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Banana starch: production, physicochemical properties, and digestibility—a review☆

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Abstract

The large quantity of green cull bananas has the potential of being used industrially and, thereby, to improve banana economics and eliminate the large environmental problem presented by banana waste. This review summarizes the present knowledge of the composition, structure, physiochemical properties, modifications, and digestibility of banana starches and provides suggestions for needed research to improve the utilization of green cull bananas.

Keywords: Banana; Starch; Structure; Physicochemical properties; Modifications; Digestibility

1. Introduction

Banana is a general term embracing a number of species or hybrids in the genus *Musa* of the family Musaceae. Almost all of the known edible-fruited cultivars arose from two diploid species, *Musa acuminata* and *Musa balbisiana*, which are native to southeast Asia. There are diploid, triploid and tetraploid hybrids composing subspecies of *M. acuminata*, and between *M. acuminata* and *M. balbisiana* (Robinson, 1996; Stover & Simmonds, 1987). Conventionally, the haploid contributions of the respective species to the cultivars are noted with the letters A and B. Cavendish subgroup banana cultivars (*M. cavendishii*), which are the mainstays of the export trades are pure triploid *acuminata* (AAA group). The two Linnaean epithets, *M. paradisiaca* and *M. sapientum*, are members of the AAB group (Stover & Simmonds, 1987). Plantains are generally the larger, more angular starchy fruits of hybrid triploid cultivars in the banana family intended for cooking, but also edible raw when fully ripe (Robinson, 1996).

Bananas are produced in large quantities in tropical and subtropical areas. World production of *Musa* in 2003 was estimated at 102 million MT of which about 68% was classified as bananas and 32% as plantains (FAO, 2003). The crop is of major importance to the people in the growing areas as it forms a major portion of the annual income and a source of food. As is the case for most tropical products, due to the special climatic conditions needed to grow bananas, they are mainly produced in developing countries. Developed countries are the usual destination for export bananas. Production, as well as exports and imports of bananas, are highly concentrated in a few countries. Ten major banana-producing countries accounted for about 75% of total production in 2003 with India, Ecuador, Brazil, and China accounting for half of the total (Table 1). Latin America and the Caribbean islands supplied more than 80% of world total exports (ca. 15 million MT), with the four leading banana exporter countries (Ecuador, Costa Rica, Philippines and Colombia) accounting for about two-thirds of world exports (FAO, 2003).

About one-fifth of all bananas harvested become culls. When banana bunches arrive at central collection stations, bananas too small for shipping are removed, along with those that have damaged or spoiled areas that could cause microbial contamination of the bunch. Rejected bananas are normally disposed of improperly. Attempts are made to use

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Table 1
World production statistics of banana and plantain in 2003 (Source: FAO, 2003)

Country	Production (×1000 MT)	Country	Production (×1000 MT)
Asia	37,140	Central America and Caribbean	8519
India	16,450	Mexico	2027
China	5827	Costa Rica	1863
Philippines	5500	Guatemala	1000
Indonesia	4312	Honduras	965
Thailand	1800	South America	15,152
Viet Nam	1220	Brazil	6518
Bangladesh	654	Ecuador	5609
Africa	6813	Colombia	1450
Burundi	1600	Europe	441
Egypt	850	Spain	405
Cameroon	689	Oceania	1174
Uganda	615	Papua New Guinea	870
		Total banana	69,286
Africa	23,308	South America	6362
Uganda	10,000	Colombia	2925
Rwanda	2408	Peru	1600
Ghana	2300	Ecuador	860
Nigeria	2110	Venezuela	760
Côte d'Ivoire	1420	Central America and Caribbean	2261
Congo	1250	Cuba	797
Cameroon	1200	Asia	1040
Kenya	830	Sri Lanka	610
		Total plantain	32,974

these culled bananas in animal feed and products such as chips, flakes and powders, but they are used only to a limited extent for these purposes due to the low value of such products. Therefore, in countries such as Costa Rica, dumping of the rejected bananas into rivers is a common practice. The high carbohydrate content of the crop creates high biochemical oxygen demand (BOD) in the rivers and, hence, reduces aquatic animal populations.

A successful industrial use of the culled bananas would alleviate the problem while offering employment and financial return to the inhabitants. Most likely, the first practical application of culled bananas would be use of the pulp for starch production or production of a low-cost banana flour ingredient. Banana starch has the potential to be a commodity starch because of its specific properties and its potential production from low-cost, cull bananas. Green banana pulp contains up to 70–80% starch on a dry weight basis, a percentage comparable to that in the endosperm of corn grain and the pulp of white potato.

Native raw banana starch is known to be resistant to the attack of α-amylase and glucoamylase, with in vivo results showing that 75–84% of the starch granules ingested reached the terminal ileum (Englyst & Cummings, 1986; Faisant, Buleon et al., 1995). Although it was found that the resistance was largely overcome by cooking to gelatinize the starch, other studies showed that the 'easily hydrolysable starch' fraction of cooked banana starch was as low as 47% and was comparable to the known low-digestible cooked yam starch (40%) (Cerning-Beroard & le Dividich, 1976; Lozano, Cabrera, & Salazar, 1973). While there is limited commercial use for raw starch in foods, there is substantial application for such a trait in cooked starch. The value of slowly digestible and low-glycemic-index starch is embodied in the current diet craze of 'low carb' foods.

In conclusion, banana starch has potential, both from its digestion properties and functional properties, to have application in processed foods and become a commercially viable starch product. Use of culls for production of starch would provide a starch that might be competitive in the world starch market, improve banana economics, and eliminate a large environmental problem presented by cull bananas.

2. Occurrence and transformation of banana starch

The composition of bananas changes dramatically during ripening. von Loesecke (1950) classified banana ripening into eight stages according to peel color. Starch is the principal component of green bananas, which undergoes important changes during ripening. The average starch content drops from 70 to 80% in the pre-climacteric (prior to starch breakdown) period to less than 1% at the end of the climacteric period, while sugars, mainly sucrose, accumulate to more than 10% of the fresh weight of the fruit. Total soluble sugar content can reach 16% or higher of the fruit fresh weight (about 80% water content), indicating a high rate of conversion (Cordenunsi & Lajolo, 1995). Amylases participate in starch hydrolysis, but they are probably not linked to sucrose synthesis. Starch–sucrose transformation during ripening of bananas involves several enzymes and more than one pathway. In spite of the importance of this transformation in terms of fruit physiology, little is known about the mechanisms involved.

Lii, Chang, and Young (1982) investigated changes during ripening of dessert bananas with respect to physical and chemical properties of their starch and their content of reducing sugars and sucrose (shown in Table 2). Terra, Garcia, and Lajolo (1983) followed starch, sucrose, glucose, and fructose concentrations and activity of some enzymes of sucrose synthesis during ripening of pre-climacteric (prior to starch breakdown) bananas (*M. acuminata*). As starch was degraded, sucrose content increased and preceded accumulation of glucose and fructose. UDP–glucose pyrophosphorylase activity remained constant, while the activity of sucrose synthase and invertase increased. The observed sugar and enzyme changes indicated that starch to sucrose transformation via glucose 1-phosphate

Table 2
Proximate compositions of the edible portion of banana at different stages as classified by the color of banana peel (Lii et al., 1982)

Stage	Peel color	Starch (%)	Reducing sugar (%)	Sucrose (%)	Gelatinization temperature (°C)
1	Green	61.7	0.2	1.2	74–81
2	Green	58.6	1.3	6.0	75–80
3	Green/a trace of yellow	42.4	10.8	18.4	77–81
4	More green than yellow	39.8	11.5	21.4	75–78
5	More yellow than green	37.6	12.4	27.9	76–81
6	Yellow with a green tip	9.7	15.0	53.1	76–80
7	All yellow	6.3	31.2	51.9	76–83
8	Yellow/a few brown spots	3.3	33.8	52.0	79–83
9	Yellow/many brown spots	2.6	33.6	53.2	–

and UDP–glucose might be the mechanism for starch disappearance during ripening.

Garcia and Lajolo (1988) detected activities of three α- and four β-amylases and α-1,4- and α-1,6-glucosidase activities at all stages of fruit ripening. They observed that their activities increased significantly, but only at the climacteric peak when much of the starch had already disappeared. Only β-amylase activity increased before onset of the respiration increase, and its activity paralleled starch decrease. Konishi, Kitazato, and Nakatani (1992) purified and partially characterized one acid α-glucosidase and two neutral isoforms of α-glucosidase from pre-climacteric banana pulp tissue. The acid α-glucosidase was determined to be a typical maltase, while the neutral isoforms of α-glucosidase were 50 times less active on maltose. The authors concluded that the acid α-glucosidase is the enzyme responsible for the hydrolysis of maltose and the malto-oligosaccharides formed by the combined action of α- and β-amylases. Only trace amounts of maltose were found in ripening banana tissue.

Changes in sucrose synthase (SS) and sucrose phosphate synthase (SPS) activities during development and ripening of bananas and the carbohydrate changes in fruit that was left to ripen on the tree, as compared to fruit that was harvested green, were studied by a Brazilian group (Cordenunsi & Lajolo, 1995; Do Nascimento, Cordenunsi, & Lajolo, 2000; Do Nascimento, Cordenunsi, Lajolo, & Alcocer, 1997). Starch contents, respiration rates, SS activity, and SPS activity in crude extracts and in partially purified preparations were followed during fruit development and ripening in both attached and detached bananas. During development of the fruit, SPS was present, but at a very low activity level, while SS activity was high and remained constant during the entire starch synthesis phase, followed by a reduction during starch breakdown (climacteric) and then disappearance (post-climacteric). Data showed that, while SS activity was almost abolished during ripening, SPS activity increased concomitantly to starch disappearance and sugar accumulation. The process was slower for attached fruits (final sucrose content 6%, SS activity 5 units, and SPS activity 33 units) when compared to detached fruits (final sucrose content 12%, no SS activity, and SPS activity 50 units).

An ethylene burst is the trigger of the banana ripening process. Indole-3-acetic acid appeared to play a role in carbohydrate metabolism in unripe bananas (*M. acuminata*, AAA group, cv. Nanicao) via delaying starch degradation, possibly by affecting the activity of hydrolytic enzymes such as β-amylase (Purgatto, Lajolo, Oliveira do Nascimento, & Cordenunsi, 2001). Also, Rossetto, Purgatto, Oliveira do Nascimento, Lajolo, and Cordenunsi (2003) reported that gibberellins play a role in starch-to-sucrose conversion in bananas, reinforcing the idea of multiple regulatory components acting in this metabolic pathway and its dependence on the equilibrium between several hormonal and metabolic signals.

The disappearance of the starch reserve during banana ripening appears to be relatively rapid because of the activities of several enzymes acting together (Cordenunsi & Lajolo, 1995; Glass & Rand, 1982; Gomes & Lajolo, 1981; Mao & Kinsella, 1981; Marriott, Robinson, & Karikari, 1981). It is, therefore, necessary to process the green bananas for starch production soon after harvest.

3. Technologies of banana starch production

3.1. Alkaline extraction

A wet-milling process is suitable for banana starch isolation due to the low level of impurities (Bello-Perez, Agama-Acevedo et al., 2000). Lii et al. (1982) reported a starch isolation technique from green Taiwan dessert bananas that involved cutting them and macerating the pulp in a sodium hydroxide solution of concentration of 0.1 M or less. The slurry was filtered first through cheesecloth, then bolting cloth. The starch was washed with water and dried. They found that green banana pulp contained 0.24% reducing sugars, 1.23% sucrose, 5.30% protein, 0.78% fat, 0.49% fiber, 62% starch, and 3.27% ash, while fully ripe banana pulp contained 33.6% reducing sugars, 53.2% sucrose, 5.52% protein, 0.68% fat, 0.30% fiber, 2.58% starch and 4.09% ash. These results are in approximate agreement with those of other workers analyzing different bananas. Ling, Osman, Fernandes, and Reilly (1982) reported that the starch of green Cavendish bananas could be isolated easily by extraction of the pulp with 1% sodium hydroxide solution.

Chiang, Chu, and Chu (1987) appear to have been the first to produce banana starch on a pilot-plant scale. Taiwan bananas (*M. sapientum*) were collected (green) 112–116 days after petal fall. They weighed an average of 82 g per finger, had a pulp to peel ratio of 1.1, a pulp weight basis of 30% of the total solids, and a pulp starch content of 81% (db); the pulp also contained, on a dry weight basis, 6.4% protein, 8.5% fiber and 2.5% pectin. Peeled bananas were sliced and milled with 0.5 M sodium hydroxide solution using a stone mill. The starch was washed on a shaker, collected by centrifugation, and then dried at 50 °C. The peel contained 5% pectin and 21% fiber. Peel removal was reported to be necessary for efficient handling. Immersion of fresh bananas in 0.5 M sodium hydroxide solution was deemed necessary for proper handling of the pulp and to obtain a 70% yield of starch with a purity of ca. 94%.

Fichtali, Owusu-Ansah, and Chang (1999) developed a process to extract starch from green, un-gassed reject bananas that were diced and disintegrated in a Fitzpatrick comminuting mill in a 0.05 M solution of sodium hydroxide. The milled banana slurry was sequentially screened to pass 60-, 80-, and 200-mesh screens to remove peel fibers and pomace. Crude starch was concentrated, counter-current washed with water, and then dewatered to a solids content of 55%. Starch thus obtained had a brownish color and was re-slurried in water for washing in a nozzle bowl centrifuge. The slurry was further centrifuged in a basket centrifuge and dried to a moisture content of 9.2%. Obtained starch (white in color) had a purity of more than 95%, less than 1% protein, and less than 0.07% ash.

3.2. Non-alkaline extraction

Kayisu, Hood, and Vansoest (1981) studied the extraction of starch from green bananas with water. Sliced bananas were disintegrated in a Waring blender at low speed. The mixture was centrifuged, and the dark material on the top of the pellet was scraped off. Crude starch was washed with water. The starch-containing suspension was decanted and allowed to stand 15 min for the starch to settle. The purity of the thus-obtained starch was 99.5%.

Whistler (1998) developed a cost-efficient process for producing starch from cull bananas. This process uses a minimum amount of processing chemicals, machinery, and processing time. Banana pulp was steeped in aqueous sodium bisulfite solution at pH of 3.5–5.5 for 2–8 h, more preferably for about 4 h, at ambient to slightly elevated temperatures. During this steeping period, the endogenous banana enzymes, such as pectinase and polygalacturonase, disintegrate the cell walls, allowing starch granules to be released into the aqueous steeping solution. The mixture was passed through wire screens to remove cell walls and other non-starch pulp-mass material, then centrifuged. Yields of dried starch (white in color) from green bananas obtained from a wholesale warehouse were 20–60%, depending on banana ripeness.

In other approaches, Bello-Perez, Agama-Acevedo, Sanchez-Hernandez, and Paredes-Lopez (1999) reported yields of starch from Macho and Criollo banana (*M. paradisiacal*) as 43.8 and 11.8%, respectively. A high yield (80.5%) of starch from commercial green bananas was also reported (Bello-Perez, Pano de Leon, Agama-Acevedo, & Paredes-Lopez, 1998). Waliszewski, Aparicio, Bello, and Monroy (2003) reported a 33.8% dry basis yield of starch from Valery bananas.

Different ripening stages and different banana species are likely the main factors behind the yield differences.

3.3. Production of dietary fiber from bananas

While starch production could alone produce a creditable outlet for cull bananas, there is also a possibility of commercial markets for other constituents of the pomace remaining after starch production. The peel of culled bananas could be a rich, low-cost source of dietary fiber (mainly hemicelluloses and pectic polysaccharides). Although little is known of the hemicelluloses of banana peel, there is a great likelihood, from initial investigations, that the hemicelluloses (constituting ca. 20% of the peel) will have solution properties, or can be given solution properties, that would make them valuable additions as gums/hydrocolloids in the food and non-food industries.

Fig. 1. Photograph of starch granules from green plantains (Zhang & Whistler, 2002).

Zhang and Whistler (2002) investigated isolation and characterization of hemicellulose from banana peel remaining after starch production. The ability of banana peel hemicelluloses to activate a macrophage cell line as an indicator of immune stimulation was determined, indicating that they have the potential to be used as a health-promoting dietary supplement (Zhang et al., 2004).

If banana starch is deemed to have potential in the world starch market, examination of its useful properties would be undertaken first, followed by a pilot-plant production. In addition, research emphasis should include realization of value from residual peels and pomace.

4. Starch granule size and microscopic appearance

In general, starch granules from various banana types, while being irregular in shape, appear microscopically as elongated ovals with ridges (Eggleston, Swennen, & Akoni, 1992; Jane, Kasemsuwan, Leas, Zobel, & Robyt, 1994; Lii et al., 1982; Ling et al., 1982; Kayisu et al., 1981; Zhang & Whistler, 2002) (Figs. 1–3). Major axes range from 6 to 80 μm, mostly between 20 and 60 μm. Eccentric birefringence was observed under polarized light (Fig. 2B) in starch granules of green Taiwan bananas. The growth rings do not appear to be elliptical around the hilum (Fig. 1) as they are in most granules. Cavendish banana starch was highly irregular in shape and size (Ling et al., 1982). Scanning electron micrographs of Valery banana starch revealed irregularly shaped granules among the elongated and spheroid forms. The spheroid forms varied from 15 to 40 μm in diameter. Elongated granules were 7–25 μm in width and 20–50 μm in length. The surface of green banana starch granules appeared smooth, while that of ripe banana granules had parallel striations (Fig. 3) (Kayisu et al., 1981), perhaps due to erosion. This likely shows that some areas are more difficult to hydrolyze that others (crystalline regions appearing after partial hydrolysis/digestion). Small granules disappeared more rapidly during ripening than large granules (Lii et al., 1982), presumably due to their greater surface area. Waliszewski et al. (2003) reported a granule shape for Valery banana starches similar to that reported by Kayisu et al. (1981), but with larger dimensions (14–88 μm in width and 21–108 μm in length). Plantain starches had a broad range of granule sizes (7.8–61.3 μm), with a number average diameter of ca. 26 μm (Table 3) (Eggleston et al., 1992).

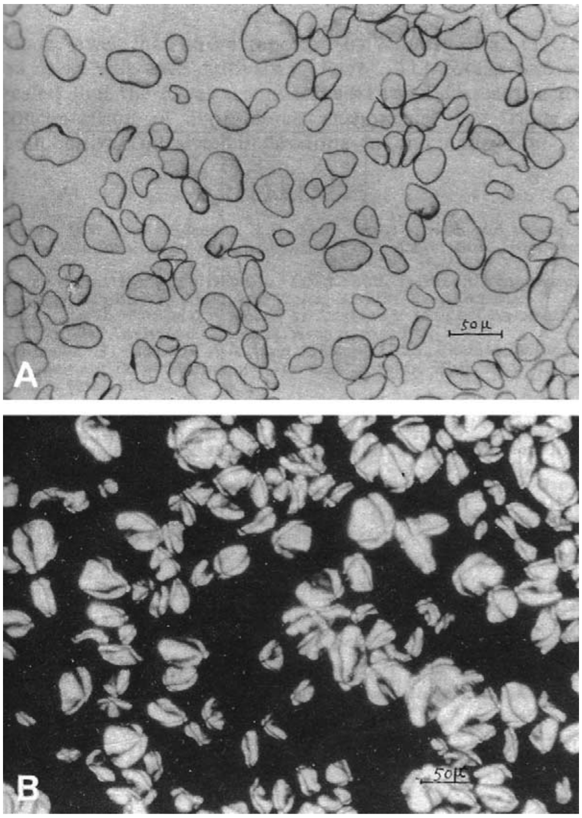

Fig. 2. Photograph of green banana starch granules: (A) under normal light; (B) under polarized light (Lii et al., 1982), reproduced with permission of the Institute of Food Technologists.

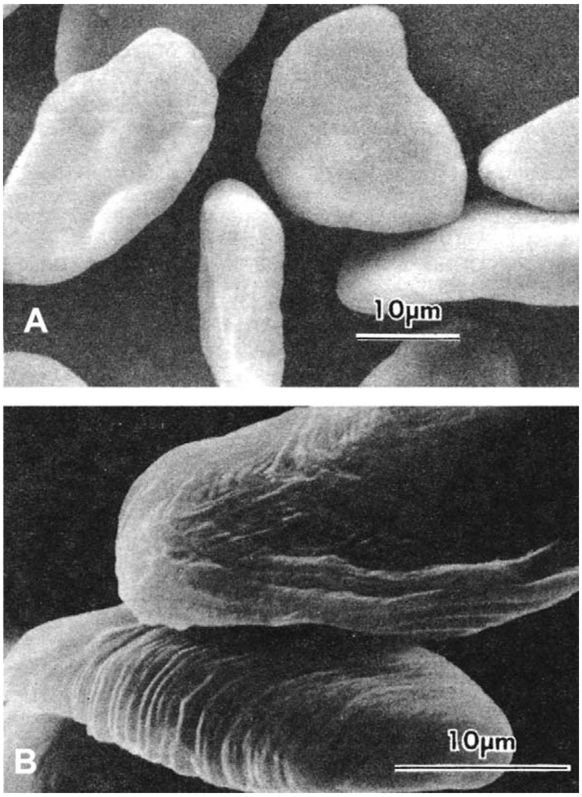

Fig. 3. Scanning electron micrographs of starch granules from green (A) and ripe (B) Valery bananas (Kayisu et al., 1981), reproduced with permission of the Institute of Food Technologists.

5. Composition and structure of banana starch granules

The functionality of starches is dependent on the proportions of their amylose and amylopectin components,

Table 3
Granular characteristics of plantain starches (Eggleston et al., 1992)

Starch	Density at 30 °C (mL/g)	Water-binding capacity (%)	Granule size (μm)	
			Average diameter	Range
Plantains				
Ihitisim	1.625	63.6	26.5	7.8–53.1
Agbagba	1.637	62.9	26.6	9.7–51.6
Obino L'Ewai	1.621	63.3	26.0	7.8–61.3
Bobby Tannap	1.621	71.7	24.1	9.1–56.4
Plantain hybrids				
548/4	1.639	64.6	26.4	6.4–69.8
548/9	1.628	62.5	26.6	9.4–65.6
582/4	1.625	62.0	29.0	6.4–69.8
566.32	1.631	62.4	35.1	7.1–74.3
Cooking bananas				
Blugoe	1.629	63.5	30.9	7.2–76.4
Fougamou	1.641	69.9	16.4	3.9–50.8

their molecular size and structures, starch granule properties, and to some degree, other components (lipids and proteins) associated with the granules.

Amylose contents of banana starch were reported to be 16% by Kayisu and Hood (1981), 19.5% (Cavendish) by Ling et al. (1982), ca. 17% (Cavendish) by Garcia and Lajolo (1988), and 40.7% (Valery) by Waliszewski et al. (2003). Chemical compositions of starches from bananas (plantains, plantain hybrids, and cooking bananas) were reported by Eggleston et al. (1992) (Table 4). Amylose contents in plantains were mostly in the 10–11% range. Cereal starches, on the other hand, typically have amylose contents in the 20–25% range. The molecular weight of banana starch amylose was reported to be 270,000 (Greenwood, 1960).

Debranching of the starch and its β-limit dextrin with pullulanase revealed that banana amylopectin has populations of $\overline{\mathrm{DP}}_n$ 45 and $\overline{\mathrm{DP}}_n$ 15 chains in a molar ratio of 1:6 (Kayisu & Hood, 1981). The β-amylolysis limit of banana starch was 67.3%, and the average chain lengths of the pullulanase-debranched starch and the debranched β-limit dextrin were 26 and 10, respectively. The $\lambda_{\max}$ of the starch–iodine complex (Valery) was reported as 563, 577, 583 nm (Macho) and 589 nm (Criollo) (Bello-Perez et al., 1999; Nunez-Santiago, Bello-Perez, & Tecante, 2004; Waliszewski et al., 2003), which gives an additional indication of the rather high amylopectin contents of these starches. Amylopectin has a $\lambda_{\max}$ of about 560 nm as compared to amylose, which is about 620 nm. Banana Naegeli dextrin had a lower concentration of singly branched chains (Fig. 4c) as compared with normal maize Naegeli dextrin (Fig. 4a). Chromatographic analysis of Naegeli dextrins indicated a closely clustered branching pattern of the banana amylopectin (Jane, Wong, & McPherson, 1997). The molecular weight and molecular distribution (polydispersity) of banana starch amylopectin has not been published.

Raw starch is a semi-crystalline material, and the degree and type of crystallinity present is dependent mainly on the structural characteristics of amylopectin, though retrograded (re-associated) amylose also produces a unique type of crystalline structure. Katz (1937) distinguished three types (A, B, and C) of crystalline structure for starch granules. Most cereal starches give A patterns; tuber, amylomaize, and retrograded starch yield B patterns; and certain root and seed starches, such as pea and bean starches,

Table 4
Composition of starches from plantains (Eggleston et al., 1992)

Starch (%)	Amylose (%)	Protein (%)	Ash (%)	Phosphorus (%)	α-Amylase susceptibility (%)
Plantains					
Ihitisim	11.2	0.94	0.34	0.022	1.10
Agbagba	11.9	0.87	0.27	0.020	1.27
Obino L'Ewai	11.1	0.98	0.32	0.020	1.70
Bobby Tannap	11.3	1.07	0.30	ND	1.83
Plantain hybrids					
548/4	10.3	1.08	ND	0.024	1.87
548/9	10.3	1.06	ND	0.031	1.83
582/4	9.1	ND	0.28	0.031	1.82
566.32	12.0	ND	0.32	ND	1.51
Cooking bananas					
Blugoe	12.9	0.99	0.41	0.021	2.64
Fougamou	17.2	1.02	0.35	0.027	2.23

ND, not determined.

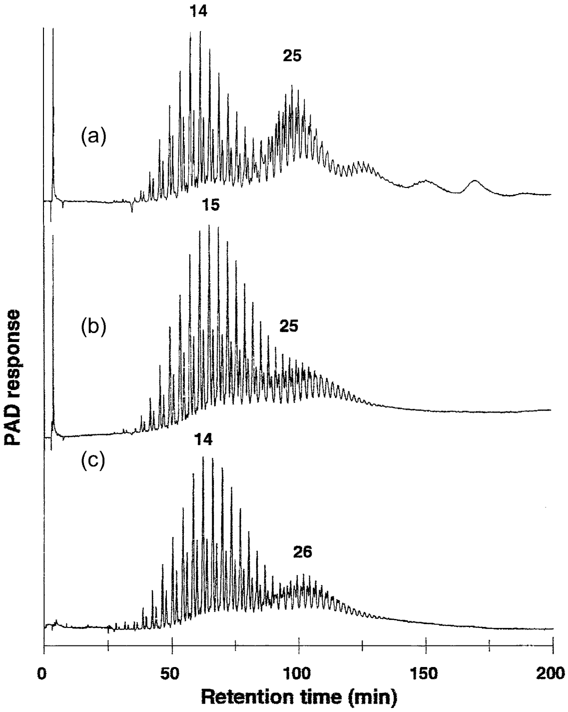

Fig. 4. HPAEC-ENZ-PAD chromatograms of normal maize (a), potato (b), banana (c) Naegeli dextrins with 66, 63, and 65% of total acid hydrolysis, respectively (Jane et al., 1997), reproduced with permission of Elsevier.

show C patterns. B-type diffraction patterns for banana starch (Fig. 5A) have been often reported (Faisant, Buleon et al., 1995; Lii et al., 1982; Teixeira, Ciacco, Tavares, & Bonezzi, 1998). Chang, Li, and Yang (1991), Jane et al. (1997) and Waliszewski et al. (2003) assigned a C-type pattern to banana starches. Bello-Perez et al. (2000) reported a typical A-type diffraction pattern for banana (Macho and Criollo) starches. So the crystalline type is not clear. We can only assume that the results of these various investigations were properly interpreted and that, therefore, banana starch can have A-type crystallinity, B-type crystallinity, or a mixture of the two depending on the varietal source and/or the growing conditions (environment) and/or the isolation technique. Percentage crystallinity has not been addressed in the literature so far.

Overall, it appears that the complete picture with respect to fine structure of banana starch from different plant sources and its relationship with functionality to application remains undetermined.

6. Physicochemical properties of banana starch

In terms of food applications, the functionality of starch is largely related to its gelatinization and pasting characteristics. When heated in water, starch granules swell dramatically, as well as lose their crystallinity, at their gelatinization temperature. Amylose typically leaches out of granules as they swell. Continued swelling results in rupturing of the swollen granule structure and solubilization (at least partially) of amylose and some amylopectin molecules. Networked amylose and amylopectin molecules and entrapped swollen granules and fragmented starch structures are responsible for viscosity and gel characteristics. The ability of amylose to retrograde rapidly and amylopectin to retrograde more slowly produces gels and affects the texture of starch-based products over time. The versatile physical structures of starch granules and the fine structure of their constituent polysaccharides are responsible for a wide variety of applications.

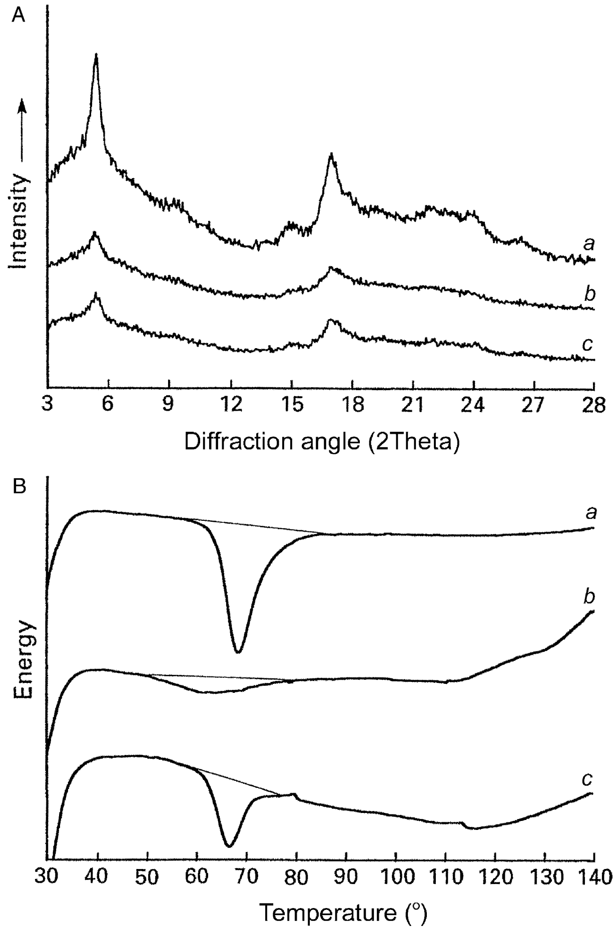

Fig. 5. X-ray diffraction patterns (A) and differential scanning calorimetry (DSC) (B) for (a) raw green banana flour, (b) a pooled ileal sample containing undigested banana starch, and (c) a resistant starch residue prepared in vitro from green banana flour (Faisant, Buleon et al., 1995), reproduced with permission of CAB International.

It is, thus, pertinent to review the numerous factors that determine banana starch functionality in foods (or for industrial purposes) and to compare them to current commercial starches.

6.1. Swelling power and solubility

Swelling power and solubility provide evidence of the magnitude of interaction between starch chains within both the amorphous and crystalline domains. The extent of this interaction is influenced by the amylose: amylopectin ratio and by the characteristics of amylose and amylopectin in terms of molecular weight distribution, degree of branching, length of branches, and conformation of the molecules (Ratnayake, Hoover, & Warkentin, 2002). Certain amylose–lipid complexes restrict swelling and solubilization (Hoover & Hadziyev, 1981). Also, protein within granules play an important role in controlling the swelling of granules (Han, Campanella, Guan, Keeling, & Hamaker, 2002a,b; Han & Hamaker, 2002).

The swelling and solubility patterns of green Valery banana starches were compared to those of other starches (Fig. 6) (Kayisu et al., 1981). Valery banana starch had a two stage-swelling pattern (Fig. 6a). Dissolution of banana starch was also compared to that of tapioca, potato, and milo (sorghum) starches (Fig. 6b). As in the case of swelling power, the solubility of banana starch was close to that of milo (sorghum) starch, and much lower than that of tapioca and potato starches.

Taiwan green banana starch exhibited a wide variation in swelling power and solubility depending on the ripening stages (Lii et al., 1982). At 95 °C, swelling power and solubility were in the ranges 30.1–35.3 (method of Leach, McCowen, & Schoch, 1959) and 16.3–21.7%, respectively, and in addition, banana starch exhibits rapid increases in swelling power (from 2.1 to 35.3) and solubility (from 0.14 to 21.7%) within the temperature range 65–95 °C. Viscoamylographic data suggested ‘cross-bonding’ in the granule (Eggleston et al., 1992; Lii et al., 1982).

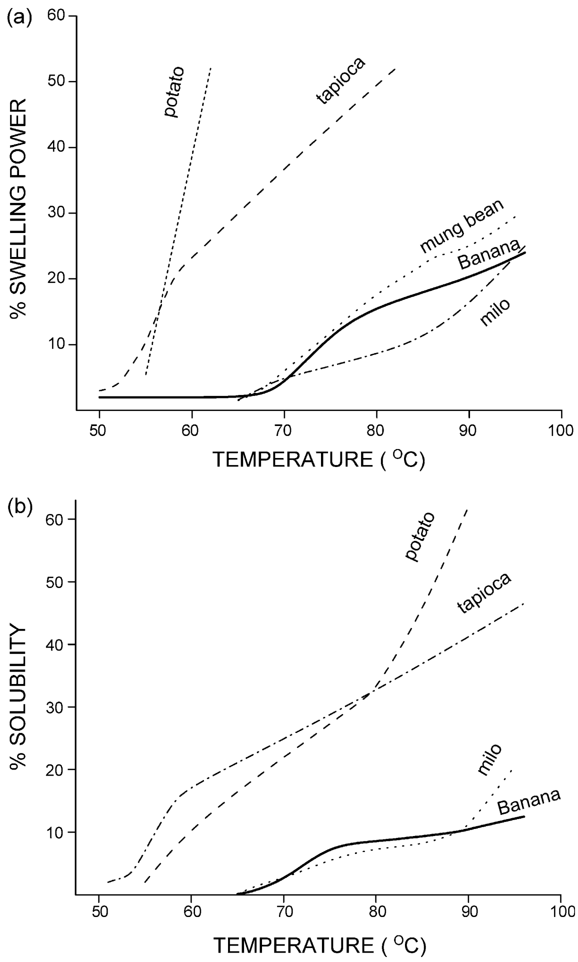

Fig. 6. Swelling (a) and solubility patterns (b) of green Valery banana starch (—) with other starches for comparative purposes (Kayisu et al., 1981), reproduced with permission of the Institute of Food Technologists.

Ling et al. (1982) reported that Cavendish starch granules, which were variable in both shape and size, exhibited surface cracking when heated in water to 65 °C; progressively greater swelling, deformation, and erosion occurred between 70° and 90 °C (Fig. 7).

6.2. Gelatinization

Starch, when heated in the presence of excess water, undergoes the order to disorder phase transition known as gelatinization over a temperature range characteristic of the starch source. This phase transition is associated with diffusion of water into the granule, water uptake by the amorphous background region, hydration and radial swelling of the starch granules, loss of birefringence, loss of crystalline order, uptake of heat, uncoiling and dissociation of double helices in the crystalline regions and amylose leaching (Donovan, 1979; Evans & Haismann, 1982). Gelatinization is followed by pasting. The gelatinization process, which is a function of the starch: water ratio, can be followed by differential scanning calorimetry (DSC). Initial (T_o), peak (T_p), and completion (T_c) gelatinization temperatures can be obtained from DSC thermograms.

The gelatinization temperature was reported to be 67–70 °C (Table 5) (Kayisu et al., 1981) and 69.5 °C (Waliszewski et al., 2003) for Valery banana starch and in the range of 70.1–74.6 °C for Cavendish banana starch (Ling et al., 1982). For Macho and Criollo banana starches, gelatinization temperatures of 77 and 74 °C were reported, respectively (Table 6) (Bello-Perez, Agama-Acevedo et al., 2000). Lii et al. (1982) investigated some physiochemical properties of dessert banana starches as a function of ripening stage; for stage 1, temperatures of 75, 77.5 and 80 °C for T_o, T_p and T_c, respectively, were found. These values are somewhat different from those reported by Waliszewski et al. (2003) (Table 6). Gelatinization enthalpy (ΔH) of Macho banana starch was found to be 14.0 and 16.8 J/g (Bello-Perez, Agama-Acevedo et al., 2000; Nunez-Santiago et al., 2004). The gelatinization temperature of starch from green bananas was found to be 69.4 °C with an enthalpy 17.1 J/g by Faisant, Buleon et al. (1995) (Fig. 5B).

6.3. Pasting properties

In general, banana starches show restricted swelling patterns with good stability, behaviors that are very similar to those of slightly chemically cross-linked starches. A banana starch paste had a Brabender viscoamylograph peak

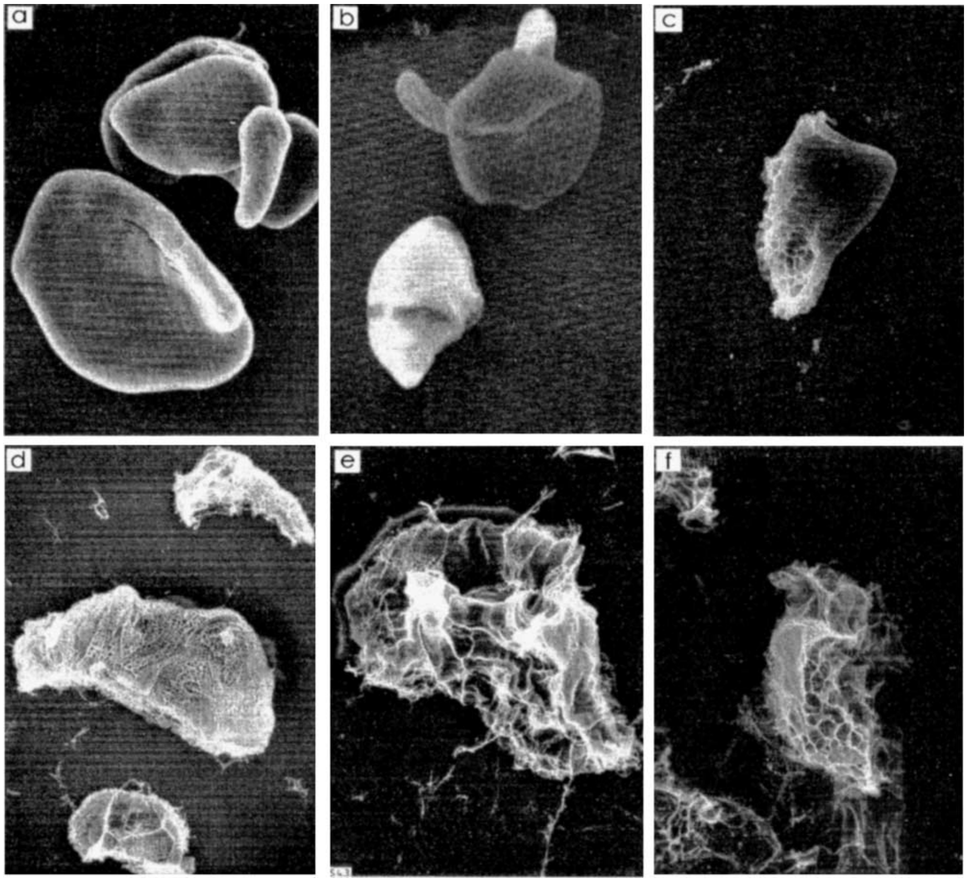

Fig. 7. Scanning electron micrographs at about 1100× magnification of green Cavendish banana starch granules: (a) room temperature, (b) 65 °C, (c) 70 °C, (d) 75 °C, (e) 85 °C, (f) 90 °C (Ling et al., 1982), reproduced with permission of Wiley-VCH.

viscosity four times that of a corn starch paste of the same concentration (6%) (Ling et al., 1982). Banana starch paste showed the highest viscoamylograph viscosities after 95°C compared to the common food starches in Table 5. Kayisu et al. (1981) reported Brabender viscosity curves for Valery banana starches (Fig. 8a). At low concentrations, the banana starch granules apparently resisted mechanical fragmentation. This explains the absence of a peak viscosity

Table 5
Brabender pasting temperature and viscosities of banana and common food starches

Starch	Pasting temperature (°C)	Brabender viscosity units				
		Peak	95 °C	95 °C hold	50 °C	50 °C hold
Banana	67–70	~960	~860	~800	~1190	~1050
Potato	61	2500	850	340	600	630
Tapioca	59	1400	520	280	500	510
Waxy corn	69	1000	400	250	390	370
Corn	73	470	470	350	830	760
Wheat	77	65	60	60	300	270

Adapted from Zobel (1984) with banana data from Kayisu et al. (1981) (Conditions: 7% starch; 1.5 °C/min heating rate; regular 60 min hold at 95 and 50 °C).

Table 6
Thermal properties of banana (*Musa paradisiacal*) starches (Bello-Perez, Agama-Acevedo et al., 2000; Nunez-Santiago et al., 2004)

Type of starch	T_o (°C)	T_p (°C)	T_c (°C)	T_c–T_o (°C)	ΔH (J/g)	T (°C)
Macho	69.6	74.5	81.6	12.0	13.0	77.3
Macho	75.5	80.7	90.0	14.5	16.8	75.0
Criollo	71.4	75.0	80.4	9.0	14.8	74.3

T, pasting temperature from RVA curves.

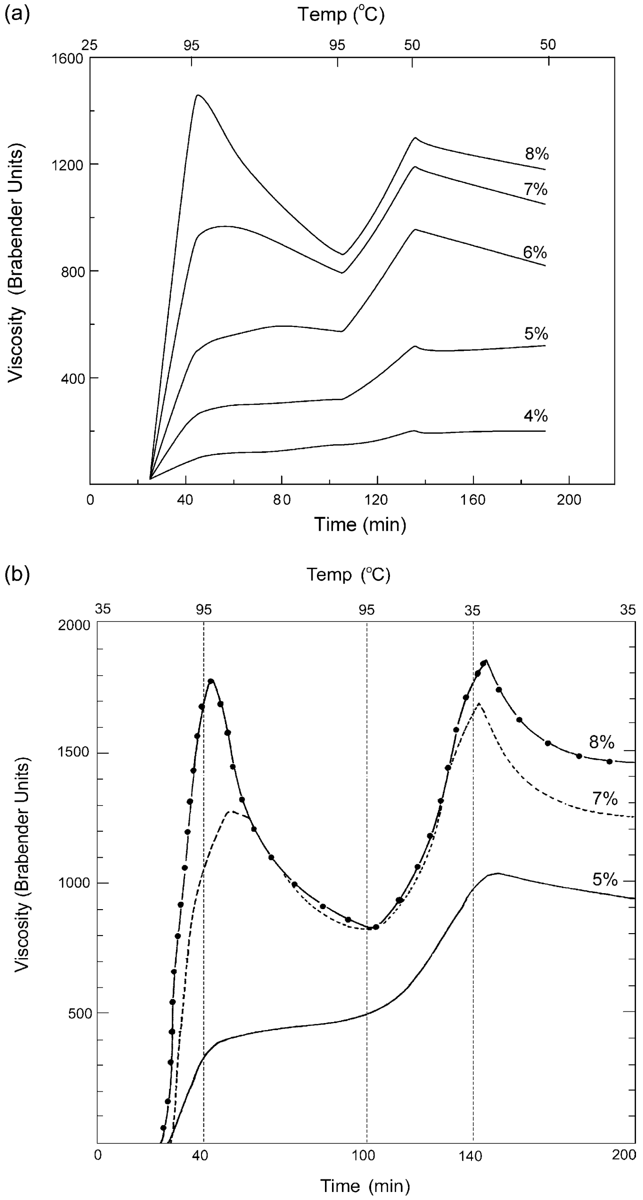

Fig. 8. Brabender viscoamylograms of green Valery banana starch (Kayisu et al., 1981) (a), and Taiwan dessert banana starch (Lii et al., 1982) (b), reproduced with permission of the Institute of Food Technologists.

and only a slight increase in viscosity during cooking. Viscosity profiles at higher concentrations (7 and 8%) demonstrated a pronounced peak viscosity and breakdown. This behavior may be explained by the fact that, at higher concentrations, swollen granules occupy most of the space and cannot move apart from each other, resulting in fragmentation. Banana starches at higher concentrations underwent pronounced setback (retrogradation) during cooling. Lii et al. (1982) reported similar result for Taiwan dessert bananas, but viscosities for were somewhat higher. Amylograms of 5% starch pastes showed no pasting peak and belonged to the restricted-swelling type (Fig. 8b). Eggleston et al. (1992) reported that no maximum paste viscosities were observed from plantains (AAB group) at 6, 7, and 8% concentrations (Fig. 9), which indicates that the swollen granules were rather resistant to breakdown on prolonged cooking. In conclusion, banana starch may have the superior property of behaving somewhat like a lightly cross-linked starch.

6.4. *Rheology*

Rotational viscometers are often used to examine the rheological properties of gelatinized starches. Bello-Perez et al. (1998) cooked banana starch in a boiling-water bath for 15 and 30 min, cooled the paste to 25 °C, and then measured the apparent viscosity with a Brookfield viscometer. The apparent viscosity of the pastes decreased when the shear rate increased from 2 to 20 rpm, indicating shear-thinning behavior (Fig. 10a) (Bello-Perez et al., 1998; Nunez-Santiago et al., 2004). Higher values of apparent viscosity of banana starch pastes were found when the suspension was heated for a longer time, and the viscosity of banana starch pastes remained stable at constant shear rate 20 rpm (Fig. 10b). The cited study did not compare the rheological properties of banana starch with those of other commercial starches.

7. Modified banana starches

7.1. *Chemical modification*

Bello-Perez, Contreras-Ramos, Jimenez-Aparicio, and Paredes-Lopez (2000) reported the effect of acetylation (DS 0.04) on banana (*M. paradisiacal* L., var. Macho) starch. The modified starch had a minor tendency to retrograde. At high temperatures, acetylated banana starch had a water retention capacity similar to that of the native starch. Acetylation considerably increased the solubility and swelling power of banana starch compared with native banana starch. When freeze–thaw stability was studied, acetylated banana starch drained approximately 60% of water in the first and second cycles, but in the third and fourth cycles, the percentage of separated water was low. Acetylation increased the viscosity of banana starch pastes. Usefulness of the modified starches as additives in frozen desserts and as thickeners in soups was suggested.

Waliszewski et al. (2003) carried out a study on properties of native and pregelatinized, phosphorylated (with sodium tripolyphosphate), phosphate cross-linked (with sodium trimetaphosphate) and hydroxypropylated banana starch. Molar substitutions (MS) of the three chemically modified starches were reported to be 0.16, 0.20, and 0.017, respectively. Hydroxypropylated banana starch had more than 50% higher water-binding capacity than the native starch. Phosphorylated and hydroxypropylated banana starches showed improvement in paste clarity; phosphorylated starch showed the best freeze–thaw stability. Hydroxypropylated and phosphorylated starches showed

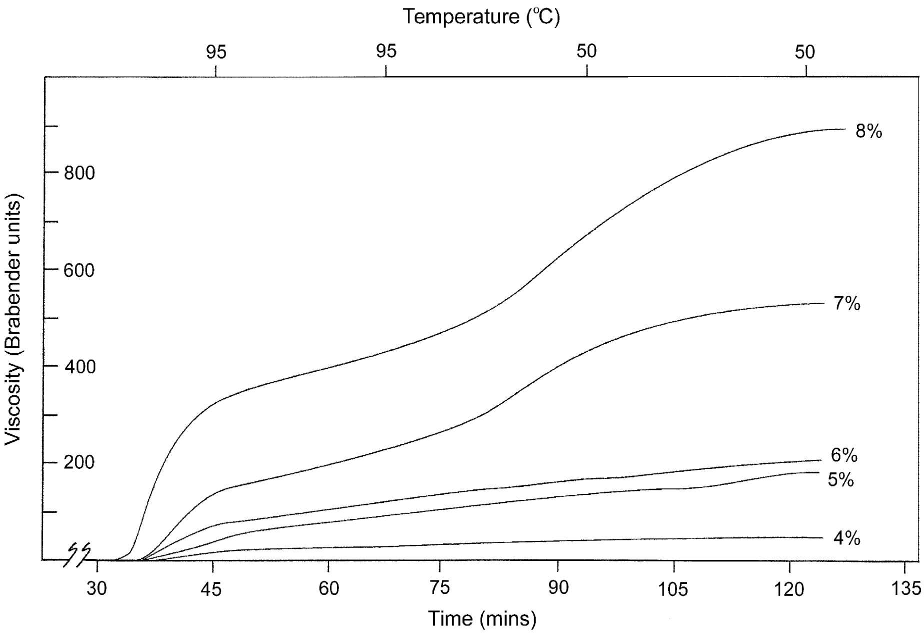

Fig. 9. Brabender viscoamylograms of 4, 5, 6, 7 and 8% green plantain hybrid starch (starch suspension was heated from 25 to 95 °C, kept at this temperature for 20 min, then cooled to 50 °C and held at this temperature for 20 min). (Eggleston et al., 1992), reproduced with permission of Wiley-VCH.

significant decreases in initial temperature of gelatinization. Results of water-binding capacity and swelling power of native and chemically modified starches submitted to heating from 50 to 90 °C are given in Table 7. Chemical modifications improved starch water-binding when hydrophilic groups were incorporated. At the lowest temperature (50 °C), the greatest increase in water-binding was observed in phosphorylated starch. When the temperature was increased to 90 °C, water-binding capacity increased, with the highest value obtained for hydroxypropylated starch. At 90 °C, this modified starch showed over 50% higher water-binding capacity than the native starch. The results again indicate that Valery banana starch has fairly restricted swelling power. Hydroxypropylated starch showed small increases in swelling power; however, phosphorylated and cross-linked starch did not. Overall, native banana starch had low solubility that was improved by chemical modification or pre-gelatinization. Phosphorylated starch had the best stability in freeze–thaw cycles, with no syneresis being observed after four cycles. After 10 cycles, only 10% syneresis occurred. Hydroxypropyl and phosphorylated starch showed significant decreases in initial temperature of gelatinization. All chemically modified starches showed significant increase in gelatinization enthalpy.

7.2. Enzymic and physical modifications

There are a number of products that may be made by treating starches with enzymes. Adams (1979) reported a small-scale production of vinegar from banana starch. Iizuka, Uenakai, Svendsby, and Yamamoto (1985) reported a process to enhance the fermentation by heating of green fingers at ca. 80 °C for 30 min. This study greatly improved the digestibility of the banana starch by glucoamylase and resulted in good alcohol production by yeast. The addition of pectic enzymes also accelerated the fermentation process.

Verhoff, Blatteis, and Barrett (1997) developed a process for conversion of green bananas to syrups using a sequence of steps involving grinding the bananas, heating the pulp, and treatment with an α-amylase to convert the starch into malto-oligosaccharides (liquefaction). They then changed conditions and treated the degraded starch molecules and other substances in the liquefied fluid with enzymes such as amyloglucosidase, pectinase, cellulase, macerase, etc. Finally the product was filtered and evaporated to a suitable concentration. A 67–69% conversion of the total solids to sugars was achieved. pH and temperature controls in each of the conversion steps were deemed important to the yield of glucose.

A granular cold-water-swelling starch was prepared from banana starch by treating it with ethanolic sodium hydroxide solution. (Bello-Perez, Romero-Manilla, & Paredes-Lopez, 2000). Solubility and swelling profiles were similar for the modified starches and the freeze–thaw stability of the modified starches was increased as compared with the poor stability of the native starch (Bello-Perez et al., 1999). Apparent viscosity of the modified banana starch pastes was higher than that of the native starch pastes. The granular cold-water-swelling starch was suggested to be useful as an ingredient of instant foods.

7.3. Prospects and challenges

New and more useful commercial starches can potentially be developed using chemical, physical, and biological

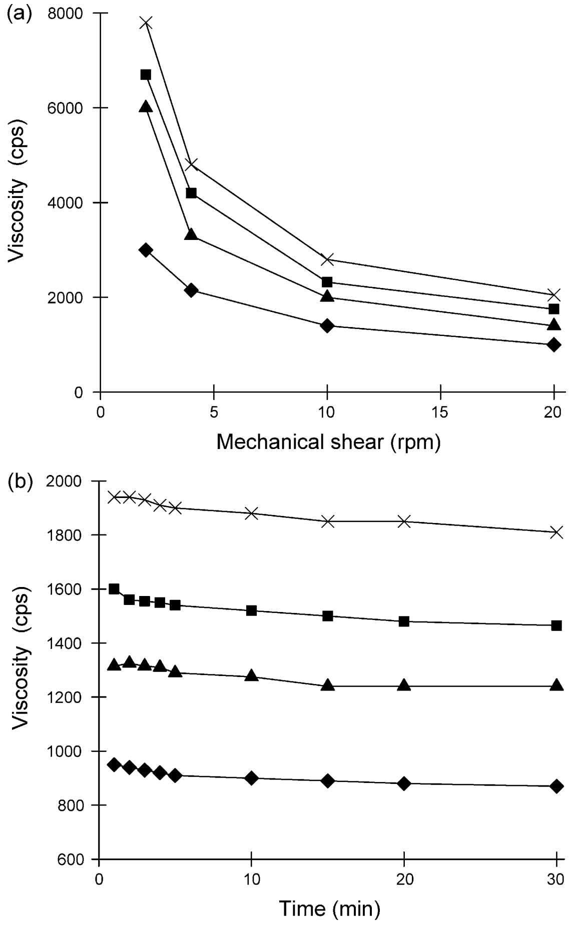

Fig. 10. Effect of mechanical shear on paste viscosity (a) and paste viscosity at constant shear 20 rpm of 5% (db) (b) banana starch paste determined using a Brookfield viscometer at 25 °C: ■ spindle No. 2 and cooked in a boiling bath for 30 min, ◆ spindle No. 2 and cooked for 15 min, × spindle No. 3 and cooked for 30 min, ▲ spindle No. 3 and cooked for 15 min (Bello-Perez et al., 1998), reproduced with permission of Wiley-VCH.

modification. The potential is even greater that new useful starch products will result from combinations of these modifications with allowable reagents and levels of addition. Native starches represent many disadvantages, such as a high tendency of their pastes to retrograde and synerese, and the poor freeze–thaw stability and cohesiveness of their pastes, thus limiting their application for food and industrial products (Fleche, 1985; Wurtzburg, 1986). Many starches available commercially have been modified physically (mainly via pre-gelatinization) or by slight and relatively simple chemical modifications to fulfill the needs of various industries.

Chemically modified food starches generally show better paste clarity and stability, increased resistance to retrogradation, and better freeze–thaw stability. Banana starch, along with rice, pea, and amaranth starches, are promising for new base starches to be employed in modification processes (BeMiller, 1997). However, it should be pointed out that the use of chemically modified starches in the food industry is somewhat restricted in some regions by sophisticated consumers, legislation, and economics (Lillford & Morrison, 1997). The value of modified banana starch, if any, will be superior properties for specific niche applications since no starch competes economically with native and modified corn starches at this time. However, the full range of allowable modifications of different banana starches has not been investigated.

8. Digestibility of banana starch

8.1. Raw starch digestibility

Digestibility of raw native starches has been attributed to the interplay of many factors, such as starch source, granule size, amylose:amylopectin ratio, extent of molecular association between starch components, degree of crystallinity, amylose chain length, and presence of amylose–lipid complexes (Cummings & Englyst, 1995). Large granules such as those of raw potato and banana starches are known to be rather susceptible to mechanical alteration, especially after being in the low pH environment of the stomach (Gallant et al., 1992). Factors imparting resistance to native starches remain obscure, but several have been proposed: the type and degree of crystallinity (Ring, Gee, Whittam, Orford, & Johnson, 1988), amylose content (Behall, Scholfield, Yuhaniak, & Canary, 1989; Cone & Wolters, 1990), and granule size (Franco, do Rio Preto, Ciacco, & Geraldo, 1992). Morphology and ultrastructure, such as the specific area and porosity of granules, should also be considered (Colonna, Leloup, & Buleon, 1992; Gallant et al., 1992).

The principal commercial starch, corn starch, is digested by hydrolytic enzymes (amylases) which access the interior of granules via channels, i.e. corn starch granules are

Table 7
Water-binding capacity (g of water retention/g of starch × 100) and swelling power (g of water/g of dry starch × 100) of native and chemically modified Valery banana starch (Waliszewski et al., 2003)

Starch type	Water-binding capacity					Swelling power				
	50 °C	60 °C	70 °C	80 °C	90 °C	50 °C	60 °C	70 °C	80 °C	90 °C
Native	8.9	19.3	35.1	40.4	44.7	1.8	2.2	2.3	7.8	8.7
Phosphate (DS 0.16)	16.7	30.7	41.4	46.1	49.1	3.3	6.1	6.7	9.0	9.8
Cross-linked phosphate (MS 0.20)	9.6	19.6	34.7	42.7	44.7	1.9	3.6	5.9	9.0	9.0
Hydroxypropyl (MS 0.017)	11.5	29.8	48.8	60.8	68.8	2.3	3.2	9.0	12.4	13.8
Pre-gelatinized	40.3	42.8	42.9	43.1	43.0	8.0	8.5	8.6	8.6	8.6

primarily hydrolyzed from the inside out (Hood & Liboff, 1983; Leach & Schoch, 1961; Nikuni & Whistler, 1957). The starch granules of corn and related cereals (sorghum and millet) have channels connecting the internal cavity with the external environment (Huber & BeMiller, 1997). The large granules of wheat, rye, and barley also contain openings to channels at the equatorial groove (Fannon, Hauber, and BeMiller, 1992). On the other hand, starches without pores and channels, such as potato, yam, and lily starches, digest through surface erosion of the granule (Gallant, Bouchet, Buleon, & Perez, 1992; Jane et al., 1997). Banana starch is in the latter category, and raw, i.e. uncooked, banana starch appears to be resistant to enzyme-catalyzed hydrolysis (Cerning-Beroard & le Dividich, 1976; Cummings & Englyst, 1991; Englyst & Cummings, 1986; Eggleston et al., 1992; Faisant, Buleon et al., 1995; Faisant, Gallant, Bouchet, & Champ, 1995; Fuwa, Sugimoto, Takaya, & Nikuni, 1979; Sugimoto, Fujita, Takaya, & Fuwa, 1980; Teixeira et al., 1998).

8.2. Resistant raw banana starch

Native raw banana starch appeared to be highly resistant to hydrolysis by enzymes (Cerning-Beroard & le Dividich, 1976; Cummings & Englyst, 1991; Eggleston et al., 1992; Englyst & Cummings, 1986; Englyst, Veenstra, & Hudson, 1996; Faisant, Buleon et al., 1995; Faisant, Gallant et al., 1995; Fuwa et al., 1979; Sugimoto et al., 1980). Microscopic observations revealed that raw banana flour contained irregularly shaped starch granules with smooth surfaces. A smooth and dense surface of native banana starch granules could partially account for their resistance. It is likely, as indicated by scanning and transmission electron microscope studies (Gallant et al., 1992), that the starch granule has an external thick layer (several μm) of larger blocklets that impede enzyme action and reduce the rate of hydrolysis. Perhaps the density of such blocklets is higher at the periphery of banana starch granules. In addition, some residual cell walls present in banana flour may have entrapped starch granules, thereby protecting them from enzymic attack (Faisant, Buleon et al., 1995; Tester & Karkalas, 2002). In conclusion, it is likely that both intrinsic resistance and encapsulation of starch granules are responsible for the low digestibility of raw banana starch and flour.

The breakdown of starch during banana ripening occurs rather rapidly, but over a period of many hours. However, as mentioned above, raw banana starch is known to present a low susceptibility to non-banana amylases, including the α-amylase of rats (Fujita, Glover, Sugimoto, & Fuwa, 1982) and humans (Englyst & Cummings, 1986). Englyst and Cummings (1986) found that up to 78% of ingested α-glucans from raw banana starch escaped digestion in the small intestine of ileostomates. They studied the digestion and absorption of banana carbohydrates from the small bowel by feeding ileostomy subjects raw banana from six batches of different ripeness and measuring the amounts excreted in the effluent. Up to 90% of the starch could be accounted for in the effluent. The amount of banana starch not hydrolyzed and absorbed in the human small intestine, and therefore passing into the colon, may be up to eight times more than the non-starch polysaccharide (fiber) present in the banana fruit, of course depending on the degree of ripeness when the fruit is eaten. Only 23% of the starch fed was recovered as starch in the ileostomy effluent, but in those cases where there was substantial starch in the banana, there was a large increase in the amounts of maltose, maltotriose, and other starch-derived saccharides recovered in the effluent. The possible, but not established, difference in the breakdown of raw banana starch in the ripening banana versus the mammalian digestive tract could be the result of different enzyme systems.

Faisant, Buleon et al. (1995) and Faisant, Gallant et al. (1995) studied the digestion of freeze-dried green banana flour in the upper gut by an intubation technique in six healthy subjects over a 14 h period. The banana flour used in their study was composed of 38 g/kg protein, 92 g/kg dietary fiber, and total α-glucans 770 g/kg (60 g/kg oligosaccharides and 710 g/kg ‘insoluble’ starch). Using the method of Englyst, Kingman, and Cummings (1992), resistant starch (RS) content (see Section 8.2) was 542 g/kg (Faisant, Buleon et al., 1995). Eighty-four percent of ingested α-glucans reached the terminal ileum, but were then almost totally fermented in the colon by the microflora, a potentially positive result relating to colonic health. Oligosaccharides and the more easily digestible fraction of RS should ferment more rapidly than the resistant part. Structural study of the resistant fraction showed that only a small part of the α-glucans that escaped digestion in the small intestine was composed of oligosaccharides from starch hydrolysis; the rest was insoluble starch in granular form with physical characteristics similar to those of raw banana starch. The gelatinization temperature of the recovered resistant starch was reduced to ca. 61 °C, compared with 69.4 °C for the raw starch (Fig. 5b). The 84% RS value (see Section 8.2) found by Faisant, Buleon et al. (1995) was greater than the about 72% RS found in vivo by Englyst and Cummings (1986) in ileostomized subjects given unripe bananas. The difference may be due to the degree of banana ripeness in the two studies.

It is important to know structures of the α-glucans that escape digestion in the small intestine since they will indicate the digestive mechanism involved and be predictive of their fate in the colon. Results with banana flour confirmed that a substantial starch fraction escaped digestion because of limited time and/or capacity for hydrolysis (Faisant et al., 1993). The major part of the starch granules collected in the terminal ileum could have been partially hydrolyzed by amylolytic enzymes. After their passage through the small intestine, banana starch granules appeared to be exo-corroded; some exhibited several irregular pits, crevices or holes (Faisant, Gallant et al., 1995).

Thus, the porosity and surface area may have been altered during passage through the small intestine.

8.3. Cooked banana starch

Starch can be classified as rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (Englyst et al., 1992). The designations of rapidly available glucose (RAG) and slowly available glucose (SAG) reflect the rate at which glucose becomes available for absorption in the human small intestine. The search for new sources of slowly digestible and low-glycemic-index starches or techniques to manipulate, and therefore moderate, starch digestion properties in ingredients will permit the formulation of starch-based processed foods with low glycemic indices and extended energy release characteristics. Starch fractions in raw banana flour (total starch content 75%) were reported to be RDS 3%, SDS 15%, RS 57%, and RAG 6% (Englyst et al., 1992).

Digestion performance of cooked banana starch would be of importance to the food industry, since the consumption of cooked starch in human food is much more common than that of raw starch, so the influence of cooking on rate and degree of banana starch digestion needs to be further investigated. No recent papers were found on digestion properties of cooked banana starch, although older citations give an implication that it may have a comparative long digestion characteristic. After cooking, the easily digestible/hydrolyzable starch fraction of banana starch was only 47% of the total, comparable to that of a known low-digestible cooked yam starch (40%) (Cerning-Beroard & le Dividich, 1976; Lozano et al., 1973).

9. Conclusion and outlook

The available literature suggests that banana starch has quality attributes that could give it a place in the commercial starch industry, both as native starch and as modified food starch. The specific properties of banana starch include, but are not limited to, the following:

(1) Relatively low amylose contents in majority of the reports (ca. 10–20%) (Eggleston et al., 1992; Garcia & Lajolo, 1988; Kayisu & Hood, 1981; Ling et al., 1982) and high (ca. 1–2%) protein contents (Bello-Perez et al., 1998, 1999; Eggleston et al., 1992; Lii et al., 1982; Nunez-Santiago et al., 2004) compared with protein contents of $<0.6\%$ for common commercial starches (Tester et al., 2004);

(2) Restricted swelling, low solubility, and negligible retrogradation. Comparably low swelling power and low solubility may reflect a more ordered, more strongly bonded, denser granule structure (Eggleston et al., 1992; Faisant, Gallant et al., 1995; Kayisu & Hood, 1981; Lii et al., 1982; Nunez-Santiago et al., 2004; Sugimoto et al., 1980; Waliszewski et al., 2003; Zhang & Whistler, 2002);

(3) Sufficient strength to maintain granule integrity during prolonged heating. Pasting and paste properties of banana starch suggest that it behaves as if it were slightly cross-linked. Brabender amylograph showed high break down and cooling viscosities for banana starch pastes (Bello-Perez et al., 1998; Ling et al., 1982; Nunez-Santiago et al., 2004; Rodriguez-Sosa & Parsi-Ros, 1984);

(4) High resistance of raw banana starch to the attack of α-amylase and glucoamylase in in vivo and in vitro digestions, with 75–84% of the starch granules ingested reaching the terminal ileum (Cerning-Beroard & le Dividich, 1976; Cummings & Englyst, 1991; Eggleston et al., 1992; Englyst & Cummings, 1986; Englyst et al., 1996; Faisant, Buleon et al., 1995; Faisant, Gallant et al., 1995; Fuwa et al., 1979; Sugimoto et al., 1980).

The large amount and low cost of cull bananas is a compelling reason to undertake a determination of the food and industrial value of banana starch. Starch can be isolated in a relatively pure state from reject bananas. There is evidence that the starch is at least as functional as corn starch and may have superior properties of behaving like slightly cross-linked corn starch, which would give it a higher market value as an unmodified/native starch in many applications. Its potential acceptance in foods is enhanced by its absence of flavor. If its properties differ sufficiently from starches of other plants, it could command a premium price as a food ingredient. Bananas are a potentially important alternative source of starch for food and non-food applications. In addition, there is evidence based on recent hemicellulose research to warrant the speculation that useful hemicelluloses can be isolated from residue peels.

In general, utilization of unmodified starches is restricted by the tendency of amylose to retrograde and shear damage to swollen granules. Functional properties of starches available on the commercial market are often slightly modified chemically so that they better meet food industry requirements of freeze–thaw stability of pastes and gels, gel transparency, stability of gels to syneresis, proper texture, improved film formation, adhesion, etc. All starches have similarities that make them somewhat interchangeable in both native and chemically modified forms in many applications. However, each starch source is also unique in one or more properties, so that the functionalities of one are not duplicated exactly by another. The challenge with regards to banana starch is to determine and exploit its uniquenesses.

Although considerable knowledge has been accumulated in the past two or three decades, a complete picture with respect to banana starch structure, properties, and applications and differences between cultivars remains lacking. The literature provides only a few answers to many questions regarding banana starch molecular architecture and how the component parts (amylose, amylopectin, lipid, and protein) interact to provide the three-dimensional granular structure that provides its properties. Moreover, on the issue of the digestion properties of raw and cooked banana starch, a number of questions remain unanswered, such as whether cooked banana starch truly has moderated digestion properties, and, if so, why. By understanding the molecular structure and composition of banana starch, its properties can be optimized.

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