Carbohydrate fractions of legumes: uses in human nutrition and potential for health

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Starch and fibre can be extracted, using wet or dry processes, from a variety of grain legumes and used as ingredients for food. α-Galactosides can be isolated during wet processes from the soluble extract. Starch isolates or concentrates are mostly produced from peas, whereas dietary fibre fractions from peas and soyabean are commercially available. The physico-chemical characteristics of fibre fractions very much depend on their origin, outer fibres being very cellulosic whereas inner fibres contain a majority of pectic substances. Inner fibres are often used as texturing agents whereas outer fibres find their main uses in bakery and extruded products, where they can be introduced to increase the fibre content of the food. Most investigations on impacts on health have been performed on soyabean fibres. When positive observations were made on lipaemia, glucose tolerance or faecal excretion, they were unfortunately often obtained after non-realistic daily doses of fibres. Legume starches contain a higher amount of amylose than most cereal or tuber starches. This confers these starches a lower bioavailability than that of most starches, when raw or retrograded. Their low glycaemic index can be considered as beneficial for health and especially for the prevention of diseases related to insulin resistance. When partly retrograded, these starches can provide significant amount of butyrate to the colonic epithelium and may help in colon cancer prevention. α-Galactosides are usually considered as responsible for flatus but their apparent prebiotic effects may be an opportunity to valorize these oligosaccharides.

Legumes: Dietary fibre: Starch: α-Galactosides: Human nutrition: Fractionation

Introduction

Grain legumes are considered to be good for health due to their mutual compatibility with cereals and for their properties in disease prevention, including cardiovascular diseases, type 2 diabetes, obesity and, possibly, colon cancer. The nutritional potential of the seeds from this group of plants is based on their high level of protein and, depending on species, a high proportion of either starch or oil (Table 1). Along with macronutrients, leguminous seeds contain appreciable amounts of some vitamins and minerals as well as dietary fibre. The most common legumes for human consumption are bean, lentil, pea, chickpea and faba bean. Most grain legumes are consumed after simple processing, as vegetables, salads, soups, mashed and cooked seeds.

However, grain legume seeds can be fractionated to obtain protein and starch concentrates and isolates, and as a by-product of the process, dietary fibre. Starch, protein and dietary fibre are indeed the main fractions of most European grain legumes, the main exceptions being lupin and soya, which are both rich in fat (Table 1).

Fractions isolated from grain legumes can be used in the food-processing industry as simple ingredients, technofunctional ingredients or additives. Apart from these technological interests, we wonder whether such products could have real nutritional properties for humans.

Dietary fibre content varies according to the species, the variety and processing of legume seeds. In most grain legumes consumed as pulses by humans, the content ranges from 8 to 27.5 %, with soluble fibre in the range 3.3–13.8 %. Dietary fibre, or cell wall material, content in the cotyledon of legume seed is generally low compared to that of the testa. Indeed, the cell walls accounted for about 90 % of the testa dry weight.

Brillouet & Carré (1983) reported values of dietary fibre contents for pea, broad pea and soyabean cotyledons in the range 6.9–9.3 % (on a dry weight basis). Lupin species

Abbreviations: ACF, aberrant crypt foci; GI, glycaemic index; RS, resistant starch; SCFA, short-chain fatty acid.

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have a special position within the *Leguminosae* family by containing a high amount of cell wall material in the cotyledons (in the range 7·5–32·1 %) in the form of rather thick cell walls (Brillouet & Riochet, 1983). This could ascribed to the high amount of galactans stored in the cell walls.

Starch content varies between genera, from negligible amounts in *Glycine max* to half the dry seed weight in a wild-type, round-seeded, pea (*Pisum sativum*) (Table 1). Mutations that affect the activities of enzymes of the starch biosynthetic pathway can profoundly affect not only starch content but also its composition. For instance, in the pea, which is one of the species that has been extensively genetically manipulated, mutations at the *r* locus, which encodes starch-branching enzyme I, reduce starch content to 30 % of dry weight and reduce the amylopectin which encodes starch-branching enzyme I, reduce starch content, whereas those at rug3, which encodes plastidial phosphoglucomutase, can completely eliminate starch (Casey, 1998).

α-Galactosides are oligosaccharides which are not digested in the upper part of the gastrointestinal tract, due to the absence of *α*-galactosidase among human endogenous enzymes, and are therefore available for bacterial fermentation in the colon. Overall α-galactoside content is within the range of 2–10 g/100 g dry matter, and stachyose is the prevalent oligosaccharide in most pulses (*Phaseolus vulgaris, Pisum sativum, Lens esculenta,* etc.) (Table 2). Lupin seeds seem to contain the highest concentration of α-galactosides among grain legume species. In faba beans, mung beans, pigeon pea, and some varieties of chickpeas, verbascose is the main oligosaccharide in the cell walls. Raffinose is present in significant amounts in lupin seeds (0·3–2·0 g/100 g) (Reddy *et al.* 1984). The α-galactoside content of soyabean is quite similar to that of most pulses; for example, raffinose, stachyose and verbascose comprise 0·7–1·3, 2·2–5·4 and 0·0–0·3 %, respectively, of seed dry matter (Reddy *et al.* 1984).

### Fractionation of grain legumes

Dry and wet separation processes have been used to fractionate grain legumes for experimental purposes but also for industrial applications (Kozlowska *et al.* 1998; Czukor *et al.* 2001). Wet separation processes are used to produce high-purity protein isolates while dry separation results in enriched fractions.

In conventional wet process, for food applications, the hulls are removed because they can contain antinutritional compounds that can be released during the extraction process. The dehulled seeds are pen milled and the legume flour is pulped with an aqueous decomposing agent (generally alkaline solution) for extracting protein (Colonna *et al.* 1981; Gueguen, 1983; Sosulski & McCurdy, 1987). The proteins are isolated from this extract by acidic precipitation or by ultrafiltration. The wet protein isolates are then dried. The liquid phase contains the α-galactosides as well as many other soluble contaminants. These oligosaccharides can be further isolated in 80 % ethanol. The solid phase left after protein separation is suspended in water and is screened through a series of sieves (Schoch & Maywald, 1968; Colonna *et al.* 1981). The starch is recovered from the under flow fraction, with the fraction rich in cell wall material remaining on the screens. The starch isolate contains 0·04–0·40 % protein, less than 4 % of cell wall material and about 0·1–1·0 % of lipid as impurities. The fibre fraction contains small amounts of proteins (4–8 %) and lipids (0·5–1·5 %).

The ‘dry’ process consists in disintegration of the dehulled seeds on pill mill and air classification into starch and protein fractions (Sosulski, 1979; Colonna *et al.* 1980; Taylor *et al.* 1981; Sosulski *et al.* 1985; Sosulski & McCurdy, 1987). The starches and dietary fibre are concentrated mostly in the light, fine fraction, and the proteins and lipids, in the heavy, coarse one. Dry processes have been carried out more successfully with grain legumes, where starch is the main storage compound rather than oil. The main advantages of air classification

### Table 1. Chemical composition (g/100 g dry matter) of some legume seeds (from Bagger *et al.* 1998)

<table>
<thead>
<tr>
<th>Legume seed</th>
<th>Protein (N × 6·25)</th>
<th>Crude fat</th>
<th>Dietary fibre</th>
<th>Starch</th>
<th>Sucrose</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Vicia faba</em></td>
<td>26–34</td>
<td>2–4</td>
<td>15–24</td>
<td>40–50</td>
<td>2·1–2·3</td>
</tr>
<tr>
<td><em>Pisum sativum</em></td>
<td>23–31</td>
<td>2–3</td>
<td>15–21</td>
<td>20–50</td>
<td>0·7–5·7</td>
</tr>
<tr>
<td><em>Lupinus luteus</em>, <em>L. angustifolius</em>, <em>L. albus</em></td>
<td>33–42</td>
<td>4–12</td>
<td>25–40</td>
<td>1–2</td>
<td>1·5–3·6</td>
</tr>
<tr>
<td><em>Glycine max</em></td>
<td>38–42</td>
<td>18–22</td>
<td>7–15</td>
<td>1–2</td>
<td>4·7–7·6</td>
</tr>
</tbody>
</table>

### Table 2. Amount of α-galactosides in the main pulse species compared to a single main source (% dry matter)*

<table>
<thead>
<tr>
<th>Legume seed</th>
<th>Phaseolus vulgaris</th>
<th>Lens esculenta</th>
<th>Cicer arietinum</th>
<th>Pisum sativum</th>
<th>Vicia faba</th>
<th>Lupinus albus</th>
<th>Glycine max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raffinose</td>
<td>&lt;0·05–0·93</td>
<td>0·3–1·0</td>
<td>0·4–1·2</td>
<td>0·3–1·6</td>
<td>0·1–0·3</td>
<td>0·5–1·1</td>
<td>0·5–1·3</td>
</tr>
<tr>
<td>Stachyose</td>
<td>0·5–4·1</td>
<td>1·7–5·1</td>
<td>2·0–3·6</td>
<td>1·3–5·5</td>
<td>0·7–1·5</td>
<td>0·9–7·4</td>
<td>2·2–4·3</td>
</tr>
<tr>
<td>Verbascose</td>
<td>0·06–4·0</td>
<td>0·6–3·1</td>
<td>0·6–4·2</td>
<td>1·6–4·2</td>
<td>1·7–3·1</td>
<td>0·6–3·4</td>
<td>0·0–0·3</td>
</tr>
<tr>
<td>Total</td>
<td>2·6–6·6</td>
<td>3·0–7·1</td>
<td>7·4–7·5</td>
<td>5·1–8·7</td>
<td>3·1–4·2</td>
<td>7·4–9·5</td>
<td>2·6</td>
</tr>
</tbody>
</table>

are reduced energy and water consumption. However, all fractions, and especially protein fractions, are contaminated by α-galactosides (Sahasrabudhe et al. 1981).

Because legumes have a variety of characteristics and differ, for example, in oil content, some modifications of the standard procedures have been adopted for optimizing the process for a particular legume (Nickel, 1988; Czuchajowska & Pomeranz, 1994; Kovacs, 1996; Krikken, 1999; Dijkink & Langelaan, 2001).

Physical and chemical characteristics of fibre and starch fractions and derivatives
The chemical structure and physico-chemical properties of starch and fibre are important for functional behaviours in food use and for diet-related health effects. Depending on the application, the use of enriched fractions may be a good alternative to high-purity isolates.

Fibre fractions
The properties of dietary fibre that influence their technofunctionality are the fibre dimensions, porosity, hydration, rheological and fat-binding properties. The colours and flavour are also of importance.

Dietary fibre preparations commercially available arise mainly from pea and soya from either the cotyledons (inner) or from the hulls (outer) (Table 3). Preparations are generally richer in dietary fibre when obtained from hulls. Indeed, preparations from cotyledons contain variable amounts of starch and protein. Inner-fibre fractions exhibit higher water retention capacity than outer fibres (Table 4). Oil-binding capacity is in the same range for both inner and outer fibres (Table 4). Inner fibres are smooth, while outer fibres have a sandy character. The inner fibre products are, in general, in the form of powder low in odour and flavour (Table 4). The outer fibres are generally available at different particle sizes. They are generally light in colour and flavour (Table 4).

Processing can be applied to improve the functional characteristics of fibre. For example, a mixture of cellulase and carboxydrase has been applied to improve the sensory properties, including the mouth-feel characteristics and smoothness of the soya fibre material (Lin Santa et al. 1996).

The composition of the dietary fibre fraction depends very much on its localization in the seed coat (outer fibre) or the cotyledons (inner fibre) (Table 5). A major difference between the inner and outer dietary fibre is the relative content of cellulosic and non-cellulosic polysaccharides. The cell walls of the cotyledons contain a range of polysaccharides, including pectic substances (about 55%), cellulose (about 9%) and non-starch non-cellulosic glucans (in the range 6–12%: Brillouet & Carré, 1983; Brillouet & Riochet, 1983; Al-Kaisey & Wilkie, 1992; Petterson, 1998; van Laar et al. 1999, 2000), while the seed coat contains large quantities of cellulosic (ranging from 35 to 57%) and lower amounts of hemicelluloses and pectins (Brillouet & Riochet, 1983; Weightman et al. 1994; van Laar et al. 1999). The cell walls from the cotyledons are non-lignified.

Testa from pea and lupin species have been shown to contain a low amount of lignin. The concentrations reported were 6·6 mg/g for alcohol-insoluble residues from pea hull, and between 0·4 and 1·7% for hulls from various lupin species (Brillouet & Riochet, 1983; Weightman et al. 1994). The lignin values were unrelated to hull colour.

Starch fractions
Most starches from grain legumes have a relatively high amylose content compared to most starches (Table 6). As a consequence their X-ray diffraction pattern is type C, which is considered to be intermediate between types A and B (Gallant et al. 1992) (Table 6). However, wrinkled peas are known to exhibit a B-type X-ray diffraction pattern which is due to its high level of amylose (Table 6).

Legume starches are kidney-like or ovoid with well-defined shells centred along an elongated hilum. Some exceptions are also known, such as the compound starch granules of the wrinkled pea, in which spheropyramidal units are associated (Gallant et al. 1992). Enzymatically treated pea starches (C-type starch) exhibit a characteristic similar to B-type starches, which is the presence of highly resistant and large blocklets (4–500 nm diameter at the peripheral level of the granules). These blocklets would explain the resistance of B and C starch granules to hydrolysis (Gallant et al. 1992).

There is a much variability in amylose content among

| Table 3. Chemical composition of some commercial dietary fibres (dry basis, %) |
|------------------|------------------|------------------|------------------|
|                  | Pea              | Soyabean         | Lupin            |
|                  | Cotyledon*       | Cotyledon†       | Cotyledon*       |
|                  | Hull*            | Hull*            | Hull*            |
| TDF              | 55              | 80              | 80              |
| SDF              | 14              | 7               | 8               |
| Protein          | 17              | 13              | 15              |
| Lipid            | 0·5             | 0·2             | 0·5             |
| Available C      | 23              | nd              | 3               |
| Mineral          | 4               | 5               | 4               |

Available C, available carbohydrates; nd, not determined; TDF, total dietary fibre; SDF, soluble dietary fibre.
† Dubois et al. (1993).
genotypes of peas (Skrabanja et al. 1999). Indeed, the wild type contains 30% amylose whereas \( r b \) and \( r \) mutants, for instance, contain, respectively, 20 and 65% amylose (Bergthaller et al. 2001). According to Bergthaller et al. (2001), these same mutants differ widely in starch extractability from cotyledons in a wet milling process but also in the purity of the extracted starch, which varied from 85.3 to 97.5% (dry matter basis) for \( r \) and \( rug4 \) mutants. Temperatures of gelatinization do not seem to be significantly different from ‘normal’ cereal or potato starches, as they range between 55 and 97°C (Table 6).

The procedure of preparation of the starch can modify the characteristics of the initial starch present in the grain. Intense damaging of the starch granules can be observed in some industrial starches (Soral-Smietana et al. 2001b). As a consequence, commercial native starches may have different properties. Apparently, Gel-Flow (native pea starch from Parrheim Foods, Canada) crystallinity, estimated by X-ray diffraction, is lower from that of Nastar (native pea starch from Coscrua S.A., Belgium) (Soral-Smietana et al. 2001a,b). As a consequence, resistant starch (RS) contents of the native pea starches are different: 43 and 19%, respectively, for Nastar and Gel-Flow. The latter starch exhibited slightly higher water and oil adsorption capacities than the former (Soral-Smietana et al. 2001a,b).

Starch has also been isolated from chickpeas. One of the starches that has been isolated seems to have similarities with native maize starch, with a relatively high temperature of gelatinization (67°C), whereas another had a low temperature of gelatinization (60°C) (Meares et al. 2001). Ionic (cationic, anionic and amphoteric) pea starch derivatives have been developed to correspond to the demand of industries in various non-food applications. The introduction of ionic substituents into the starch molecules significantly affects their physico-chemical properties, such as gelatinization temperature, swelling characteristics, solubilization and iodine complexation (Lewandowicz et al. 2001).

\( \alpha \)-Galactosides

\( \alpha \)-Galactosides are derived from sucrose and contain 1–3 units of galactose linked by \( \alpha-1,6 \) linkages. They are highly soluble in aqueous media and very rapidly fermented by colonic microflora. The role of \( \alpha \)-galactosides seems to be multiple, as they are an energy source for the plant and disappear during germination. They are stored by seeds during the final stage of ripening when they dry. They seem to help protect against abiotic stresses such as cold and desiccation (Jones et al. 1998). Some agricultural factors seem to affect \( \alpha \)-galactoside content in faba bean seeds. For example, the concentration of stachyose and verbascose can decrease when optimal irrigation is applied (Szukala et al. 2001).

Soaking, the most common treatment for partial elimination of \( \alpha \)-galactosides from grains, becomes more efficient when bicarbonate is added, due to the greater

### Table 4. Properties of some commercial dietary fibres (from Ploertner & Fisher, 2001)

<table>
<thead>
<tr>
<th>Dietary fibre</th>
<th>Colour</th>
<th>Flavour</th>
<th>WRC</th>
<th>Oil retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotyledon Pea</td>
<td>White</td>
<td>Neutral beany</td>
<td>9–11</td>
<td>1·5–2·0</td>
</tr>
<tr>
<td>Soya</td>
<td>Light cream</td>
<td>Bland</td>
<td>7–8</td>
<td>4·0</td>
</tr>
<tr>
<td>Lupin</td>
<td>White</td>
<td>Nearly neutral</td>
<td>8–11</td>
<td>1·5–2·0</td>
</tr>
<tr>
<td>Hull Pea</td>
<td>Creamy white</td>
<td>Neutral</td>
<td>4–5</td>
<td>1·8–2·0</td>
</tr>
<tr>
<td>Soya</td>
<td>Light tan</td>
<td>Neutral nutty</td>
<td>3–5</td>
<td>1·4–1·7</td>
</tr>
<tr>
<td>Lupin</td>
<td>Creamy light</td>
<td>Neutral nutty</td>
<td>7–8</td>
<td>1·6–1·7</td>
</tr>
</tbody>
</table>

WRC, water retention capacity.
Main uses of fibre and starch fractions

Fibre fractions

Inner fibres are generally used as texturing or bulking agents. The high water-binding capacity, fat-binding and texturing effect allow the control of migration in food preparation by providing stability towards industrial manufacturing and storage processes as well as desirable texture. They may, in many cases, replace food additives, offering advantages such as a ‘clean labelling’. The dosage rate is 1–5 % of the final product weight. They are used in bread and baked goods, particularly biscuits. They can also be used to enrich mousses, jellies and drinks to provide tasty desserts. These could be part of the diet of dysphagic groups and other groups who might otherwise have low fibre intake. Outer fibre is used primarily to enrich the fibre content of food without modifying the technical properties of the end products. It finds applications in bakery and extruded products, snacks, cereals or diet specialities.

Starch fractions

Starch from peas is used in deep-frozen dishes, dressings, extruded bakery products, instant soups and puddings. It can also be used for non-food applications (the paper and board industry, detergent manufacture, water-treatment industry, textiles, plastics and pharmaceutical production), as it is the case for maize and potato starches (Kozlowska et al. 1998). The production of legume starches is still small compared to the overall production of starch, which is over 6 millions tonnes each year (Kozlowska et al. 1998). However, the characteristics of legume starches, and particularly their amylose content, offer a large potential for new applications, both in non-food uses and in human nutrition.

Wrinkled-pea starch seems to be favourable for the functional properties of bioplastics (Funke & Lindhauer 1994; Colonna et al. 1995). Legume starches also have potential in agrochemical and pharmaceutical industries as an encapsulation agent, binding material to make up tablets, or a disintegrating agent (Kozlowska et al. 1998). The nutritional potential of legume starches will be discussed below.

α-Galactosides

Due to their characteristics, it is highly probable that prebiotic properties of α-galactosides will be confirmed in the future, as has been demonstrated for fructooligosaccharides, for instance. These properties will be discussed below.

Is there a potential use of fibre and starch fractions for health?

There is a large literature on the nutritional aspects of grain legumes, including the digestibility of main nutrients (mainly proteins, starch and dietary fibre), colonic fermentation, post-prandial glycaemia and insulinaemia and some data on lipid metabolism. These observations are, for the most part, very positive and would tend to demonstrate that grain legumes should be promoted as part of a healthy diet. We wonder if such beneficial effects could be, at least

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<table>
<thead>
<tr>
<th>Species</th>
<th>X-ray diffraction pattern</th>
<th>Amylose content (% of starch)</th>
<th>Temperature of gelatinization (°C)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>B</td>
<td>66–72</td>
<td>55–125</td>
<td>Colonna &amp; Mercier (1985)</td>
</tr>
<tr>
<td>Wrinkled</td>
<td>C</td>
<td>33–35</td>
<td>95</td>
<td>Colonna &amp; Champ (1990)</td>
</tr>
<tr>
<td>Lens esculenta</td>
<td>C</td>
<td>23·9–27·8</td>
<td>60·1–67·3</td>
<td>Meares et al. (2001), Soral-Śmietana et al. (2001a)</td>
</tr>
<tr>
<td>Cicer arietinum</td>
<td>C</td>
<td>24</td>
<td>97</td>
<td>Duprat et al. (1980), Colonna &amp; Champ (1990)</td>
</tr>
<tr>
<td>Vicia faba</td>
<td>A</td>
<td>22·7</td>
<td>82–94</td>
<td>Colonna &amp; Champ (1990), Soral-Śmietana et al. (2001a)</td>
</tr>
<tr>
<td>Wheat</td>
<td>A</td>
<td>22·1</td>
<td>55–70</td>
<td>Colonna &amp; Mercier (1985), Soral-Śmietana et al. (2001a)</td>
</tr>
<tr>
<td>Maize (normal)</td>
<td>B</td>
<td>25·0</td>
<td>66–90</td>
<td>Colonna &amp; Champ (1990), Soral-Śmietana et al. (2001a)</td>
</tr>
<tr>
<td>Potato</td>
<td>B</td>
<td>25·0</td>
<td>66–90</td>
<td>Colonna &amp; Champ (1990), Soral-Śmietana et al. (2001a)</td>
</tr>
</tbody>
</table>

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Table 6. Some characteristics of legume starches compared to other common starches
<table>
<thead>
<tr>
<th>Source of dietary fibre</th>
<th>Patients or animals</th>
<th>Dose</th>
<th>Adaptation period</th>
<th>Results</th>
<th>Remarks</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Glucose response and tolerance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soya cotyledon fibre</td>
<td>Obese NIDDM patients</td>
<td>10 g/d</td>
<td>Post-prandial study</td>
<td>Improved glucose tolerance</td>
<td></td>
<td>Tsai et al. (1987)</td>
</tr>
<tr>
<td>Pea cotyledon fibre</td>
<td>Healthy subjects</td>
<td>33 g/d</td>
<td>2 weeks</td>
<td>No effect on glycaemic response</td>
<td>DF added to a normal diet</td>
<td>Sandström et al. (1994)</td>
</tr>
<tr>
<td>Soya hulls</td>
<td>Healthy subjects</td>
<td>26 g/d</td>
<td>30 d</td>
<td>Improved glucose tolerance</td>
<td>Lower PP insulin</td>
<td>Munoz et al. (1979)</td>
</tr>
<tr>
<td>Soya fibre (?)</td>
<td>NIDDM patients</td>
<td>26 g and 52 g/d</td>
<td>4 weeks</td>
<td>Improved glucose tolerance</td>
<td>Decreased fasting insulin (when 130 mg/100 ml at time 0)</td>
<td>Mahalik et al. (1984)</td>
</tr>
<tr>
<td></td>
<td>NIDDM patients</td>
<td>40 g/d</td>
<td>4 and 12 weeks</td>
<td>Improved glucose tolerance</td>
<td>Decreased fasting insulin (12 weeks)</td>
<td>Madar et al. (1988)</td>
</tr>
<tr>
<td>Lipaemia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soya cotyledon fibre</td>
<td>Hypercholesterolaemic patients</td>
<td>25 g/d</td>
<td>9 weeks</td>
<td>Lowering effect on cholesterol (total, LDL)</td>
<td>Decreased cholesterolaemia</td>
<td>Lo et al. (1986)</td>
</tr>
<tr>
<td>Obese NIDDM patients</td>
<td>10 g/d</td>
<td>Post-prandial study</td>
<td>No effect on cholesterol (total, LDL)</td>
<td>Decreased cholesterolaemia</td>
<td></td>
<td>Tsai et al. (1987)</td>
</tr>
<tr>
<td>Normocholesterolaemic, mildly or moderately hypercholesterolaemic patients</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tsai et al. (1983), Schweizer et al. (1983), Shorey et al. (1985), Lo &amp; Cole (1990)</td>
</tr>
<tr>
<td>Pea cotyledon fibre</td>
<td>Healthy subjects</td>
<td>33 g/d</td>
<td>2 weeks</td>
<td>Decreased fasting and PP plasma TG</td>
<td>Decreased fasting and PP plasma TG</td>
<td>DF added to a complex meal</td>
</tr>
<tr>
<td>Soya hulls</td>
<td>Healthy subjects</td>
<td>26 g/d</td>
<td>28–30 d</td>
<td>Decreased cholesterolaemia</td>
<td>Decreased cholesterol near normal plasma TG and TC</td>
<td>Typical American diet</td>
</tr>
<tr>
<td>NIDDM patients</td>
<td>52 g/d</td>
<td>4 weeks</td>
<td>Decreased cholesterolaemia</td>
<td>No effect on plasma TG and TC</td>
<td>Hypercholesterolaemic diet</td>
<td>Mahalik et al. (1984)</td>
</tr>
<tr>
<td>Rats</td>
<td></td>
<td>5 g/100 g</td>
<td>4 weeks</td>
<td>No effect on HDL–cholesterol</td>
<td></td>
<td>Uberoi et al. (1992)</td>
</tr>
<tr>
<td>Pea hulls</td>
<td>Normolipaemic subjects</td>
<td>10 g</td>
<td>Post-prandial study</td>
<td>No effect on PP plasma TG</td>
<td>Decreased cholesterol (most esterified cholesterol)</td>
<td>High-fat, high-cholesterol diet</td>
</tr>
</tbody>
</table>
Mineral absorption
Soya fibre
Healthy subjects 25–30 g/d No effect on mineral absorption and excretion Fischer et al. (1985), Heymsfield et al. (1988), Taper et al. (1988), Tsai et al. (1983)
Rats 30 % of the diet 3 weeks Enhanced absorption of Ca and Mg in the large intestine Levrat et al. (1991)

Large intestine physiology
Soya cotyledons fibre
Healthy subjects 25 g/d 17 d Increased stool weight Low DF diet Tsai et al. (1983)
Healthy subjects 21 g/d 3 weeks Increased stool weight Normal diet Schweizer et al. (1983)
Healthy subjects 30–60 g/d 10 d No effect on TT and stool frequency Liquid diet Slavin et al. (1985)
Constipated, tube-fed non-ambulant patients 20–22.3 g/d 2 weeks Increased stool weight Enteral preparation Fischer et al. (1985)
Diarhoeic, tube-fed non-ambulant patients 21 g/l per d 15 d No effect on TT Enteral preparation Dobb & Towler, (1990)
Infants with acute diarrhoea (>6 months old) 0.7 g DF. D per kg infant’s weight 10 d Reduction of the duration of the diarrhoea Liquid diet Vanderhoof et al. (1997)
Soya hulls
Healthy subjects 26 g/d 28–30 d Increased number of stools per week Munoz et al. (1979)
Healthy subjects 30 g/d 15 d Increased stool weight Normal diet Cherbut et al. (1991)
Healthy subjects 15 g/d 3 weeks No effect of fine particles (<100 μm) on TT No effect in subjects with short TT Guédon et al. (1996)
Rats 5 % of the diet nm Increased faecal bulk Coarse particles decrease mean TT Focant et al. (1990)

DF, dietary fibre; DM, dry matter; NIDDM, non-insulin-dependent diabetes mellitus; PP, post-prandial; SF, soluble fibre; TC, total cholesterol; TG, triacylglycerols; TT, transit time; nm, not mentioned in the paper.
partly, attributed to the starch and/or the dietary fibre (total or one specific fraction) and thus if purified or semi-purified starches and fibres could be of interest for health.

**Fibre fractions**

The literature on isolated dietary fibre from legume seeds is very scarce, and mainly concerns soya and, to a lesser extent, pea fibres. Most of these studies are summarized in Table 7. It is very difficult to draw definitive conclusions from these data as doses of fibre, duration and design of studies are not comparable. However, there are the following tendencies:

1. according to several studies, consumption of fibre from pea or soya would improve glucose tolerance;
2. some of the studies indicated a positive effect of soya and pea fibre on cholesterolemia and/or postprandial triglyceridaemia but others did not show any effect;
3. most studies, performed with healthy subjects, showed an increased of the stool weight when they ate soya or pea fibres (usually more than 20 g/d).

Part of the physiological effects of these fibres could be explained by their fermentation pattern. The fermentability of fibres has been studied in vitro in batch systems (Cherbut et al. 1991; Titgemeyer et al. 1991; Bourquin et al. 1993; Barry et al. 1995; Cloutour, 1995; Guillot et al. 1995; Casterline et al. 1997; Lebet et al. 1998; Van Laar et al. 2000). The results showed that fibres from cotyledons were highly degraded (percentage of fermentability: 57–91%) while fibres from hulls were fermented only to a limited extent (percentage of fermentability: 22–41%). Acetate was always the major short-chain fatty acid (SCFA) of the medium (about 47–89%), followed by propionic (7–45%) and then butyric acid (6–22%), the other acids being present in very low concentration. Compared to other sources of highly fermented dietary fibre such as pectins, sugarbeet or apple fibres, soyabean fibre (inner fibre) fermentation was generally characterized by relatively high proportions of propionic acid and butyric acid fermentation was generally characterized by relatively high proportions of propionic acid and butyric acid (Table 8).

**Table 8. Short-chain fatty acid production during in vitro fermentation of substrates (mmol/g original substrate dry matter)**

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Total SCFA (mmol/g)</th>
<th>Acetate</th>
<th>Propionate</th>
<th>Butyrate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Better basic 872 oat fibre</td>
<td>0·42</td>
<td>61·9</td>
<td>16·7</td>
<td>21·4</td>
<td>Bourquin et al. (1993)</td>
</tr>
<tr>
<td>Bleached oat hull</td>
<td>0·37</td>
<td>87·3</td>
<td>11·6</td>
<td>1·1</td>
<td>Casterline et al. (1997)</td>
</tr>
<tr>
<td>Oat bran</td>
<td>2·66</td>
<td>49·6</td>
<td>36·1</td>
<td>14·3</td>
<td>Casterline et al. (1997)</td>
</tr>
<tr>
<td>Fibrim soya fibre</td>
<td>5·75</td>
<td>64·5</td>
<td>19·5</td>
<td>16·0</td>
<td>Bourquin et al. (1993)</td>
</tr>
<tr>
<td>Fibrim soya fibre</td>
<td>1·94</td>
<td>71·4</td>
<td>20·6</td>
<td>8·1</td>
<td>Casterline et al. (1997)</td>
</tr>
<tr>
<td>Fibrim soya fibre</td>
<td>2·55</td>
<td>46·7</td>
<td>44·7</td>
<td>8·6</td>
<td>Casterline et al. (1997)</td>
</tr>
<tr>
<td>Duo sugarbeet fibre</td>
<td>1·16</td>
<td>92·6</td>
<td>6·6</td>
<td>0·8</td>
<td>Casterline et al. (1997)</td>
</tr>
<tr>
<td>Apple fibre</td>
<td>1·56</td>
<td>67·9</td>
<td>26·3</td>
<td>5·8</td>
<td>Casterline et al. (1997)</td>
</tr>
<tr>
<td>Arabic gum</td>
<td>8·19</td>
<td>65·7</td>
<td>22·8</td>
<td>11·3</td>
<td>Bourquin et al. (1993)</td>
</tr>
<tr>
<td>Arabic gum</td>
<td>6·94</td>
<td>66·2</td>
<td>25·3</td>
<td>8·4</td>
<td>Casterline et al. (1997)</td>
</tr>
<tr>
<td>Centara II pea fibre</td>
<td>0·76</td>
<td>74·1</td>
<td>16·7</td>
<td>9·2</td>
<td>Casterline et al. (1997)</td>
</tr>
<tr>
<td>Centara III pea fibre</td>
<td>1·99</td>
<td>73·4</td>
<td>21·1</td>
<td>5·5</td>
<td>Casterline et al. (1997)</td>
</tr>
</tbody>
</table>

SCFA, short-chain fatty acid.

In vivo, the increase in SCFA in the caecum of rats fed soyabean fibre was accompanied by an increase in SCFA absorption (Levrat et al. 1991; Key & Mathers, 1993). The caecum was enlarged and the wall hypertrophied. There was a moderate and transitory induction of enzymes (ornithine decarboxylase and thymidine kinase) involved in proliferative processes of the colonic epithelium (Levrat et al. 1991). Nevertheless, the degree of induction of the enzymes was less than that reported for other fermentable substrates (Calvert et al. 1989).

**Starch fractions**

Bioavailability of native and cooked starches from grain legumes is known to be relatively poor compared to most cereal starches (Hildebrandt & Marlett, 1991; Granfeldt et al. 1992; Björck et al. 1994; Tovar, 1996; Brighenti et al. 1998; Seewi et al. 1999). When inside an intact grain, starch granules are entrapped inside the cell wall, making them unavailable in the upper part of the digestive tract unless these cell walls are disrupted during the preparation of the food or by chewing. The low bioavailability of these starches is also explained by the starch itself, which is relatively rich in amylose. Indeed, (1) when raw, it is more resistant than most cereal starches due to its higher crystallinity; (2) it needs a higher temperature to be fully gelatinized and has a higher risk of being insufficiently cooked; (3) after appropriate cooking, it has a higher capacity to retrograde than most starches with a lower content in amylose. This retrogradation is a recrystallization of the linear chains of amylose and, later on, of the branched chains of amylpectin. As a consequence, part of these starches can be ‘resistant’ to digestion in the small intestine (Noah et al. 1998) and ferment in the colon, producing SCFA and gases (CO₂, H₂ and, in some, CH₄). The fraction that is digested in the small intestine is slowly available and contributes to the low glycaemic index of the wholegrain legumes. The resistant starch fraction seems to be interesting due to the production of a large amount of butyrate (one of the three main short-chain fatty acids) during colonic fermentation. This nutrient is the
main fuel of the colonocyte and seems to play a role in the prevention in a number of colonic diseases, including colon cancer.

Recently Soral-Śmietana et al. (2001a) proposed using native pea starches to produce resistant starches. They obtained an RS preparation from two commercial peas starches (Nastar and Gel-Flo) with 38 % RS (% dry matter), the initial native pea starches containing respectively 43 and 19 % RS (% dry matter).

Pure pea starch (NASTAR, Cosucra BV, Rosendaal, The Netherlands) elicited less hyperglycaemia (−47 %), hyperinsulinaemia (−54 %), and C-peptide secretion (−37 %) as compared to corn starches (modified and unmodified) (P<0.05) in healthy subjects (Seewi et al. 1999). No differences in flatulence nor breath hydrogen were observed between both starches, suggesting no significant differences in RS content between the two starches.

In a study on pigs, van der Meulen et al. (1997) concluded that ileal digestibilities of native maize and pea starches were equal, but that the rate of appearance of glucose in the portal vein was higher for maize starch. Net portal glucose flux was lower for pea starch, but after 8 h post-prandially, portal glucose flux was significantly higher than with maize starch. Net portal SCFA flux, being higher with pea starch than with maize starch, did not apparently confirm the results of ileal digestibility, but that could be explained by different uptakes of SCFA by the colonic mucosa as already suspected with other RS (Martin et al. 2000).

Mung bean (Phaseolus aureus) and waxy maize starches were incorporated in the diet of rats to provide, respectively, a low- and a high-glycaemic-index (GI) diet (Kabir et al. 2000). After 12 weeks, the group fed the low-GI food had higher plasma leptin and ob mRNA than the other group, but no effect was observed on food intake, basal plasma glucose, insulin or triacylglycerols. It was suggested that leptin sensitivity was increased in the ‘high-GI group’ and that this step might precede weight gain and increase in fat mass. Earlier, the same group (Kabir et al. 1998) showed that the high-GI diet stimulated fatty acid synthase activity and lipogenesis, and might have undesirable long-term metabolic effects.

The same mung bean starch has been compared with corn starch and glucose in humans to quantify the rate of net post-hepatic appearance of glucose after ingestion of both starches (Lang et al. 1999). Glycaemic indices of maize and mung bean starches were respectively 95 ± 18 and 51 ± 13. Post-hepatic appearance of glucose from glucose, corn and mung bean starches represented respectively 79.4 ± 5.0, 72.6 ± 4.0 and 35.6 ± 4.6 % of the glucose load after 4.5 h post-prandially. This big difference has been attributed to the fact that mung bean starch contains about 11 % of RS, and to a long absorption period of mung bean starch which was probably not finished 4.5 h after the meal.

Recently, Fukushima et al. (2001) observed the lowering of serum total cholesterol in rats by starches of two different varieties of beans (Phaseolus vulgaris) (15 g/kg). The total cholesterol:HDL–cholesterol ratio in these bean starch groups was also significantly lower than in the control group (maize starch) at the end of the 4-week feeding period. This effect was attributed to the enhancing effect of RS on the hepatic LDL receptor mRNA level.

The pattern of large intestine SCFA after consumption of starchy grain legumes has been confirmed to be rich in butyrate. Indeed, Key & Mathers (1993) observed a considerable increase in butyrate between 1 and 3 d and up to 14 d of adaptation of rats to a diet containing cooked P. vulgaris. No RS was recovered in the faeces of the animal, showing the complete colonic fermentation of this fraction.

\( \alpha \)-Galactosides

Due to their high fermentability, \( \alpha \)-galactosides induce the production of gases (mainly CO\(_2\), H\(_2\) and, in some populations, CH\(_4\)) responsible for the digestive discomfort related to pulse consumption. These oligosaccharides are quite characteristic of grain legumes and are present in all species, with large variabilities among different varieties. Although \( \alpha \)-galactosides are claimed to be solely responsible for flatulence in soybeans or pulses, the flatulence activity of some grain legumes (e.g. smooth-seeded field peas) may also be due to indigestible oligosaccharides and cell wall fibre constituents (Fleming, 1981).

Besides causing digestive discomfort in most populations, flatus production may be a more acute problem in individuals with colonic pathologies such as irritable bowel syndrome. For instance, the local bean diet has been identified as one of the most common aggravating factors of irritable bowel syndrome in Nigerians (Atoba, 1988). Flatus production needs to be lowered in these patients by reducing consumption of fermentable carbohydrates such as beans or lentils (Friedman, 1991).

For most of the population, it might seem desirable to remove \( \alpha \)-galactosides from pulses by technological or genetic means. However, these non-digestible oligosaccharides have been identified as prebiotic agents (Van Loo et al. 1999), i.e. food ingredients potentially beneficial to the health of consumers. At the present time in Europe, the main prebiotics are inulin-type fructans, characterized by the presence of fructosyl units bound to the \( \beta-2,1 \) position of sucrose. Prebiotics escape enzymatic digestion in the upper gastrointestinal tract and enter the caecum without change to their structure. None are excreted in stools, which indicates that they are fermented by colonic flora to produce a mixture of SCFA (acetate, propionate and butyrate), L-lactate, CO\(_2\) and H\(_2\). Their stimulation of bifidobacteria may have several beneficial implications for health:

1. Potential protective effects against colorectal cancer and infectious bowel diseases through inhibition of putrefactive (Clostridium perfringens) and pathogenic bacteria (Escherichia coli, salmonella, Listeria sp. and shigella), respectively. The effects of prebiotics on colon carcinogenesis and tumour growth have been evaluated in animals (mostly on azoxymethane- or dimethylhydrazine-treated rats), and development of colonic aberrant crypt foci (ACF) is the marker most often described. ACF are putative preneoplastic lesions...
from which adenomas and carcinomas may develop in the colon (Reddy, 1999).

2. Improvement of carbohydrate and lipid metabolism. This possibility has gained support from the observation that dietary oligofructosaccharides cause suppression of hepatic triacylglycerol and VLDL synthesis in animals, resulting in marked reductions in triacylglycerol and, to a lesser extent, cholesterol levels (Taylor & Williams, 1998).

3. Providing fibre-like properties by decreasing renal nitrogen excretion.

4. Increasing the availability of essential minerals.

5. Acting as a low cariogenic factor.

It has been shown clearly in human volunteers that nondigestible oligosaccharides, particularly fructooligosaccharides, stimulate the growth of bifidobacteria selectively, modifying the composition of the colonic microbiota significantly (Roberfroid, 1997).

These potentially beneficial effects have been largely studied in animals, but have not really been tested in humans (Roberfroid, 1998; Grizard & Barthomeuf, 1999; van Loo et al. 1999). Human clinical trials are likely to broaden our insight concerning the importance of prebiotics in health and disease.

Although prebiotic effects have been demonstrated extensively with oligofructose, fructooligosaccharides and inulin, there is no evidence (a lack of studies) of such effects with α-galactosides. However, like low molecular weight fructans, they are quickly fermented (Bradburn et al. 1993) in the colon and could be expected to have beneficial properties similar to those of fructooligosaccharides.

Conclusion

Apart from being eaten as a vegetable, grain legumes can be considered as a source for raw material for the processing industry. Legume starch and fibre both have useful functional properties and can be used readily in food products. Procedures have been developed for isolating these fractions. Legume starch has unique properties, having a good stability to high temperature and high point viscosity compared with equivalent cereal or tuber starch. The technofunctional properties can be further improved by starch processing, including chemical and biotechnological methods. Moreover, mutant genes affecting starch synthesis may enlarge the spectrum of starch that could suit a wide range of food and non-food applications. The fibre fraction from the seed embryo has excellent water hydration properties that could be utilized to structure food and replace fat in areas such as confectionery, dressings or meat.

Starch and fibre can also be proposed as ingredients for their beneficial health effects. Legume seed starch is a source of RS, which seems to be interesting for the production of a large amount of butyrate on its fermentation by colonic bacteria. Fibre provides a broad range of positive effects, both physiological and metabolic, at least in subjects suffering from disorders. These effects are related to the source of fibre (from cotyledon or hull), are dose related and depend on the form in which it is ingested.

Scientific research must be undertaken to substantiate the potential long-term positive effects of legume starch and fibre ingestion on health, in both normal individuals and subjects suffering from disorders. Fundamental knowledge of the behaviour of starch and fibre fractions in complex food systems is still required in order to be able to propose ingredients and adaptations to formulations for appetizing foods with good nutritional properties.

References


Carbohydrate fractions of legumes S303


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