Available online at www.sciencedirect.com
SCIENCE DIRECT®
Food Chemistry 89 (2005) 261–270
Food Chemistry
www.elsevier.com/locate/foodchem

The quality of boiled cassava roots: instrumental characterization and relationship with physicochemical properties and sensorial properties

Wilfrid Padonou [a], Christian Mestres [b,*], Mathurin Coffi Nago [a]

[a] *Faculté des Sciences Agronomiques, Université d'Abomey Calavi, 01 BP 526 Cotonou, Benin*
[b] *CIRAD-CA, Programme Cultures Alimentaires, TA 70/16, 73 Avenue JF Breton, 34398 Montpellier Cedex 5, France*

Received 17 June 2003; received in revised form 16 February 2004; accepted 16 February 2004

Abstract

The physicochemical properties of twenty promising new improved cassava cultivars (13 sweet and 7 bitter), harvested at maturity in Benin, were assessed. In parallel, instrumental measurements and sensorial tests were performed to assess boiled cassava quality. These properties and physicochemical properties were tentatively correlated. The colour score of boiled cassava tuber was closely correlated with ΔE measured on fresh pulp, while mealiness (or friability) could be assessed by resistance to penetration, measured on cooked tuber slices. Mealiness could also be predicted from starch functional properties (such as apparent viscosity after pasting), cyanide potential and the water content of fresh tubers. The cassava tubers had a narrow amylose content range (18.2%–22.6% starch basis). In addition, bitter cultivars appeared to be quite homogeneous with, in particular, high sugar and protein contents but low fibre contents. They also had original starch functional properties, with high solubility and low paste viscosity.

Keywords: Cassava; Colour; Texture; Functional properties; Sensory properties

1. Introduction

Cassava (*Manihot esculenta*, Crantz) is one of the most important root crops in tropical countries. In Benin, production has multiplied almost fivefold in the last 20 years, reaching an estimated 2 million tons in 1997 (FAO, 1997). Cassava roots are consumed in Benin in several forms, including boiled in water, roasted, fried or after conversion into intermediate products, such as gari, flour (from dried chips), tapioca or starch. Boiled cassava (fingnin dida) is one of the most common forms of consumption in both rural and urban areas. It is prepared by peeling, cutting and boiling fresh cassava roots. The main quality attributes of boiled cassava are whiteness, sweetness and friability, all of which should be high.

The sensory quality of cassava roots is an important factor for the acceptance of new improved cultivars by farmers (Safo-Kantaka, Boampong, & Asante, 2002). It is also one of the major reasons for the use of a harmful bitter cultivar in Malawi, as farmers there believe that bitter cultivars give a whiter flour and a less elastic stiff porridge (Chiwona-Karltun et al., 1995). However, although some publications deal with variation in starch quality with cultivar and age of plant (Defloor, Dehing, & Delcour, 1998; Eggleston, Omoaka, & Arowshegbe, 1993; Moorthy & Ramanujam, 1986) particularly with a view to industrial use, very little is known about the cultivar effect on the quality of traditional dishes prepared from cassava roots. Studies by Wheatley and Gomez (1985) and Asaoka, Blanshard, and Rickard (1991) showed an effect of both cultivar and age at harvesting on the organoleptic properties (taste and texture) of boiled cassava pieces from four cultivars. However, they were unable to find any relationship between organoleptic quality and the physicochemical

* Corresponding author. Fax: +33-46-761-4444.
E-mail address: mestres@cirad.fr (C. Mestres).

0308-8146/$ - see front matter
doi:10.1016/j.foodchem.2004.02.033

characteristics of tubers or starch and concluded that further data on cassava root quality were required.

More data are available on the texture of boiled potato, particularly with regard to its friability (or mealiness), the principal sensory attribute of boiled potato tuber (Unrau & Nylund, 1957). It is generally held that tuber friability is due to cell rupture on chewing (Warren & Woodman, 1974). Several authors have related potato friability to starch content or starch properties. Starch swells during boiling, inducing a distension of the cell wall which facilitates cell separation in mealy potatoes (McComber, Osman, & Lohnes, 1988). However, no clear correlation has been found between starch content or starch properties and potato friability (McComber et al., 1988; Warren & Woodman, 1974) and other authors have hypothesized that friability should also or primarily be linked to cell wall properties (Iritani, Powers, Hudson, & Weller, 1977; Nonaka, 1980).

The aim of this paper is to assess the organoleptic properties of boiled cassava roots from 20 promising new improved cultivars harvested at maturity in Benin, to develop instrumental tests than can be routinely used to screen cassava cultivars for root quality, and to attempt to relate the sensory qualities of cassava roots to their physicochemical properties.

2. Materials and methods

2.1. Material

Twenty cassava cultivars were grown at the Centre for Food Plant Research in Niaouli, part of the Benin National Institute of Agronomic Research. Thirteen of these cultivars were sweet and seven bitter. The roots were harvested 13–15 months after planting and immediately transferred to the laboratory, where they were stored at 4 °C and analyzed within a few days. Part of the sample of each cultivar was peeled, cut into pieces, oven-dried at 45 °C for several days, then milled in a centrifuge mill (Roetsch, Haan, Germany) with a 250 μm outlet sieve.

2.2. Sensory evaluation

Roots were peeled, cut into pieces, washed twice and boiled for 40–45 min. Four samples were prepared simultaneously for each test and assessed by a panel of twenty people. The panel was previously selected and trained for taste and colour attributes of yam thick paste (Mestres, Dorthe, Akissoé, & Houhouigan, 2004). Three attributes were considered to be the most important by the panel considering boiled cassava roots: colour, friability and taste. The assessors were thus trained to quantify these attributes on a semi-structured scale (1–5) by tasting 4 cultivars among the 20 (two sweet and two bitter) with 4 replications. The scale was fitted by consensus for the three attributes: from yellowish (1) to perfectly white (5) for the colour, from hard (1) to very friable (5) for the friability (this was evaluated by the disintegration ability between fingers and in the mouth) and from bitter (1) to very sweet (5) for the taste. After training, each cultivar was tested once and mean value and standard error calculated.

2.3. Penetration test

A penetration test was performed to determine the firmness of the cooked roots. Two roots of each cultivar were peeled and three 2.5 mm thick slices were cut from each root and cooked with open steam for 20 min. Firmness was assessed using a Texture Analyser (Stevens-LFR) equipped with a cone penetrator moving at 2 mm/s to a final penetration depth of 3 mm. Firmness was defined as the maximum value reached during the test. Each result was expressed as the mean value (in Newton) of 72 readings. Twelve measurements were made on each slice (four different readings for the outer, the middle and the inner part of the slice).

2.4. Colour

Colour was evaluated using a chromameter (Minolta) on fresh cassava pulp obtained by crushing the peeled root with a pestle and mortar. The chromameter was calibrated each day with a white ceramic. The International Lab system (L*, a* and b) was used and ΔE, the total difference from the white ceramic standard, was calculated (Hounhouigan, Nout, Nago, Houben, & Rombouts, 1993).

2.5. Proximate analysis

The water content of fresh roots was determined after heating root pieces at 105 °C for several days. All other functional and physicochemical analyses were performed on cassava flour in duplicate. Moisture content was determined after heating at 105 °C for 24 h. Protein content was calculated from nitrogen determination by the Kjeldahl procedure using 6.25 as conversion factor, while lipid content was determined after extraction with petroleum ether (AACC, 1984). Total sugar content was determined using the Luff–Schoorl procedure (Lees, 1968) and total fibre content according to Osborne and Voogt (1978). Total cyanide content was assessed by the procedure of Essers (1995) except that linamarase was replaced by beta-glucosidase from almonds (Sigma # G 0395).

2.6. Starch physicochemical and functional properties

The amylose content of the cassava flour was determined using differential scanning calorimetry according to Mestres, Matencio, Pons, Yajid, and Fliedel (1996), while gelatinization onset temperature and enthalpy change were determined during the heating run at 10 °C min^{-1} (Mestres & Rouau, 1997a). Intrinsic viscosity was measured at 35 °C in 0.2 N potassium hydroxide solution according to Mestres and Rouau (1997a). The pasting behaviour of the flour was determined on 8% (db) water dispersion using a Rapid Visco Analyser (RVA, Newport Scientific, Narabeen, Australia). The dispersion was heated from 35 to 80 °C at 6 °C min^{-1}, held at 80 °C for 3 min then cooled to 50 °C at 6 °C min^{-1}. Pasting temperature and maximum and final viscosities (V_{max} and V_{fin}, respectively) were recorded on the profile. Solubility and swelling power were determined on 4% dry matter paste prepared in the RVA: the dispersion was heated from 35 to 70 °C at 6 °C min^{-1}, then held at this temperature for 3 min. The paste was immediately centrifuged and swelling and solubility determined according to Mestres, Nago, Akissoë, and Matencio (1997c).

2.7. Statistical analysis

Analysis of variance and comparison of means were performed using Minitab 13.2 (Minitab Sarl, Paris, France), considering two groups of cultivars (with low and high cyanide content). Principal component analysis and regression models were also performed, using STAT-ITCF software (ITCF, Boigneville, France).

3. Results and discussion

3.1. Chemical composition

A great variation in the water content of fresh roots was observed: it ranged from 60.3% to 87.1% (wb) without any significant difference between sweet and bitter cultivars (Table 1). The range lay between that observed by Wheatley and Gomez (1985) on four cultivars harvested at various ages and seasons (from 65 to 74% wb) and the extremely wide one observed by Zakhia, Wheatley, O'Brien, and Dufour (1994) on a collection of 565 cultivars (from 52 to 87% wb). Proximate analysis of the dried roots revealed a low lipid content (mean value of 0.56% db) with a very low variation between cultivars (coefficient of variation of 12%). The variation was two to three times higher in the case of the total sugar, fibre and protein contents. Bitter cultivars had higher total sugar and protein contents but lower fibre content. This was particularly striking in the case of total sugar content, which was more than twice as high in bitter cultivars (mean value of 5.5% db) reaching a value of 8.9% (db) for the TMS91/02324 cultivar. The

Table 1
Chemical composition of peeled cassava roots (first column, wet basis) and cassava flours (other columns, dry basis)

Cultivars	Water	Amylose	Total sugars	Fibres	Proteins	Lipids	Cp[a]
Sweet cultivars							
TMS 94/0177	75.2	18.1	2.09	2.63	1.67	0.53	10.3
TMS 94/0461	69.6	16.5	2.28	4.71	1.66	0.64	8.8
TMS 92B/00061	78.8	18.1	2.22	3.29	3.17	0.45	8.2
TMS I 94/0270	67.4	17.6	1.92	3.97	3.03	0.61	8.0
TMS I 94/0239	64.0	17.4	1.76	4.19	2.76	0.56	10.1
TMS I 94/0237	65.4	16.7	2.12	4.52	3.88	0.42	8.3
TMS 94/0583	62.1	15.7	2.16	4.92	1.97	0.50	9.7
TMS 94/0192	66.8	16.4	1.90	4.01	3.07	0.58	10.1
TMS 91B/00455	87.1	15.5	2.57	4.48	2.73	0.65	9.9
TMS 92B/00068	73.8	18.0	2.43	3.41	2.86	0.62	20.0
BEN 86052	60.3	18.9	2.44	2.78	2.16	0.63	10.9
MCN 85043	65.2	19.2	2.44	3.99	2.51	0.57	11.0
RB 89509	72.4	16.8	2.09	4.42	2.65	0.53	11.4
Mean value	69.8	17.3	2.19	3.95	2.62	0.56	10.5
Bitter cultivars							
TMS 93/0700	80.9	17.3	4.68	3.40	2.38	0.59	15.0
TMS 92/0057	63.1	19.0	2.97	4.20	4.08	0.55	9.5
TMS 91/02327	63.1	18.1	4.92	2.65	3.47	0.50	11.9
TMS 93/0614	72.9	17.1	5.63	3.83	3.08	0.63	9.7
TMS 91/02324	63.8	17.4	8.93	2.63	3.68	0.47	9.9
TMS 93/0560	61.3	16.4	7.50	2.77	3.10	0.63	11.5
TMS 93/0517	75.3	15.9	3.60	3.24	2.82	0.59	10.1
Mean value	68.6	17.3	5.46	3.24	3.23	0.57	11.1
Overall mean value	69.4	17.3	3.3	3.70	2.84	0.56	10.7
Cvc[b]	11	6	37	20	24	12	26

[a] Cyanide potential (ppm or mg/kg).
[b] Coefficient of variation between cultivars.

total cyanogenic potential of the flour did not vary significantly with type of cultivar. The mean value (10.7 ppm, db) was around the FAO/WHO limit for cassava flour (10 ppm, cited by Essers, 1995) and in the same range as that measured by Kemdirim, Chukwu, and Achinewhu (1995) on Nigerian cassava flour. The cyanogenic potential was measured on flour, i.e. after a drying process known to dramatically lower the cyanogenic potential of cassava roots. This explains the low value found in our samples, particularly for bitter cultivars. It follows that measured values cannot be used to confirm the classification of cassava cultivars by bitterness.

3.2. Starch physicochemical and functional properties

The coefficients of variation of amylose content and of the thermal characteristics of starch gelatinization were low and mean values were similar for bitter and sweet cultivars (Table 2). Calculated on a starch basis (assuming a starch content of 85% db), the amylose content varied from 18.2 to 22.6%, with a mean value of 20.4%. These values and their narrow range are in agreement with previous results (Asaoka et al., 1991; Defloor et al., 1998; Moorthy, 1994; Sriroth et al., 1999), which all showed a relatively constant amylose content (around 20% ± 2%) for cassava starch regardless of cultivar or harvest conditions. The mean values of the enthalpy change and onset temperature of starch gelatinization (11.5 J g^{-1} db and 65.7 °C, respectively) were within the range of previous data (Defloor et al., 1998; Mestres & Rouau, 1997a; Moorthy, 1994), but in the low and high parts respectively. Intrinsic viscosity had a high coefficient of variation (25%), ranging from 39 ml/g (TMS 94/0583) to 139 ml/g (TMS 92/0057). However, both sweet and bitter cultivars had similar mean values of close to 100 ml/g, lower than the 170 to 190 ml/g reported in previous works (Bertolini et al., 2001; Mestres & Rouau, 1997a). This may be linked to interactions with other constituents, as intrinsic viscosities were measured, not on purified starch, but directly on the flour in the present study. The sample with the lowest intrinsic viscosity (TMS 94/0583) in fact had the highest fibre content (Table 1).

Dry matter solubility, after pasting at 70 °C, was significantly higher (at 10% level) for bitter cultivars, whereas their swelling power mean values were not significantly different from that of sweet cultivars (11.1 versus 12.4 g/g, Table 3). Swelling power values, mea-

Table 2
Starch physicochemical characteristics

Cultivars	Gelatinization		Intrinsic viscosity (ml/g db)
	Enthalpy (J/g db)	Onset temperature (°C)	
Sweet cultivars			
TMS 94/0177	13.3	66.6	133
TMS 94/0461	11.1	65.4	63
TMS 92B/00061	13.2	66.7	125
TMS I 94/0270	13.5	69.0	113
TMS I 94/0239	11.5	65.7	94
TMS I 94/0237	10.8	64.8	98
TMS 94/0583	7.6	65.7	39
TMS 94/0192	11.1	63.6	96
TMS 91B/00455	10.6	65.8	72
TMS 92B/00068	12.1	66.0	82
BEN 86052	12.6	64.0	99
MCN 85043	12.3	63.9	111
RB 89509	12.5	69.1	85
Mean value	11.7	65.9	93
Bitter cultivars			
TMS 93/0700	11.8	63.2	91
TMS 92/0057	11.8	70.3	139
TMS 91/02327	10.8	63.9	92
TMS 93/0614	12.1	65.5	95
TMS 91/02324	10.3	63.9	95
TMS 93/0560	9.5	66.0	71
TMS 93/0517	11.7	65.5	92
Mean value	11.4	65.5	96
Overall mean value	11.5	65.7	94
Cvc[a]	12	3	25

[a] Coefficient of variation between cultivars.

Table 3
Functional properties of cassava flours

Cultivars	Solubility (mg/ml)	Swelling (g/g)	V_{max} (RVU)	V_{fin} (RVU)
Sweet cultivars				
TMS 94/0177	22.8	11.8	138	103
TMS 94/0461	37.5	13.2	73	19
TMS 92B/00061	35.4	15.5	167	127
TMS I 94/0270	19.3	8.3	110	64
TMS I 94/0239	38.4	16.2	127	93
TMS I 94/0237	33.7	17.8	152	169
TMS 94/0583	11.2	8.8	102	73
TMS 94/0192	36.6	16.6	122	51
TMS 91B/00455	19.7	10.0	69	47
TMS 92B/00068	26.9	10.1	87	34
BEN 86052	10.2	12.4	126	131
MCN 85043	30.6	11.2	74	14
RB 89509	34.1	9.7	62	2
Mean value	27.4	12.4	108	71
Bitter cultivars				
TMS 93/0700	40.8	11.6	70	10
TMS 92/0057	29.0	6.0	60	3
TMS 91/02327	40.8	14.8	81	22
TMS 93/0614	36.8	7.2	47	4
TMS 91/02324	43.4	15.5	74	13
TMS 93/0560	41.2	12.7	58	3
TMS 93/0517	30.1	9.6	92	27
Mean value	37.4	11.1	69	12
Overall mean value	30.9	11.9	94	50
Cvc[a]	13	28	31	42

[a] Coefficient of variation between cultivars.

Table 4
Cassava root quality

Cultivars	Instrumental measurements		Sensory scores		
	Colour ΔE	Firmness (N)	Colour	Friability	Taste
Sweet cultivars					
TMS 94/0177	18.7	1.18	3.0	1.9	3.2
TMS 94/0461	17.0	1.47	3.3	1.8	3.2
TMS 92B/00061	21.3	1.84	2.7	1.3	3.6
TMS I 94/0270	17.2	1.58	3.3	2.1	3.4
TMS I 94/0239	18.2	0.87	2.8	3.8	2.9
TMS I 94/0237	17.1	0.87	3.1	3.6	3.4
TMS 94/0583	23.9	2.02	1.4	1.6	3.0
TMS 94/0192	19.4	1.87	2.4	1.4	3.4
TMS 91B/00455	24.1	1.69	1.5	1.7	3.6
TMS 92B/00068	17.9	0.93	3.4	3.5	3.8
BEN 86052	24.8	1.04	1.5	2.6	4.1
MCN 85043	19.1	1.53	2.7	1.8	3.8
RB 89509	17.7	1.81	3.4	1.2	3.1
Mean value	19.7	1.44	2.6	2.2	3.4
Bitter cultivars					
TMS 93/0700	18.5	2.06	2.2	1.8	3.0
TMS 92/0057	19.0	1.99	1.5	1.7	2.1
TMS 91/02327	19.7	1.8	2.9	2.2	3.3
TMS 93/0614	17.8	1.87	3.7	2.2	3.8
TMS 91/02324	17.8	1.86	2.8	2.4	2.4
TMS 93/0560	18.1	1.82	2.3	2.4	2.3
TMS 93/0517	17.1	2.13	3.1	2.0	2.3
Mean value	18.3	1.93	2.6	2.1	2.8
Overall mean value	19.2	1.6	2.6	2.1	3.2
Cvc[a]	13	21	28	35	48

[a] Coefficient of variation between cultivars.

sured at 70 °C, were lower than those measured on cassava starch at 65 °C or 75 °C: 22 and 31 g/g, respectively (Mestres, Zakhia, & Dufour, 1997b; Mestres, Boungou, Akissoë, & Zakhia, 2000). This may be linked to the presence of residual cell walls in the flour, which can limit the swelling of the starch trapped within the cell structure. A similar phenomenon is observed when comparing the swelling power of maize flour with that of maize starch (Mestres et al., 1997c).

In addition, bitter cultivars had much lower hot paste viscosities, with a V_{fin} mean value of 12 RVU against 71 RVU for sweet cultivars (Table 3). Several bitter cultivars had a V_{fin} value close to zero, whereas several sweet ones had V_{fin} values of over 100 RVU. Similarly, Zakhia et al. (1994) reported that starch from bitter cultivars generally gave lower paste viscosities measured with a Viscoamylograph. Also, Malawi farmers claim that bitter cultivars give a less elastic stiff porridge than sweet cultivars (Chiwona-Karltun et al., 1995).

3.3. Characterization of roots

The total difference of freshly ground cassava pulp from the white ceramic standard (ΔE) varied between 17.0 and 24.8, with no significant difference between the two types of cultivar (Table 4).

After boiling in water, the root slices were scored for colour, friability and taste. Standard deviation for individual determinations ranged between 0.55 and 0.76 and standard deviation of mean score for the 20 assessors was 0.13 for colour and friability and 0.17 for taste. Mean scores were then used as single determinations for ANOVA processing. Colour scores ranged from 1.4 for TMS 94/0583, which had a yellowish colour, to 3.7 for TMS 93/0614, the whitest sample. There was no significant difference in the colour scores between sweet and bitter cultivars. However, Chiwona-Karltun et al. (1995) reported that farmers in Malawi prefer bitter cultivars as these give a much whiter flour. This discrepancy may be linked to the drying process, as colour was evaluated on freshly ground pulp or boiled root slices in our study.

The sensory score for the colour of boiled cassava roots was very significantly correlated with the ΔE of the fresh pulp ($r = 0.78$; Fig. 1). The colour score could thus be predicted from the instrumental measurement of pulp whiteness according to the formula:

$$\text{Colour score of boiled cassava} = 7.0 - 0.23 \times \Delta E \text{ of fresh pulp.}$$

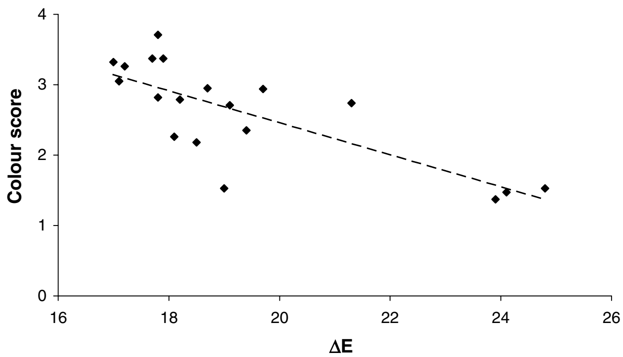

Fig. 1. Relationship between ΔE measured on fresh pulp and colour score of boiled tubers.

Firmness, determined on steam cooked root slices, ranged from 0.87 N (TMS I 94/0237 and TMS I 94/0239) to 2.13 N (TMS 93/0517) (Table 4). Sweet cultivars had a significantly lower firmness than bitter ones (mean values of 1.44 and 1.93 N, respectively). In parallel, the panel scored the boiled cassava slices for friability. Scores ranged from 1.2 for RB89509 to 3.8 for TMS I 94/0239, the most friable sample. Despite great variability between samples (coefficient of variation of around 30%) there were no significant difference in the friability scores between sweet and bitter cultivars. However, the three cultivars with a friability score of over 3.5 were sweet. In addition, the four cultivars with a firmness of close to or below 1 N had the highest friability scores, i.e. close to or above 3. A firmness of close to or below 1 N should thus be chosen when screening cassava cultivars for friability. Sensory friability was in fact inversely correlated with instrumental firmness ($r = -0.75$; Fig. 2) and could be predicted from the latter according to the formula:

$$\text{Sensory friability} = -1.3 \times \text{Firmness } (N) + 4.2.$$

Similarly, Unrau and Nylund (1957) showed a negative correlation between the cooked potato mealiness and the energy required to shear mashed potato. It is generally held that tuber friability (or mealiness) is due to cell rupture on chewing. Accordingly, the higher the instrumental cohesion force between cells, the lower the sensory mealiness. It should be noted, however, that many other publications reported a positive correlation between potato mealiness and resistance to deformation, resulting in a rejection of the cell wall separation theory (Warren & Woodman, 1974).

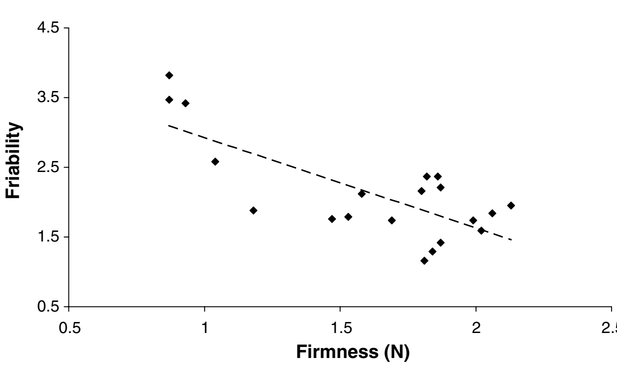

Fig. 2. Relationship between firmness of boiled tubers measured by penetration test and their friability score.

BEN 86052 had the sweetest taste after boiling (score of 4.1) and TMS 92/0057 the most bitter, with a score of 2.1. As expected, bitter cultivars were rated significantly lower (mean value of 2.8) than sweet ones (mean value of 3.4), and it was possible to set the boundary between sweet and bitter cultivars at 3. However, it should be noted that several sweet cultivars were rated around or even below this limit (such as TMS I 94/0239) while some bitter cultivars had scores of above 3 (such as TMS 93/0614). This may be linked to the higher soluble sugar content of bitter cultivars (Table 1), which may mask their bitterness. In Amazonia, bitter cultivars are thus considered to give sweeter products (Dufour & Wilson, 1996).

3.4. Principal component analysis

A principal component analysis was performed to evaluate the most important variables for describing cassava quality and those able to discriminate between sweet and bitter cultivars. The first three components accounted for 21.0, 17.7 and 14.1% of the variation, respectively. The first component showed an opposition between paste viscosity (V_{max} and V_{fin}) and firmness of boiled cassava slices (Fig. 3). Solubility was also negatively correlated with this axis. The second component was highly correlated with colour parameters (sensory colour opposed to ΔE) and proximate composition (protein content opposed to fibre content). Flour total sugar content was plotted in opposition to boiled root taste, in an intermediate position between the first and second axes. Several starch physical properties (gelatinization temperature and enthalpy change, swelling power) were highly correlated with the third component.

The 20 cultivars were plotted on a plan, with the percentage of variation associated with the first and second components (Fig. 4). Bitter cultivars were all located in the top left-hand quarter. According to variable plotting (Fig. 3), bitter cultivars were thus mainly characterized by low paste viscosities, high firmness after boiling and high solubility (negative part of the first axis) and high sugar and protein contents (positive part of the second axis), but low fibre content. Sweet cultivars were scattered over the other three quarters without any common trend. Three were plotted separately at the bottom of the graph, because of their high ΔE and poor colour score. The other sweet cultivars were scattered mainly along the first axis, revealing that the main var-

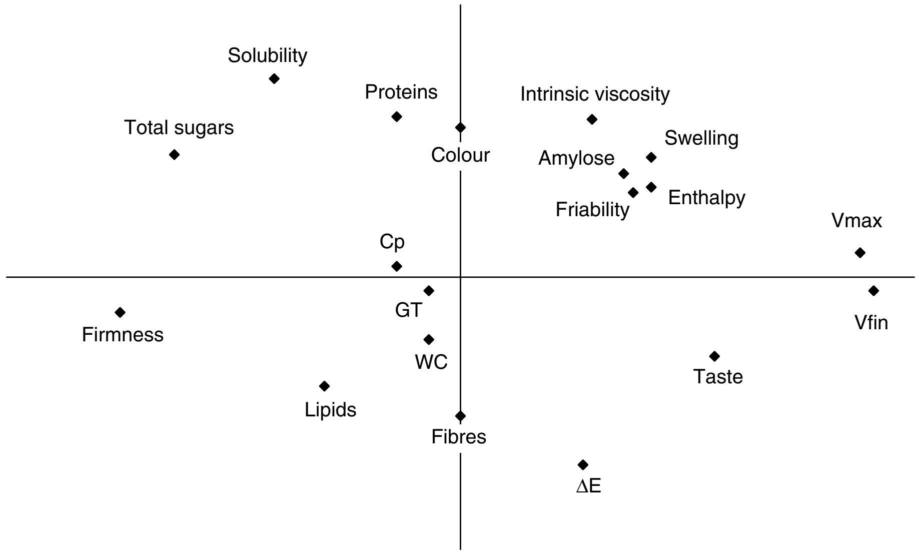

Fig. 3. Principal components plots of sensory, instrumental and physicochemical variables: first and second component; Cp, cyanide potential; GT, gelatinization temperature; WC, tuber water content.

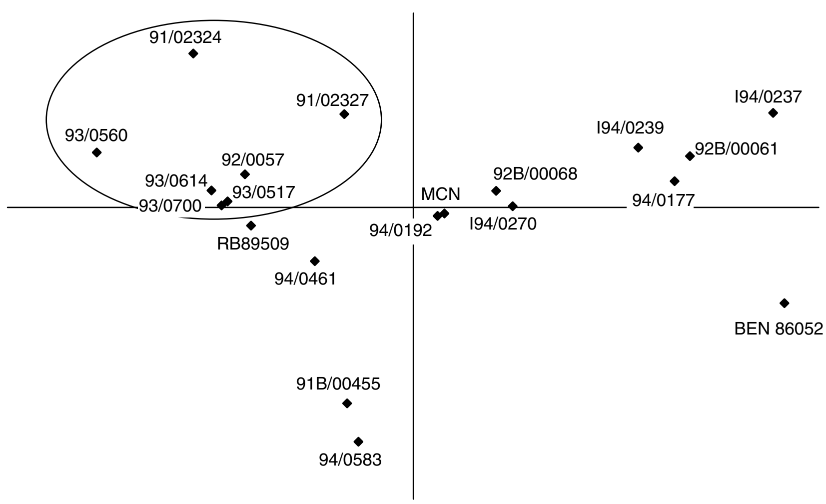

Fig. 4. Plotting of the 20 cultivars according to loadings on first and second components of principal component analysis.

iability was linked to functional properties: paste viscosity, solubility and firmness after boiling.

3.5. Regressions

None of the physicochemical characteristics was directly correlated with boiled cassava friability (Table 5). However, multiple regression analysis showed that (V_{fin}), cyanide potential (Cp) and tuber water content (WC) was able to explain 45% of sensory friability, each variable having a partial correlation coefficient of between 0.45 and 0.54:

$$\text{Sensory friability} = 2.9 + 0.007 \times V_{fin} + 0.13 \times \text{Cp} - 0.04 \times \text{WC}.$$

Instrumental firmness was however highly significantly correlated with V_{fin} (Table 5) and a regression model including V_{fin} and cyanide potential was able to explain 51% of firmness variability. In the case of potato, a positive correlation between mealiness and specific gravity is often reported even though the relationship is not always observed, particularly when agro-climatic conditions vary (Unrau & Nylund, 1957; Warren & Woodman, 1974). As specific gravity decreases as water content increases, the negative regression coefficient between cassava water content and friability agreed with general findings on potato tuber mealiness. The partial correlation with cyanide potential observed for both friability and firmness is very questionable, as it was determined on flour and certainly did not represent the

Table 5
Correlation coefficients between cassava physico-chemical characteristics and boiled cassava quality

	WC	Amylose	Total sugars	Fibres	Proteins	Lipids	Cp	Enthalpy	GT	Intrinsic viscosity	V_{max}	V_{fin}	S70	G70	Firmness	ΔE	Colour	Taste
Amylose	−0.29	1																
Total sugars	−0.17	−0.07	1															
Fibres	0.07	−0.39	−0.56*	1														
Proteins	−0.22	0.13	0.36	−0.10	1													
Lipids	0.20	−0.12	−0.01	0.04	−0.39	1												
Cp	0.18	0.17	0.10	−0.28	−0.11	0.28	1											
Enthalpy	0.31	0.63	−0.30	−0.30	0.00	0.14	0.03	1										
GT	0.05	0.10	−0.29	0.29	0.17	0.01	−0.21	0.25	1									
Intrinsic viscosity	0.04	0.62	−0.06	−0.39	0.41	−0.27	−0.18	0.73***	0.41	1								
V_{max}	−0.04	0.12	−0.51*	−0.07	−0.06	−0.49	−0.29	0.28	−0.09	0.32	1							
V_{fin}	−0.06	0.08	−0.49*	0.03	−0.07	−0.43	−0.31	0.18	−0.09	0.18	0.92***	1						
S70	0.00	−0.04	0.53*	−0.20	0.41	−0.20	0.07	−0.04	−0.24	0.14	−0.25	−0.40	1					
G70	−0.19	−0.05	0.06	−0.21	0.14	−0.47*	−0.13	−0.10	−0.56**	0.03	0.57**	0.48*	0.45*	1				
Firmness	0.17	−0.29	0.40	−0.01	0.15	0.01	−0.18	−0.28	0.08	−0.08	−0.48*	−0.60**	0.21	−0.37	1			
ΔE	0.04	−0.01	−0.22	0.04	−0.27	0.05	−0.08	−0.24	−0.16	−0.26	0.19	0.33	−0.65**	−0.07	0.04	1		
Colour	0.12	0.04	0.06	−0.09	0.06	−0.06	0.08	0.39	0.06	0.13	−0.01	−0.12	0.46*	0.12	−0.21	−0.78***	1	
Taste	0.22	0.26	−0.43	0.08	−0.30	0.18	0.16	0.37	−0.28	−0.13	0.28	0.38	−0.36	0.06	−0.44*	0.37	0.15	1
Friability	−0.32	0.10	0.05	−0.08	0.20	−0.03	0.29	−0.04	−0.20	−0.09	0.22	0.36	0.04	0.31	−0.74***	−0.20	0.18	0.07

* Significant at 5%.
** Significant at 1%.
*** Significant at 0.1%.

real value of fresh tubers when consumed. The positive correlation between friability and hot paste viscosity agreed with the findings of Unrau and Nylund (1957) on potato. It should be noted, however, that other authors found no relationship between starch functional properties and potato or cassava friability (McComber et al., 1988; Asaoka et al., 1991). No correlation was found between friability and total fibre content, which tends to contradict the role of cell wall properties in tuber friability. However, we did not perform any specific determination of pectic substances and hemicelluloses, which were found to be linked to the texture properties of boiled sweet potato (Walter, Collins, Tuong, & Fine, 1997). Recent research has shown that these substances are important constituents of cassava pulp fibres (Salvador, Suganuma, Kitahara, Tanoue, & Tchiki, 2000). It can thus be inferred that they ought to play a role in the friability of cassava tubers. In addition, it can be hypothesized that phenolic compounds present in cassava pulp (Buschman, Reilly, Rodriguez, Tohme, & Beeching, 2000), such as cinnamic acids, may also contribute to tuber mechanical properties by establishing crosslinks between hemicellulose chains, as observed in wheat bran (Peyron, Chaurand, Rouau, & Abecassis, 2002).

Accordingly with previous results on maize flour paste (Mestres et al., 1997c), swelling power and solubility were highly correlated with V_{fin} and V_{max} (Table 5). Seventy nine percent of V_{fin} variability was explained by solubility (S) and swelling power (G) measured at 70 °C and by intrinsic viscosity (IV):

$$V_{fin} = -29 - 4.2 \times S + 12.8 \times G + 0.61 \times \text{IV}.$$

This confirmed the preponderant role of swelling power and solubility in starchy paste viscosity. Moreover, swelling power appeared to be negatively correlated with onset gelatinization temperature and lipid content, these two variables explaining 53% of swelling power variability. Fibre content did not appear in the regression models, confirming that the functional properties of cassava flour were mainly linked to intrinsic properties of starch and not to interaction with residual cell wall material. Although the presence of residual cell walls can explain the relatively low solubility and swelling power of cassava flour compared to those of pure starch, they may not play a major role in inter-sample variability.

4. Conclusion

The colour and friability scores of boiled cassava tuber can be assessed by instrumental methods and these could be used to screen cultivars for root quality. Friability appeared to be related to starch functional properties (such as apparent viscosity after pasting), cyanide potential and fresh tuber water content. However, further work is required to improve our understanding of the origin of tuber friability, in particular the respective role of starch and cell wall characteristics.

Bitter cultivars formed an homogeneous group with, in particular, high sugar and protein contents but low fibre content. They also had original starch functional properties, with high solubility and low paste viscosity. The origin of these unique starch functional properties has so far not been explained from their physicochemical properties and will be investigated in further studies.

Acknowledgements

The authors thank the Benin National Institute of Agronomic Research for providing cassava tubers, Françoise Matencio for her technical assistance and Garth Evans for his assistance with the English.

References

American Association of Cereal Chemists (1984). Approved methods of the AACC. 8th edition. St Paul, Minnesota (USA).

Asaoka, M., Blanshard, J. M. V., & Rickard, J. E. (1991). Seasonal effects on the physico-chemical properties of starch from four cultivars of cassava. *Starch, 43*(12), 455–459.

Bertolini, A., Mestres, C., Raffi, J., Buléon, A., Lerner, D., & Colonna, P. (2001). Photodegradation of cassava and corn starches. *Journal of Agricultural and Food Chemistry, 49*(2), 675–682.

Buschman, H., Reilly, K., Rodriguez, M. X., Tohme, J., & Beeching, J. R. (2000). Hydrogen peroxide and flavan-3-ols in storage roots of cassava (*Manihot esculenta* Crantz) during postharvest deterioration. *Journal of Agricultural and Food Chemistry, 48*, 5522–5529.

Chiwona-Karltun, L., Tylleskär, T., Rosiling, H., Ngoma, J., Mahungu, N. M. & Saka, J. (1995). Reasons for use of bitter cassava – a priority in cassava production in Malawi. In *Root crops and poverty alleviation* (pp. 313–315). ISTRC-AB.

Defloor, I., Dehing, I., & Delcour, J. A. (1998). Physico-chemical properties of cassava starch. *Starch, 50*(2–3), 58–64.

Dufour, D. L., & Wilson, W. L. (1996). La douceur de l'amertume : une ré-évaluation des choix du manioc amer par les Indiens Tukano d'Amazonie. In A. H. C. M. Hladik, H. Pagezy, O. F. Linares, G. J. A. Koppert, & A. Froment (Eds.), *L'amélioration en forêt tropicale: Interactions bioculturelles et perspectives de développement* (pp. 875–896). Paris: CNRS/UNESCO.

Eggleston, G., Omoaka, P. E., & Arowshegbe, A. U. (1993). Flour, starch and alternative (wheatless) breadmaking quality of various cassava clones. *Journal of the Science of Food and Agriculture, 62*, 61–66.

Essers, A. J. A. (1995). *Removal of cyanogens from cassava roots: Studies on domestic sundrying and solid-substrate fermentation in rural Africa*, Landbouwuniversiteit, Wageningen.

FAO. (1997). *Annuaire de production*. Roma (Italie): FAO.

Hounhouigan, D. J., Nout, M. J. R., Nago, C. M., Houben, J. H., & Rombouts, F. M. (1993). Composition and microbiological attributes of mawè, a fermented maize dough from Benin. *International Journal of Food Science and Technology, 28*, 513–517.

Iritani, W. M., Powers, M. J., Hudson, L., & Weller, L. (1977). Factors influencing time to breakdown (TTB) of cooked potato tissue. *American Potato Journal, 54*, 23–32.

Kemdirim, O. C., Chukwu, O. A., & Achinewhu, S. C. (1995). Effect of traditional processing of cassava on the cyanide content of gari and cassava flour. *Plant Foods for Human Nutrition, 48*, 335–339.

Lees, R. (1968). *Laboratory Handbook of Methods of Food Analysis*. London: Leonard Hills Books.

McComber, D. R., Osman, E. M., & Lohnes, R. A. (1988). Factors related to potato mealiness. *Journal of Food Science, 53*(5), 1423–1426.

Mestres, C., Matencio, F., Pons, B., Yajid, M., & Fliedel, G. (1996). A rapid method for the determination of amylose content by using Differential Scanning Calorimetry. *Starch, 48*(1), 2–6.

Mestres, C., & Rouau, X. (1997a). Influence of natural fermentation and drying conditions on the physicochemical characteristics of cassava starch. *Journal of the Science of Food and Agriculture, 74*, 147–155.

Mestres, C., Zakhia, N., & Dufour, D. (1997b). Functional and physico–chemical properties of sour starch. In *Starch: Structure and functionality* (pp. 42–50). The Royal Society of Chemistry.

Mestres, C., Nago, M., Akissoë, N., & Matencio, F. (1997c). End use quality of some African corn kernels. 2. Cooking behavior of whole dry-milled maize flours; incidence of storage. *Journal of Agricultural and Food Chemistry, 45*(3), 565–571.

Mestres, C., Boungou, O., Akissoë, N., & Zakhia, N. (2000). Comparison of the expansion ability of fermented maize flour and cassava starch during baking. *Journal of the Science of Food and Agriculture, 80*, 665–672.

Mestres, C., Dorthe, S., Akissoé, N. & Houhouigan, J. (2004). Prediction of sensorial properties (colour and taste) of amala, a paste from yam chips flour of West Africa, through flour biochemical properties. *Plant Foods for Human Nutrition, [in press]*.

Moorthy (1994). Tuber crop starches. *Technical Bulletin Series, 18*, 5–40.

Moorthy, S. N., & Ramanujam, T. (1986). Variation in properties of starch in cassava varieties in relation to age of the crop. *Starch, 38*(2), 58–61.

Nonaka, M. (1980). The textural quality of cooked potatoes. I. The relationship of cooking time to the separation and rupture of potato cells. *American Potato Journal, 57*, 141–149.

Osborne, D. R., & Voogt, P. (1978). *The Analysis of Nutritients in Foods*. London: Academic Press.

Peyron, S., Chaurand, M., Rouau, X., & Abecassis, J. (2002). Relationship between bran mechanical properties and milling behaviour of durun wheat (*Triticum durun Desf.*). Influence of tissue thickness and cell wall structure. *Journal of Cereal Science, 36*, 377–386.

Safo-Kantaka, O., Boampong, E. Y. & Asante, I. K. (2002). Morphological characterization of a collection of cassava germplasm in Ghana. In *Proceedings of potential of root crops for food and industrial resources, 12th symposium of ISTRC* (pp. 77–81). ISTRC.

Salvador, L. D., Suganuma, T., Kitahara, K., Tanoue, H., & Tchiki, M. (2000). Monosaccharide composition of sweetpotato fiber and cell wall polysaccharides from sweetpotato, cassava and potato analyzed by the high-performance anion exchange chromatography with pulsed amperometric detection. *Journal of Agricultural and Food Chemistry, 48*, 3348–3454.

Sriroth, K., Santisopari, V., Petchalanuwat, C., Kurojanawong, K., Piyachomkwan, K., & Oates, C. G. (1999). Cassava starch granule structure-function properties: influence of time and conditions at haverst on four cultivars of cassava starch. *Carbohydrate polymers, 38*, 161–170.

Unrau, A. M., & Nylund, R. E. (1957). The relationship of physical properties and chemical composition to mealiness in the potato. I. Physical properties. *American Potato Journal, 34*, 245–253.

Walter, W. M., Jr., Collins, W. W., Tuong, V.-D., & Fine, T. I. (1997). Physical, compositional, sensory properties of french fry-type products from five sweet potato selections. *Journal of Agricultural and Food Chemistry, 45*, 383–388.

Warren, D. S., & Woodman, J. S. (1974). The texture of cooked potatoes: A review. *Journal of the Science of Food and Agriculture, 25*, 129–138.

Wheatley, C., & Gomez, G. (1985). Evaluation of some quality characteristics in cassava storage roots. *Qualitas Plantarum. Plant Foods for Human Nutrition, 35*, 121–129.

Zakhia, N., Wheatley, C., O'Brien, G., & Dufour, D. (1994). Screening of Ciat cassava germplasm diversity: the relationship between cyanogenic potential and cassava starch functional properties. *The cassava biotechnology network* (Vol. 2, pp. 823–830). Bogor (Indonesia): CBN.