Most legume starches have rather restricted swelling and are encompassed by groups (ii), (iii) and (iv). The classification suggested by Schoch & Maywald (1968), although qualitatively useful, does not offer a quantitative basis to distinguish different classes. One such quantitative approach would be to measure thermodynamic properties such as the determination of endotherms under specified conditions. This would enable the determination of the energy requirement for a specified amount of swelling. Alternatively, under specified conditions of environment and energy, the determination of degree of swelling may be useful.

Like other properties, pasting of legume starches is affected by several parameters including pH, ionic strength, amount of water, presence/absence of impurities (lipids, proteins, sugars and fiber in particular), method of preparation (notably drying), starch modification and the source and composition (amylose and amylopectin concentration, ratio and chain length) of starch. Theoretically, factors which 'weaken' the starch granule should facilitate water imbibition, thereby improving swelling. They would also decrease resistance to fragmentation, thus leading to a higher viscosity than that of the native counterpart.

Other properties
Several other important properties of legume starches such as oil absorption, convertibility into syrups or maltodextrins, gelling ability, textural attributes and flavor characteristics remain nearly unexplored.

NUTRITIONAL QUALITY

Carbohydrate digestibility (*in vitro* and *in vivo*) has been reported to vary among legumes (Rao, 1969, 1976; Fleming & Vose, 1979; Kumar & Venkataraman, 1976; Geervani & Theophilus, 1981; Jyothi & Reddy, 1981).

In vitro digestibility

Relatively few investigations have been carried out on the *in vitro* digestibility of legume carbohydrates because of an uncertain relationship with *in vivo* digestibility. However, the data that are available to indicate *in vitro* carbohydrate digestibility of various whole beans and bean cotyledons are presented in Tables 6 and 7. Most of the *in vitro* studies were based on the amount (milligrams) of maltose released per 100 mg legume flour after amylolysis for specified periods of time with α-amylases from various sources (hog pancreatic α-amylase; bacterial α-amylase and malt α-amylase). Dry mature beans are reported to be less

TABLE 6
Effects of Processing on *In Vitro* Digestibility of Whole Bean Carbohydrates by Enzymes from Bacterial and Animal Origin

Legume	*Raw*	*Boiled*	*Cooked*	*Roasted*	*Germinated (48 h)*
		α-amylase from hog pancreas			
Red gram	24·8[a]	44·7	—	32·3	34·0
Black gram	35·0	53·7	—	41·0	44·7
Green gram	45·3	58·3	—	44·7	52·3
Bengal gram	39·3	56·2	—	43·3	47·7
Cowpea	51·7	57·7	—	50·5	56·7
Horse gram	38·7	54·7	—	37·7	46·7
		Bacterial α-amylase			
Bengal gram	6·2–11·6	—	36·2	—	13·2–20·8
Green gram	10·2–13·9	—	40·8	—	25·2–29·6
Cowpea	5·2	—	38·2	—	16·2

[a] Values are milligrams of maltose released per 100 mg of ground bean flour in 4 h at 37 °C.
Sources: Kumar & Venkataraman (1976); Jaya & Venkataraman (1980); Jyothi & Reddy (1981).

digestible when compared with immature beans because of the compositional changes in starchy and non-starchy components (Greenwood & Thomson, 1962; Elbert & Witt, 1968). *In vitro* digestibility of legume carbohydrates with α-amylase from animal sources (hog pancreatic α-amylase) is higher than with α-amylase from microbial sources (Tables 6 to 8). Among the raw legumes studied, cowpea is found

TABLE 7
Effects of Processing on *In Vitro* Digestibility of Carbohydrates from Bean Cotyledons

Legume	*Raw*	*Boiled*	*Pressure-cooked*	*Roasted*	*Parched*	*Fermented*
Red gram cotyledons	17·5[a]	37·2	36·8	19·6	—	—
Bengal gram cotyledons	22·3	40·2	37·6	28·5	29·5	—
Black gram cotyledons	25·2	43·7	43·9	24·7	—	42·6
Green gram cotyledons	22·5	45·8	52·3	21·9	—	—

[a] Values are milligrams of maltose released per 100 mg of starch after incubation with hog pancreatic α-amylase at 37 °C.
Source: Geervani & Theophilus (1981).

to be superior with regard to *in vitro* digestibility by hog pancreatic α-amylase (Table 6). The next best legume is green gram, followed by Bengal gram, horse gram, black gram, and red gram. Several processes (boiling, pressure-cooking, cooking, roasting, parching, germination and fermentation) have been reported to be effective in increasing the *in vitro* carbohydrate digestibility by α-amylases from animal or microbial sources (Kumar & Venkataraman, 1976; Rao, 1969; Subbulakshmi *et al.*, 1976; Geervani & Theophilus, 1981; Jyothi & Reddy, 1981; Khader & Rao, 1981; Jaya & Venkataraman, 1980). A significant increase in *in vitro* carbohydrate digestibility is observed following boiling of the legume (whole beans and bean cotyledons). Ungerminated legumes are less digestible when compared with germinated and other processed legumes. Germination can be considered as a process for improving digestibility and reducing or eliminating the flatus factors of various legumes. However, the optimum period of germination for maximum carbohydrate digestibility and eliminating natural toxicants and other unwanted components from legumes is not generally known. The rate of α-amylolysis (bacterial α-amylase) in cooked legumes (Bengal gram, green gram and cowpea) is about four to six times that observed with uncooked legumes (Table 6). The enhancement of *in vitro* carbohydrate digestibility by α-amylase in cooked legumes and starches can be attributed to the swelling and rupturing of starch granules, the disintegration of various bean components during cooking and inactivation of α-amylase inhibitors. Cooking facilitates dissociation and fragmentation of starch granules, thus making substrate more accessible to the active site for α-amylosis (Subbulakshmi *et al.*, 1976; Jyothi & Reddy, 1981). Pretreatment methods, including pretreatment of legume flours with HCl–pepsin for 1 h (Jaya & Venkataraman, 1980; Kumar & Venkataraman, 1976), and a special processing method, consisting of soaking of beans overnight in water, followed by blending and cooking (Khader & Rao, 1981) were reported to enhance *in vitro* carbohydrate digestibility. Roasting also improves carbohydrate digestibility in red gram, black gram, and Bengal gram, but not as much as germination or boiling or cooking. In other legumes (green gram, horse gram, and cowpea) roasting does not improve the carbohydrate digestibility. Interestingly, no data are as yet available to indicate the *in vitro* carbohydrate digestibility of US dry beans such as Great Northern and California Small White beans.

Isolated starches from various legumes also differ in their digestibility

TABLE 8

In Vitro Digestibility of Raw and Cooked Legume Starches by Enzymes from Bacterial and Animal Origin[a]

Legume starches	*Digestibility*	
	Raw	*Cooked*
	Hog pancreatic α-amylase	
Red gram	30·5	88·9
Bengal gram	32·4	88·6
Black gram	36·1	94·8
Green gram	37·2	96·5
	Bacterial α-amylase	
Bengal gram	16·0	78·8
Bengal gram germinated (24 h)	18·0	76·0
Bengal gram germinated (72 h)	28·8	81·0
Green gram	22·8	94·8
Green gram germinated (24 h)	21·4	79·6
Green gram germinated (72 h)	36·2	81·2
Cowpea	20·4	88·6
Cowpea germinated (24 h)	23·6	87·4
Cowpea germinated (72 h)	37·2	63·4

[a] Source: Kumar & Venkataraman (1976); Geervani & Theophilus (1981).
[b] Milligrams of maltose released per 100 mg of starch.

(*in vitro*) by either hog pancreatic α-amylase or bacterial α-amylase (Table 8). These differences in digestibility are attributed to: (i) varying amylose content, with the higher amylose content starches being lower in digestibility (Borchers, 1962; Rao, 1969, 1976), (ii) degree of polymerization, (iii) microheterogeneity of starch, (iv) botanical source of starch, (v) presence or absence of non-starchy components, particularly lipids, (vi) presence or absence of α-amylase inhibitors, (vii) presence of other carbohydrate substances such as cellulose, hemicelluloses and galactose-containing oligosaccharides, (viii) nature of the enzyme acting on the starch and (ix) drying and isolation or fractionation methods used (Hellendoorn, 1973, 1977; Biliaderis *et al.*, 1981*a*). The action of α-amylase is essentially a random endohydrolysis of the α-1,4-glucosidic linkages in both linear and branched starch components, while β-amylase is highly specific for exo-hydrolysis of terminal α-1,4-glucosidic bonds and catalyzes the stepwise hydrolysis of alternate linkages with liberation of maltose (Jaya & Venkataraman, 1980). Processes such as germination (Jaya, 1978; Jaya & Venkataraman, 1980; Kumar & Venkataraman, 1976), cooking (Rao, 1969; Hellendoorn, 1973; Kuman & Venkataraman, 1976; Fleming, 1982*b*) and heat treatment (hydrothermal and culinary) (Telanov & Yakovenko, 1973) are reported to increase the *in vitro* starch digestibility of various legumes. The germination process will also alter some of the other properties of starches and increase swelling power and solubility (Jaya, 1978). These changes may enhance the starch digestibility by weakening the starch granule and thus improving physical access by the enzyme. Germination of Bengal gram, green gram and cowpea for 72 h has been shown to significantly increase their starch digestibility (Table 14). Cooking further increases the digestibility of starches from germinated beans. The digestibility of starches from cooked beans is about four to five times higher than that observed with the starches from uncooked raw beans. The increase in the digestibility of starch from legumes on cooking can be attributed to gelatinization, swelling and rupturing of starch granules (Rockland & Jones, 1974). This facilitates random hydrolysis of starches by α-amylase. Sathe & Salunkhe (1981*a*) reported that the hog pancreatic α-amylase hydrolyzed isolated starch from Great Northern bean more readily than did malt α-amylase under similar conditions. Hog pancreatic α-amylase hydrolyzed 8·2% starch of Great Northern bean in a 2-h period at room temperature (21 °C) compared with 5·2% by malt α-amylase. They indicated that the low degree of hydrolysis by α-amylase may be due to the starch nature and a relatively low temperature (21 °C) during incubation.

In vivo digestibility

Shurpalekar *et al.* (1979*a*) and Geervani & Theophilus (1981) evaluated *in vivo* digestibility of various legume carbohyrates. They measured *in vivo* digestibility by determining carbohydrate intake and excretion in rats. *In vivo* digestibility of the carbohydrates of green gram is significantly higher than that of red gram, Bengal gram and black gram (Table 9). Processing (boiling, pressure-cooking and roasting) does not improve the digestibility of carbohydrates in black gram, and green gram cotyledons and in whole beans (Bengal gram and green gram). The digestibility coefficients of roasted red gram and Bengal gram cotyledons were less than those of the boiled and pressure-cooked cotyledons. Fermentation of black gram

TABLE 9
Effects of Processing on *In Vitro* Digestibility of Legume Carbohydrates[a]

Process	*Red gram*	*Bengal gram*	*Black gram*	*Green gram*
		Bean cotyledons		
Raw (unprocessed)	84·7[b]	87·2	89·9	92·2
Boiled	91·6	92·3	89·2	92·6
Pressure-cooked	89·0	92·8	90·3	93·2
Roasted	86·0	88·4	90·3	92·3
Fermented	—	—	93·7	—
		Whole beans		
Raw (unprocessed)	93·9	93·8	95·6	96·7
Boiled	—	87·5	—	86·1
Germinated (24 h)	—	87·5	—	85·1

[a] Sources: Shurpalekar *et al.* (1979*a*); Geervani & Theophilus (1981).
[b] Digestibility coefficient in per cent.

appreciably improves the *in vivo* carbohydrate digestibility. Shurpalekar *et al.* (1979*a*) and Geervani & Theophilus (1981) further noted that there was no correlation between *in vitro* and *in vivo* carbohydrate digestibility. Clearly, the relationship between *in vivo* and *in vitro* digestibility does need further investigation. Other possible reasons for differences in *in vivo* and *in vitro* amylolysis are: (i) product inhibition, i.e. accumulation of maltose slows down the rate of hydrolysis by α-amylase and (ii) in an *in vivo* situation enzymes other than α-amylase such as glucoamylase and maltase are also active. Glucoamylase hydrolyzes dextrins (particularly less than six subunits) and maltase quickly hydrolyzes maltose to glucose. Glucose is then absorbed very quickly. These factors in an *in vivo* situation may improve the hydrolysis of carbohydrates. The mechanisms for the *in vivo* and *in vitro* digestion of bean carbohydrates have not been conclusively demonstrated; however, the mechanism given above appears to be the most likely explanation. Shurpalekar *et al.* (1979*b*), however, reported that incorporation of carbohydrates prepared from different legumes as a sole source of carbohydrates promoted growth at a rate comparable with that shown by corn starch.

Rao (1976) studied *in vivo* digestibility of carbohydrates in children (aged between 3 and 4 years) by measuring blood glucose content. The children were given daily morning test meals of equal quantities of green gram and/or Bengal gram for 1 week. The peak blood glucose levels were reached with green gram at the end of 30 min and, in the case of Bengal gram, at the end of 60 min. This further supports the *in vivo* observation that carbohydrates in green gram are more rapidly digested and more easily available than those in Bengal gram and other legumes. The lower digestibility of the legume carbohydrates may be due to the presence of carbohydrates other than starch.

TABLE 10
In Vivo Digestibility of Raw and Cooked Legume Starches

Legume starches	*Digestibility coefficient (%)*	
	Raw	*Cooked*[a]
Wrinkled field pea	96·9	96·5
Smooth field pea	99·9	99·7
Navy bean	99·8	99·5
Kidney bean	99·6	99·5
Bengal gram	99·8	99·7
Green gram	99·9	99·5
Lentil	99·9	99·7

[a] Starches were cooked in a stainless steel steam-jacketed pressure kettle at 121 °C for 15 min and spray dried.
Source: Fleming & Vose (1979).

Fleming & Vose (1979) and Fleming (1982*a*) investigated the *in vivo* digestibility of starches from several legumes. They estimated *in vivo* starch digestibility by determining the starch content of the rat caecum and compared this with wheat starch (100 % digestible). Starches from all legumes, excluding the high amylose wrinkled pea, were nearly 100 % digestible (Table 10). However, these legume starches reduced the digestibility of casein protein by 3 to 4 %. They (Fleming & Vose, 1979; Fleming, 1982*a*) further reported that various methods of cooking and drying do not improve starch digestibility. This is an apparent contradiction to *in vitro* studies.

Dietary carbohydrate availability from legumes can also be measured by slope-ratio analysis of weight gain and plasma ketones of rats (Karimzadegan *et al.*, 1979). It was found that the apparent availabilities of the carbohydrates (i.e. nitrogen-free extract) in soybean meal, lima bean and Bengal gram, respectively are 35, 70 and 80 %.

FLATULENCE PROBLEM

Cause of flatulence

Ingestion of large quantities of beans is known to cause flatulence in humans and animals. Accumulation of flatus in the intestinal tract results in discomfort, abdominal rumblings, cramps, pain, diarrhea, etc. A number of excellent papers and reviews have been published on flatus and flatus formation (Alvarez, 1942; Berk, 1968; Calloway & Murphy, 1968; Calloway, 1973; Levitt, 1972; Cristofaro *et al.*, 1974; Hellendoorn, 1969, 1973, 1976; Rackis, 1975; Olson *et al.*, 1975, 1981; Rabkin & Silverman, 1979). The oligosaccharides of the raffinose family of sugars (raffinose, stachyose, and verbascose) from beans have been identified as one of the important contributors to flatus in humans and experimental animals (Cristofaro *et al.*, 1973; Murphy *et al.*, 1972). Members of the raffinose family of sugars are not digested by man because the intestinal mucosa lack the hydrolytic enzyme α-1,6-galactosidase (Gitzelmann & Aurricchio, 1965) and the raffinose family sugars themselves are unable to pass through the intestinal wall (Cristofaro *et al.*, 1974; Rackis, 1975). The microflora in the lower intestinal-tract then metabolize these oligosaccharides and produce large amounts of carbon dioxide and hydrogen and small quantities of methane in the process; the pH is also lowered (Cristofaro *et al.*, 1974; Rackis, 1975; Anderson *et al.*, 1979; Olson *et al.*, 1981; Rackis, 1981).

The varying quantitites of the raffinose family of oligosaccharides (Table 1) in different dry beans may cause differing degrees of flatulence. However, removal of these oligosaccharides from beans does not completely eliminate the flatus-producing capacity of dry beans (Table 11). Recent studies clearly indicate that, even after oligosaccharide removal, dry beans can still induce appreciable flatus (Wagner *et al.*, 1976, 1977; Olson *et al.*, 1975, 1982; Fleming, 1981, 1982*b*; Hellendoorn, 1976, 1979; Kamat & Kulkarni, 1981). The active compound(s) in the residue and/or extracted beans causing flatulence have not yet been identified but they are presumably distinct from the raffinose family of sugars. Olson *et al.* (1975) and Van Stratum & Rudrum (1979) reported that the protein-rich fractions from California Small White beans and soybeans could not significantly contribute to flatulence in rats and humans. This means that the active substances (causing flatulence) in the residue are compounds other than proteins and the raffinose family of

TABLE 11
Flatulence Activity of Oligosaccharide-Free Bean Residues by Rat Bioassay

Beans	*Diet (g per feeding)*	*Per cent beans in diet*	*Hydrogen produced*	*Reference*
CSW beans				
Basal diet	10·0	0·0	0·7–1·0 ml	Olson *et al.* (1982)
Whole beans	10·0	40·0	6·6 ml	Wagner *et al.* (1976)
Oligosaccharide-free residue	10·0	40·0	3·7–5·2 ml	
Extracted beans[a]	10·0	21·3	4·3 ml	
Light kidney beans				
Whole beans	10·0	25·0	8·3 ml	Olson *et al.* (1982)
Extracted beans[a]	10·0	20·4	3·5 ml	
Baby lima beans				
Whole beans	10·0	25·0	9·4 ml	Olson *et al.* (1982)
Extracted beans[a]	10·0	21·3	3·3 ml	
Smooth peas				
Basal diet	3·0	0·0	31·5–47·5 μmoles	Fleming (1982*b*)
Whole bean	3·0	66·7	171·4 μmoles	
Sugar-free residue	3·0	66·7	78·7 μmoles	

CSW = California Small White beans.
[a] Extracted CSW, light kidney, and baby lima beans contained 5·3 %, 15·2 % and 6·3 %, respectively of the original concentrations of the raffinose family of oligosaccharides.

sugars. Fiber or roughage is one of the major undigestible components of the bean residue, which may be involved in the fermentation by microorganisms and subsequent flatulence production (Hellendoorn, 1976, 1979; Kamat & Kulkarni, 1981). Fiber is primarily composed of structural polymeric materials including cellulose, hemicelluloses and lignin. Tadesse & Estwood (1978) have reported that a hemicellulose preparation increases hydrogen production in man, while cellulose, lignin and pectin do not. Further research is needed to understand the possible rôle of fiber in flatus formation and its fate in the intestinal tract.

Several methods have been employed to measure flatus in humans and animals. Hedin & Adachi (1962) developed a routine procedure for assessing the magnitude and composition of intestinal gases following ingestion of experimental diets. In their method, stomach and intestine segments were analyzed at various intervals to determine gas production

TABLE 12
Flatulence Activity of Various Beans by Rat Bioassay

Beans	*Diet (g per feeding)*	*Per cent beans in diet*	*Flatulence activity (H_2 produced per feeding)*	*Reference*
Basal diet	3·0	0·0	42·1 μmoles	Fleming (1980, 1981)
Navy beans	3·0	66·7	105·5–147·4 μmoles	
Kidney beans	3·0	66·7	133·4 μmoles	
Red kidney beans	3·0	66·7	157·9 μmoles	
Garbanzo beans	3·0	66·7	95·9 μmoles	
Mung beans	3·0	66·7	82·0 μmoles	
Wrinkled pea	3·0	66·7	117·6 μmoles	
Smooth pea	3·0	66·7	86·4 μmoles	
Green lentil	3·0	66·7	66·3 μmoles	
Basal diet	12·0	0·0	1·6 ml	Reddy *et al.* (1980)
Black gram (whole)	12·0	50·0	22·9 ml	
Black gram (cotyledons)	12·0	50·0	16·6 ml	
Great Northern beans (whole)	12·0	50·0	17·7 ml	Sathe & Salunkhe (1981*b*)
Basal diet	10·0	0·0	1·0 ml	Olson *et al.* (1982)
CSW[a] beans	10·0	25·0	9·0 ml	
Light kidney beans	10·0	25·0	8·3 ml	
Baby lima beans	10·0	25·0	9·4 ml	

[a] CSW = California Small White beans.

patterns. They showed that gas was formed in the intestines 1–8 h after feeding. Calloway *et al.* (1966) and Calloway & Murphy (1968) suggested a method for measuring flatulence in humans. Their method involved analysis of breath samples for hydrogen and methane. They were able to correlate measurements of hydrogen and methane in expired air with intestinal gas production. Their theory was based on the assumption that most of the intestinally produced hydrogen and methane diffuses into the intestinal lumen and blood, from where it is transported to the lungs and released in the expired air. Levitt & Ingelfinger (1968) used an intubation technique to measure the hydrogen and methane, which were produced in the colon of an experimental person following ingestion of a fermentable carbohydrate. They related the hydrogen and methane produced in the colon to fermentable carbohydrate. Most of the *in vivo* methods dealing with humans and animals do not permit a measure of total gas volume and are expensive, especially the methods involving humans.

Gumbmann & Williams (1971) developed an *in vivo* rat bioassay method for flatus measurement after feeding with various bean diets. The method involved the use of a life-support system in which hydrogen evolved from bacterial fermentation in the intestines of a rat is collected for a period of 20 h or more and quantitatively determined by gas chromatography. In this system, carbon dioxide is continuously removed by soda lime and replaced by oxygen. They interpreted the amount of hydrogen produced by the rat following ingestion of a test diet as an indication of total flatus. In the life-support system, the amount of hydrogen evolved by rats increases with increasing consumption of beans. As an example, a typical dose–response curve between the cooked bean cotyledons and hydrogen produced by rats can be seen in Fig. 1 (Reddy *et al.*, 1980). Using bean diets, Wagner *et al.* (1977) found a positive significant correlation between hydrogen production in the rat and flatulence in man and proposed that such a relationship could be used for predicting the flatus potential of legumes and legume products. Recently, Fleming (1980) modified the method of Gumbmann & Williams (1971) by replacing anhydrous calcium sulfate with dry ice and soda lime with granulated calcium hydroxide in order to collect and measure hydrogen and methane gases produced by the rat. This modification allows the quantitative measurement of methane which was not possible in the earlier method of Gumbmann & Williams (1971).

The flatulence potential of various bean products in rats, humans and pre-school children is presented in Tables 12 and 13. Data related to

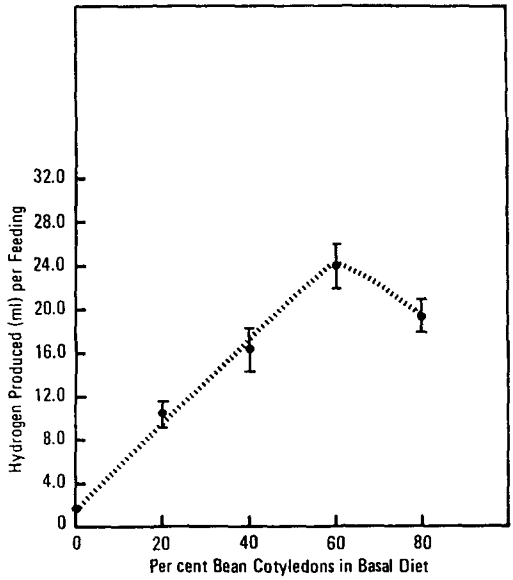

Fig. 1. Dose–response relationship between bean cotyledons and hydrogen produced by rats. Vertical bars indicate standard errors (SE). (Source: Reddy *et al.*, 1980.)

flatulence activitity of several beans are pooled from various sources. Fleming (1980, 1981, 1982) reported the flatulence activity of bean (navy, kidney, red kidney, garbanzo and mung beans; smooth and wrinkled peas and green lentil) products in μmoles based on a 3·0 g diet containing 66·7 % beans. Others (Reddy *et al.*, 1980; Olson *et al.*, 1982; Sathe & Salunkhe, 1981*b*) reported the flatulence activity of black gram, Great Northern beans, California Small White beans, light red kidney, and baby lima beans in millilitres of hydrogen produced per feeding based on a 10–12·0 g diet containing various proportions of bean products. Mung beans and green lentils seem to be less flatulent than others.

Flatus experiments on humans and pre-school children are much more difficult to execute than those on animals. Results obtained depend in part on the physical state and psychological attitude of the subject. Therefore, interpretation of results is difficult and can lead to inaccurate conclusions. In humans, a basal diet produced an average of 13 ml of flatus per hour (Table 13). Soy flour diets are less flatulent than are navy bean diets. The latter caused an average of 179 ml of flatus per hour and the former an average of 30–71 ml of flatus per hour in man. Geervani & Theophilus (1981) studied the flatus inducing effect of processed legumes in pre-

TABLE 13
Flatulence Activity of Various Processed Bean Products in Adults and Pre-School Children

Bean preparation	*Grams in basal diet*	*Flatus (ml/h)*	*Range (ml/h)*
		Adults[a]	
Basal diet	—	13	0–28
Full fat soy flour	146	30	0–75
Defatted soy flour	146	71	0–290
Navy bean meal	146	179	5–465
		Pre-school children[b]	
Basal diet	—	19·0	—
Red gram cotyledons (boiled)	40	48·0	—
Bengal gram cotyledons (boiled)	40	44·0	—
Bengal gram cotyledons (roasted)	40	58·0	—
Bengal gram whole (boiled)	40	52·0	—
Green gram cotyledons (boiled)	40	30·0	—
Green gram whole (germinated and boiled)	40	29·0	—

[a] Steggerda *et al.* (1966).
[b] Geervani & Theophilus (1979).

school children (age group of 4 to 5 years old). The mean volume of flatus in pre-school children produced by basal diet is about 19 ml per hour (Table 13), which is less than the flatus produced by diets containing various processed beans. The flatus-inducing capacities of green gram preparations were lower compared with red gram and Bengal gram preparations. Roasting of Bengal gram cotyledons caused more flatus in pre-school children than with boiling. Several investigators (Richards *et al.*, 1968; Rockland *et al.*, 1969; Rackis *et al.*, 1970; Kurtzman & Halbrook, 1970; Sacks & Olson, 1979) have implicated spore-forming clostridia (*Clostridium perfringens*) in flatus formation.

Means of overcoming the flatulence problem

Various approaches have been suggested in order to decrease the flatulence-causing factors of food legumes. Conceivably, special legume varieties with low levels of the raffinose family of oligosaccharides can be developed by genetic manipulation. Murphy (1973) reviewed the possibility of eliminating the flatulence effect by genetic selection, and examined a number of bean varieties for flatulence activity. Kidney, pinto and California Small White beans essentially had the same flatulence activity, while a sample of 'Pike's Jacobs Cattle bean' (*Phaseolus vulgaris* L.) showed less than half the flatulence activity of other beans (kidney, pinto and CSW beans). A variety of lima bean (fordhook) (*Phaseolus vulgaris* L.) was found to give a non-flatulent dry bean. Degree of maturity of seed also influences the flatulence activity. For example, the immature green seeds are non-flatulent compared with dry mature seeds (Murphy, 1973).

Several researchers (Richards & Steggarda, 1966; Kakade & Borchers, 1967; Steggarda, 1968) have demonstrated that *in vitro* and *in vivo* flatus production can be inhibited by antibiotics (penicillin and streptomycin) and bacteriostat (iodochlorhydroxyquin) when given along with the leguminous seed preparations. Essentially, these antibiotics inhibit the intestinal microflora activity and subsequently flatulence-causing compounds will be eliminated intact. The addition of these compounds to foods should not be considered as an acceptable or routine practice for the prevention of flatulence in normal human subjects. Further, addition of these compounds to beans may change their organoleptic properties and make them unacceptable. However, use of antibiotics in legume foods may have limited medical application when special diets are required.

Raffinose, stachyose and verbascose are soluble in water. Therefore, soaking beans in water and then discarding the water will remove most of these sugars from beans. Various investigators reported a reduction in the raffinose family of sugars from several beans as a result of soaking: 90·6 % and 88·1 %, respectively in black eye and pink beans (Silva & Luh, 1979), 32·8–51·0 % in Great Northern, kidney, and pinto beans (Iyer *et al.*, 1980), and 45–80 % in black gram cotyledons (Iyengar & Kulkarni, 1977).

Discarding cook-water also reduces the raffinose family of sugars in beans. Usually soaking of beans precedes cooking. Ku *et al.* (1976) reported that boiling soybeans in a 1:10 bean/water ratio removed 33–59 % of the raffinose family of sugars depending on the time in the initial soaking water. Reduction in the raffinose family of oligosaccharides has been observed in Great Northern, kidney and pinto beans after soaking in distilled water and cooking for 90 min at 100 °C (Iyer *et al.*, 1980). The decrease was about 70·3–80·2 % when both soak and cook water were discarded. Iyengar & Kulkarni (1977) reported 60·8, 69·4, 66·2

TABLE 14
Effects of Germination on Oligosaccharides of the Raffinose Family of Sugars

Legume	*Germination (h)*	*Per cent oligosaccharides hydrolyzed*	*References*
Green gram (Var. T_1)	96	93·6	Gupta & Wagle (1980)
Black gram (Var. M_{1-1})	96	93·1	Gupta & Wagle (1980)
Black gram	48	100·0	Reddy & Salunkhe (1980)
Navy bean	96	78·6	Snauwaert & Markakis (1976)
Blackeye bean	96	100·0	Silva & Luh (1979)
			Labaneiah & Luh (1981)
Pink bean	96	100·0	Silva & Luh (1979)
Red kidney bean	96	89·5	Labaneiah & Luh (1981)
Red gram	72	87·8	Rao & Belavady (1978)
	48	76·2	Jaya & Venkataraman (1981)
Bengal gram	72	88·6	Rao & Belavady (1978)
Phaseolus mungoreus (cross between black gram and green gram)	96	91·5	Gupta & Wagle (1980)

and 72·2% reduction in the oligosaccharides in red gram, Bengal gram, green gram and lentil, respectively, after cooking. Removal of oligosaccharides from beans during cooking is primarily due to leaching (discarding of soak and cook water) (Reddy & Salunkhe, 1980).

A combination of various treatments can also be used to remove oligosaccharides from whole dry beans. About 70% of the raffinose plus stachyose were removed from soybeans by a combination of various treatments (pH adjustment, soaking and germination) (Kim *et al.*, 1973). Olson *et al.* (1981, 1982) recently developed a boil–soak method for removing the sugars from dry beans. Whole beans were boiled for 3–4 min (in 5–10 times their weight of water) and then allowed to cool and stand in the same water for 16 h at room temperature. During this time most of the oligosaccharides diffused into the soak water which was then discarded in order to minimize the flatulence potential. By this method over 90% of the raffinose family of sugars were removed from various beans (CSW, light red kidney, baby lima, garbanzo, soy, pinto, large lima, black eye, and Jacob cattle beans).

Published data (Table 14) indicate that over 70% of the raffinose family of sugars can be removed from several dry beans by germination. Depletion of these sugars during germination leads to subsequent reduction in flatulence activity of the germinated beans (Reddy *et al.*, 1980). In contrast, others (Shurpalekar *et al.*, 1973; Calloway *et al.*, 1971; Venkataraman & Jaya, 1975; Geervani & Theophilus, 1979) reported that sprouting of green gram, cowpeas, chickpea, CSW beans and soybeans did not alter their flatus-inducing property, when tested along with basal diets in experimental animals and humans.

Fermentation is also used to prepare legume-based foods (Reddy *et al.*, 1982). Fermentation improves organoleptic properties and the nutritional quality of the legume-based food and also reduces or eliminates some of the flatulence-causing compounds from beans. For example, in tempeh, most of the flatulence-causing sugars disappear after 72 h of fermentation (Shallenberger *et al.*, 1967).

Several groups (Sugimoto & Van Buren, 1970; Rohm and Haas Company, 1972; Delente *et al.*, 1974) have developed enzymatic processes using exogenous microbial sources of α-galactosidases to degrade the raffinose family of sugars in bean products. So far there has been little success because of hydrolysis, final product acceptability, high cost and/or questionable effectiveness in reducing flatulence. Reynolds (1974) developed an immobilized α-galactosidase continuous flow reactor for application to water extracts of beans containing the raffinose family of sugars. About 47·2–65·8 % of the sugars can be hydrolyzed in soymilk by incubating it with the undisrupted mycelium of *Mortieralla vinacea* at 5 °C for 6 h (Thananukul *et al.*, 1976). Goel & Verma (1980) reported that

TABLE 15

Autolysis of Oligosaccharides of the Raffinose Family of Sugars in Legumes[a,b]

Legume	*Autolysis (h)*	*Per cent oligosaccharides hydrolyzed*
CSW bean	48	79·0
Great Northern bean	48	65·4
Green gram	48	61·1
Red kidney bean (Royal)	48	63·6
Soybean (Yellow Lee)	48	95·4
Red Mexican bean	24	37·8

CSW = California Small White beans.

[a] Data from Olson *et al.* (1975).

[b] Five grams of ground bean powder (20 mesh) shaken with 50 ml 0·1 M sodium acetate buffer (pH 5·20) for 2 h at 25 °C then incubated at 45 °C with shaking.

most of the oligosaccharides are removed from green gram, black gram and lentils by fermenting them with either *Leuconostoc mesenteroides* or *Lactobacillus acidophilus*.

Kon *et al.* (1973); Becker *et al.* (1974); Wagner *et al.* (1975) and Olson *et al.* (1975) optimized the conditions for the endogenous bean α-galactosidase to hydrolyze the raffinose family of sugars in various beans and bean products. Under their conditions, 37·8–95·4% hydrolysis of these sugars occurred when several types of bean were incubated for 24–48 h at 45 °C (Table 15). Those investigators also observed that the rate of hydrolysis in dry beans (*Phaseolus vulgaris* L.) was slower than for soybeans. Various extraction methods (Murphy *et al.*, 1964; Calloway *et al.*, 1971; Rackis, 1975; Sathe & Salunkhe, 1981*a*, *b*) and membrane filtration techniques (Omosaiye *et al.*, 1978) have been employed to eliminate much of the flatus-causing factors from beans.

Beneficial physiological activity of bean carbohydrates

Hellendoorn (1976, 1979) proposed several beneficial physiological actions by ingestion of cooked leguminous seeds. Dry beans are relatively high in fiber (non-digestible food components) compared with other foods (Chen & Anderson, 1981), and these may be physiologically beneficial. Fermentation of the non-digestible food components (mainly dietary fiber and oligosaccharides) by anaerobic bacteria in the intestine gives rise to gas formation and to the formation of lactic acid and volatile fatty acids (VFA). These acids are reported to promote rapid intestinal transit of faeces and a more bulky, softer stool (Hellendoorn, 1978, 1979). Lack of fiber in the western diet is believed to result in constipation, and to be a main factor in the appearance of diverticular and colon-related diseases. Hellendoorn (1969, 1973, 1976, 1978, 1979) suggested that the ingestion of appreciable amounts of beans along with other foods eases or relieves constipation, and other colon related diseases.

Experiments with rats (Hellendoorn, 1969) demonstrated a reduction in transit time of the food residue through the bowel after ingestion of beans. Results of her experiments are presented in Table 16. The beans were soaked overnight, and cooked or retorted in the soaking water. The food containing 15 or 30% of beans (each percentage replacing an equivalent amount of wheat starch) was transported more quickly through the intestine of the rats than the control (wheat starch). Velocity of bowel transit was highest with beans cooked for only 5 min and given

TABLE 16
Transit Times of Food in Rats, While on a Bean Ration[a]

Rations	*Average transit time (min) of food with:* 30% beans	15% beans
Unheated beans	260	270
Beans heated to boiling	271	284
Beans cooked for 5 min	211	249
Beans cooked for 10 min	222	249
Beans cooked for 30 min	233	250
Beans cooked for 60 min	232	255
Beans retorted at 120 °C for 120 min	251	266
Control (without beans)	303	325

[a] Hellendoorn (1969).
[b] All beans were of good cooking quality and soaked overnight.

in the higher concentration (Table 16). With rats, other researchers (Rao & Desikachar, 1964; Saraswathi & Shurpalekar, 1981) also observed a reduction in transit time of the food residue through the bowel and more bulky and softer stools after ingestion of beans (Bengal gram, black gram, field beans and soybeans). Similar results were noted by Rao & Desikachar (1964) when boys (16–17 years of age) were fed various legume preparations.

CONCLUSIONS

Dry beans supply significant amounts of protein and calories for both rural and urban populations of underdeveloped countries. These beans contain up to 60% carbohydrates (mainly starch). Oligosaccharides of the raffinose family of sugars are one of the flatus-producing factors found in legumes. Substantial amounts of flatus-producing components from beans can be eliminated by various common processes (soaking, cooking and discarding the cook water, germination, fermentation and a combination of the aforementioned processes) and addition of antibiotics or bacteriostats to bean products.

Starch granule microheterogeneity affects food functional attributes which are related, in turn, to molecular weight, gelatinization temperature, and granule size distribution. Information on size distribution is essential to assist in understanding structure–function relationships. Also, such information as that listed above should lead to improved comprehension of certain starch properties such as gelation, gelatinization, water-holding capacity, swelling and solubility.

Judging from the literature, *in vitro* digestibility appears to be consistently lower than *in vivo*. The reasons for this phenomenon, to our knowledge, remain unknown.

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