The utilisation of high amylose maize starch in animal and human nutrition

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Summary

Starch is the main storage carbohydrate in many higher plants. Due to its ready availability, multiple functionality and relatively low cost, starch and starch derivatives have been widely used in food and industrial applications for many years. However in recent times the versatility and importance of starch based materials have been highlighted as research has endeavoured to learn of its impact on our health. Some starches have been identified as being resistant to digestion and they appear to have important physiological effects in the gastrointestinal tract.

Introduction

Starch is quantitatively the most important dietary carbohydrate. In economically developed countries it contributes between 20 and 40 percent of the energy intake (Asp et *al.* 1986). Research in recent years has observed that starch may be contributing more to our physiological well-being than originally thought. Cassidy et *al.* (1994) reported that in countries that consumed greater amounts of starch, such as India and China, there was a lower incidence of colorectal cancers than in countries which consume less starch, such as the USA and Australia. No trend was observed between the amount of non-starch polysaccharide consumed in the countries included in the study and the rate of colorectal cancer rates reported. This apparent protective effect related to starch intake may be based on the observation made in the 1980's that starch was the major complex carbohydrate found in the caecal contents of people who were the victims of sudden death (Cummings *et al.* 1990).

Resistant starch

A number of mechanisms have been proposed to explain the in vitro indigestibility or malabsorption of starch. Firstly in some food particles the starch is physically inaccessible to digestion. This occurs in whole or coarsely milled grains, cereals, legumes or other starch containing materials where the size or composition of the food particles prevent or delay the action of the digestive enzymes. Secondly there are native starch granules with a coformation which are resistant to digestion. The granules obtained from a number of plant species, including potato, banana, legumes and high amylose (HA) maize, demonstrate this natural resistance. Thirdly, retrograded starch polymers are produced when starch is cooled after gelatinisation (Englyst *et al.* 1992); the dispersed molecules of amylose and amylopectin re-associate spontaneously and can form crystallites that resist enzymatic hydrolysis (Sievert and Pomeranz, 1989). Apart from these types of resistant starch it has been suggested that some chemically modified starches also resist enzymatic hydrolysis and that these starches merit separate classification (Brown *et al.* 1995). Modifications such as esterification and etherification are used commercially to improve the functionality of the starch in conditions associated with food processing, transportation, storage and consumption. The ubiquitous distribution of such modified starches in processed foods suggests that they might be an important dietary source of resistant starch.

Small quantities of resistant starch are present in many of the starchy foods that we consume, such as bread, breakfast cereals, biscuits and pasta (Crawford, 1987). In the European Union Dysseler and Hoffem (1994) estimated that the daily intake of resistant starch was between 3.22 g/day to 5.74 g/day. In Australia, Baghurst et *al.* (1996) estimated that people typically consume approximately 5 to 6 grams of resistant starch per day. It has been suggested that beneficial physiological responses may be obtained by the consumption of higher levels of resistant starch, possibly in the range 15 to 20 g/day (Baghurst et *al.* 1996).

Small intestine

The effects of resistant starch entering the small intestine are related to increasing the bulk of foods and the reduction in the amount of glucose released fiom the starch due to the action of amylases, and the associated effects of reduced insulin response. These factors are believed to be important in the prevention and management of non-insulin dependent diabetes mellitus (NIDDM), which is a disease of high prevalence in western countries (Granner and O'Brien, 1992). The type of dietary starch appears to be able to influence the development of NIDDM. Bymes et *al.* (1995) found that in rats fed a diet containing waxy maize starch (readily digested starch) insulin resistance was detectable after 12 weeks of feeding whereas in rats consuming a HA maize starch (a granular resistant starch) diet, insulin sensitivity was unimpaired (Table 1). The mechanism is at present unclear.

Noakes et *al.* (1996) found that in a diet where 33% of the carbohydrate was in the form of HA maize starch there was a 17% reduction in the concentration of postprandial plasma insulin relative to a control diet which included the readily digested **waxy** maize starch.

Large bowel

HA starch granules have been observed in the caecal **digesta** of test animals, such as pigs (Topping *et al.* 1997) and human ileostomates (Muir *et al.* 1995). These granules exhibited the effects of surface erosion by digestive enzymes (Brown *et al.* 1994b). The inclusion of HA maize starch in the diet leads to significant quantities of starch being detected entering the caecum

Table I Incremental Area Under the Plasma Insulin Curves Following Intravenous Glucose Challenge for AAW Rats.(Byrnes *et al.* 1995).

Diet Period	Area under plasma insulin curve (mU/ml after 120 minutes)	
	HA Maize starch diet	Waxy maize starch diet
4 weeks	1387 ± 72	1490 ± 23
8 weeks	1651 ± 379	2208 ± 379
12 weeks	1955 ± 207	4194 ± 309

Table 2 Concentrations (mg/g of **digesta)** of starch in the caecal **digesta** of individual pigs with caecal **cannula** which were fed either conventional starch or a high **amylose** maize starch (Topping *et al.* 1997).

Starch type	Time after feeding (hours)		
	5	7	9
Waxy maize			
Pig 1	1.1	2.2	0.8
Pig 2	15.7	5.5	8.6
Hig amylose maize			
Pig 3	29.6	65.9	No sample
Pig 4	48.6	50.1	71.0

Table 3 Total starch fed to subjects and total starch recovered in the effluent from ileostomates fed low and high resistant starch test meals. (Muir et *al.* 1995)

	Total starch consumed (g)	Starch in effluent (g)
Low resistant starch meal	51.8	2.4
High resistant starch meal	52.7	19.9

in pigs (Table 2) or in the effluent collected from human ileostomates (Table 3).

Upon reaching the large bowel the resistant starch acts as a fermentable substrate for the native microflora. A large number of bacterial species, including *bifidobacteria* and some *lactobacilli*, has been found to utilise HA maize starch as a fermentation substrate ***in vitro*** (Brown ***et al.*** 1994a). A primary product of the fermentation in the bowel is short chain fatty acids (SCFA). In the pig, the consumption of HA maize starch, when compared to waxy maize starch, led to an increase in the total pool of SCFA (Table 4) including acetate, propionate and butyrate.

Support for these findings was provided by the clinical study conducted by Phillips ***et al.*** (1995) using the same HA maize starch that was used in the animal trials. It was noted that the consumption of 39g of resistant starch per day over a three week period reduced the faecal pH fiom 6.9 to 6.3 and increased the levels of acetate (by 38% mmol/day) and butyrate (by 100% mmol/da). In a separate experiment with hypertriglyceridemic human subjects, Noakes ***et al.*** (1996) observed an increase of 34% in the faecal excretion of butyrate after the consumption of a diet which provided 25% of the carbohydrate as HA maize starch. The amounts of SCFA measured in the faeces may underestimate the actual amounts produced in the large bowel, experimental evidence suggesting that absorption of SCFA may be enhanced at low pH (Sellin ***et al.*** 1993). Starch appears to be a desirable substrate for microbial fermentation in the bowel because it encourages some microorganisms to produce large quantities of SCFA. In particular, starch is excellent for stimulating the synthesis of butyrate, which appears to be important in regulating gene expression and the cell growth of colonocytes. Butyrate has also shown antineoplastic characteristics (Dexter ***et al.*** 1984).

Reduction in colonic pH, for example due to the increased production of SCFA has been shown to decrease the solubility of bile acids that are cytotoxic to colonic cells (Lapre and van der Meer, 1992). The lower pH has also been shown to inhibit the bacterial transformation of primary to secondary bile acids. The experiments using the pig indicated that HA maize starch in the diet could cause a decrease in the concentration of the secondary bile acids, lithocholate and deoxycholate (Table 5).

Similar effects have been demonstrated when human subjects were consuming foods containing HA maize starch (Noakes ***et al.*** 1996).

Phillips ***et al.*** (1995) found that the consumption of HA maize starch increased faecal bulk from 13 8 to 197 grams wet weight per day. In addition, the number of bowel movements per day and the ease of defecation increased. This observation has since been supported by the studies of Noakes ***et al.*** (1996).

Use in foods

A novel and practical means of increasing the resistant starch content of foods has been undertaken in Australia. It was found through the examination of many natural sources of resistant starch that a conventionally bred high amylose maize variety developed in Australia

Table 4 Concentrations of total and individual short chain fatty acids in the faeces of pigs after consuming waxy and high amylose maize starch for 5 days (Topping et *al.* 1997).

Starch type	Acetate (mmol/L)	Propionate (mmol/L)	Butyrate (mmol/L)	Total (mmol/L)
Waxy maize starch	47.8	22.1	7.4	85.4
High amylose maize starch	63.9	47.8	13.7	126.9

Table 5 Concentration of individual bile acids in gall bladder bile of pigs fed waxy maize, high amylose and a combination of waxy and high amylose maize starches.(Topping et *al.*1997).

Starch type	Lithocholate (mmol/L)	Deoxycholate (mmol/L)
Waxy maize starch	0.2	0.5
High amylose maize starch	0.0	0.1
High amylose plus wazy maize starches	0.0	0.1

could provide significant levels of resistant starch, analysed mainly as dietary fibre, and contribute to the functionality of foods without interfering with their taste or texture (Brown, 1993). HA maize starch is now incorporated into bread, breakfast cereals, pasta, noodles, cakes, biscuits, snacks and foods for groups with specialist nutritional requirements and pharmaceutical products.

In Australia health authorities have recommended that Australians should consume more dietary fibre and increase their intake of cereal products, such as bread, in an effort to improve public health. During the past few decades the level of dietary fibre consumption has increased for both men and women. However starch consumption has not increased. Some segments of the population, particularly children, have been reluctant to change their food preferences in order to obtain more fibre in their diets. In this regard consumer focus groups found that some people refrain from consuming the high fibre multigrain and wholemeal breads because they preferred white bread. Conventional types of dietary fibre, such as wheat bran, have always coloured the bread, changed its texture by making it more fibrous and chewy or decreased the softness and volume of the loaf HA maize allowed the manufacture of a soft high fibre white bread with excellent keeping qualities. Market surveys show more people consuming white bread (8%) with an increase of 1.4% in the total Australian bread market. This was the first time in many years that bread consumption increased in Australia. A similar white bread containing HA maize has been released in New Zealand with similar effects on bread consumption (Brown *et al.* 1995).

Use with probiotic microrganisms

One special application of the ability of HA maize starch . to survive digestion and be fermented in the large bowel was the realisation that it could specifically assist some bacteria that could confer a health benefit. Some of these 'probiotic' bacteria, including the bifidobacteria, have been assessed in vitro as being able to ferment HA maize starch (Table 6).

In addition the ability of bacteria species and individual strains to utilise the HA maize starch is significantly affected by the type and extent of the chemical treatment of the starch.

Table 6 Carbohydrate residue remaining after 48 hours of the *in vitro* fermentation of native and treated high amylose maize starches.(Brown et *al.* 1994a).

Starch type	Total carbohydrate residue (mg/mL)					
	1	2	3	4	5	6
Bifido X8ATI	6.43	4.99	5.57	4.68	4.97	6.41
Cl. butyricum	5.62	4.09	6.16	4.88	6.18	4.99
B. bifidum	6.70	5.20	6.09	5.79	6.00	6.68
Medium control	9.31	9.87	9.92	9.30	9.70	9.80

Starch type 1 = hydroxypropylated
Starch type 2 = acetylated
Starch type 3 = octenyl succinated
Starch type 4 = carboxymethylated
Starch type 5 = succinated
Starch type 6 = native or unmodified

Table 7 Faecal concentrations and daily excretion of bifidobacteria of pigs fed either a waxy or a high amylose maize starch with live *Bifidobacterium longum.*

Starch type	Faecal concentration (log 10 cfu/g wet weight)	Faecal excretion (log 10 cfu/day)
Waxy maize starch	8.12	10.76
High amylose maize starch	8.91	11.73
SED	0.20	0.19
Difference between starch types	P< 0.01	P<0.01

It has been demonstrated (Brown *et al.* 1997) that HA maize starch, compared with a readily digested waxy maize starch, can be included in the diet for pigs together with bacteria, Bifidobacterium longum, and lead to a significant increase in the level of viable bifidobacteria recovered in the pig faeces (Table 7).

The increase in bifidobacteria numbers persisted in the faeces of the test animals even after the addition of the probiotic bacteria to the diet had ceased (Brown *et al.* 1994a). The use of HA maize starch in foods could allow for the more flexible and reliable use of some probiotic microorganisms and help maintain appropriate levels of beneficial bacteria in the large bowel to assist in improving the health of an individual. The resistant starch could be included in foods such as breakfast cereals, or combined with the beneficial bacteria in cultured products such as yoghurt.

The role of starch in the diet is now the focus of both Australian and international research. This research has led to the development of resistant starch products that can be included in a wide variety of foods and feeds to assist in improving the health of both animals and people.

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