Research Article

Received: 31 January 2023 Revised: 1 August 2023 Accepted article published: 7 February 2024 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/jsfa.13363

Definition of sensory and instrumental thresholds of acceptability for selection of cassava genotypes with improved boiling properties

Paula Iragaba,[a] Laurent Adinsi,[b,c] Luis Fernando Delgado,[d] Ann Ritah Nanyonjo,[a] Ephraim Nuwamanya,[a] Enoch Wembabazi,[a] Michael Kanaabi,[a] Laurenda Honfozo,[b] Francis Hotegni,[b] Imayath Djibril-Moussa,[b] Luis Fernando Londoño,[d] Christophe Bugaud,[e,f] Dominique Dufour,[e,f] Robert Sezi Kawuki,[a] Noël Akissoé[b] and Thierry Tran[d,f,g*]

Abstract

BACKGROUND: Consumers of boiled cassava in Africa, Latin America and Asia use specific preference criteria to evaluate its cooking quality, in terms of texture, colour and taste. To improve adoption rates of improved cassava varieties intended for consumption after boiling, these preference criteria need to be determined, quantified and integrated as post-harvest quality traits in the target product profile of boiled cassava, so that breeding programs may screen candidate varieties based on both agronomic traits and consumer preference traits.

RESULTS: Surveys of various end-user groups identified seven priority quality attributes of boiled cassava covering root preparation, visual aspect, taste and texture. Three populations of contrasted cassava genotypes, from good-cooking to bad-cooking, in three countries (Uganda, Benin, Colombia) were then characterized according to these quality attributes by sensory quantitative descriptive analysis (QDA) and by standard instrumental methods. Consumers' preferences of the texture attributes mealiness and hardness were also determined. By analysis of correlations, the consumers' preferences scores were translated into thresholds of acceptability in terms of QDA scores, then in terms of instrumental measurements (water absorption during boiling and texture analysis). The thresholds of acceptability were used to identify among the Colombian and Benin populations promising genotypes for boiled cassava quality.

CONCLUSION: This work demonstrates the steps of determining priority quality attributes for boiled cassava and establishing their corresponding quantitative thresholds of acceptability. The information can then be included in boiled cassava target product profiles used by cassava breeders, for better selection and adoption rates of new varieties.

* *Correspondence to: T Tran, Alliance Bioversity – CIAT, KM17 Recta Cali-Palmira, Cali, Colombia. E-mail: thierry.tran@cirad.fr*

a *National Crops Resources Research Institute (NaCRRI), Kampala, Uganda*

b *Faculté des Sciences Agronomiques, Université d'Abomey-Calavi, Cotonou, Benin*

c *Ecole des Sciences et Techniques de Conservation et de Transformation des Produits Agricoles, Université Nationale d'Agriculture, Sakété, Benin*

d *Alliance Bioversity – CIAT, Cali, Colombia*

e *CIRAD, UMR Qualisud, Montpellier, France*

f *QualiSud, University of Montpellier, CIRAD, Institut Agro, University of Avignon, University of La Réunion, Montpellier, France*

g *CIRAD, UMR Qualisud, Cali, Colombia*

Supporting information may be found in the online version of this article.

Keywords: consumer preferences; post-harvest processing; boiled cassava; cassava breeding; product profile

INTRODUCTION

Boiling is one of the simplest ways of cooking and consuming cassava. Boiled cassava is eaten in almost all cassava-growing regions of Africa, Latin America and Asia.[1] Cassava cooking behaviour depends not only on genotype[2] but also on genotype × environment interaction.[3] Cassava breeders are aware of these factors but are focusing on the improvement of primarily agronomic traits (yield, tolerance to pests and diseases). For instance, Akinwale *et al.*[4] studied genetic variability among 43 cassava genotypes in three agro-ecological zones of Nigeria through the evaluation of cassava mosaic disease, plant height, root number, root weight etc.; while Jiwuba *et al.*[5] highlighted the effect of genotype × environment interaction on resistance to green mite and yield performance of cassava. Research works that include end-users' expectations as criteria for the selection of new varieties are still relatively few,[6] as are evaluations of the impact of new varieties in economic terms with respect to investment.[7] While the evaluation of agronomic traits remains imperative, levels of adoption could be improved with a better understanding of end-user expectations for cooking quality attributes of cassava. The most important consumers' quality attributes for boiled cassava are known, including mealiness/crumbliness, hardness (with preference for less hard textures), and sweet taste.[8-11] For breeders to integrate and use these quality attributes for routine evaluation of candidate clones, additional components are necessary. First, the sensory thresholds of acceptability (acceptable range) of the quality traits need to be available, based on consumer preferences and descriptive sensory analysis tests. Second, the sensory thresholds need to be translated into robust and objective instrumental thresholds for more timely and cost-effective screening of quality traits. Several studies have reported the relationship between sensory and instrumental parameters of boiled cassava but few have integrated sensory nor instrumental thresholds.[9,10] As multi-environment and multi-year field trials are necessary to comprehend genotype × environment interactions and identify varieties with the best probability of adoption,[3] it is important to employ methods for accurate screening of both agronomic criteria and consumer quality traits as early as possible in the breeding cycle, in order to minimize costs.

Breeding cassava for boiled consumption therefore presents particular challenges. Improved genotypes should not only have better agronomic traits (yield, tolerance to pests and diseases), but also match or exceed the cooking quality of current varieties. Consequently, selection of improved cassava genotypes for boiling requires: (i) multi-environment testing; (ii) an accurate product profile that reflects the expectations of farmers, processors and consumers and their thresholds of acceptability; and (iii) sensory or instrumental methods to measure the quality attributes defined in the product profile. Accordingly, the objectives of this study were to: (i) develop a product profile of cooking quality traits for boiled cassava, including thresholds of acceptability; (ii) develop laboratory protocols (sensory and instrumental) to characterize cooking quality of boiled cassava; (iii) investigate correlations between quality attributes and laboratory methods in order to validate that the laboratory methods are able to predict quality attributes and can be used as accurate tools for breeding selection.

MATERIALS AND METHODS

Determination of the product profile of boiled cassava

We determined the boiled cassava product profile by following five key steps of an interdisciplinary methodology[12] to identify preferred quality attributes among diverse end-user groups along a given food value chain. The high quality attributes from each step were prioritized and organized into three categories: attributes of the raw product, processing and end product. This part of the study was done in Uganda, where a large breeding collection of contrasted African cassava varieties is available.

Characterization of boiled cassava by sensory analysis

Quantitative descriptive analysis (QDA) was undertaken by trained panellists at UAC-FSA (Benin), NaCRRI (Uganda) and CIAT (Colombia) following steps highlighted in Iragaba *et al.*[8] and Adinsi *et al.*[13] In each country, 13 to 15 panellists participated in the QDA tests. Based on consumers surveys, 21 possible sensory attributes were pre-selected. To avoid panellists fatigue, priority attributes were selected, reducing the number to respectively 10, 7 and 5 in Uganda, Benin and Colombia. Local differences in appreciation of boiled cassava resulted in the selection of different priority attributes among the three countries. Two sensory attributes describing texture were common to the three countries: mealiness and hardness, and two more (stickiness and sweetness) were common to two of the three countries. The panellists scored the randomly coded boiled cassava samples for each sensory attribute on a 0–10 unstructured linear scale, which was considered as quantitative. Additionally, at NaCRRI a consumers preference test was also conducted, for which the panellists evaluated the samples for liking according to each sensory attribute using a 1–9 hedonic scale, where 1 and 9 represented extremely dislike and extremely like, respectively. Results obtained with such scale are categorical but can be converted into numbers (1 to 9) and treated as quantitative for statistical analyses.[14,15] Combining results from the consumers preference test and QDA, the thresholds of acceptability of the texture attributes mealiness and hardness were then defined.

Characterization of boiled cassava by instrumental measurements

Dry matter content (DM) was assessed in triplicate by oven drying,[16] on samples of fresh cassava roots and of cooked cassava roots after 30 min boiling. Total cyanide content was assessed in triplicate by the procedure of Essers[17] slightly modified: the linamarase was replaced by betaglucosidase. Penetration, compression and texture–extrusion tests were performed at UAC-FSA, NaCRRI and CIAT according to Adinsi *et al.*,[18] Tran *et al.*[2,19] respectively using a texturometer (model TA-XT plus, Stable Micro Systems, Godalming, UK). For each test, at least six replications were performed per sample, and up to 18 replications when possible for better representativeness – for example, in the case of texture–extrusion. Water absorption after boiling 30 min (WA30) was evaluated at CIAT.[2]

Cassava root materials and cooking protocols for sensory and biophysical/texture analyses

In Uganda, 25 cassava genotypes were grown at NaCRRI (Namulongue) and harvested at 10 months after planting (MAP). Ten roots per genotype were collected, peeled, washed and cut into cylinders (6 cm long, 5–5.5 cm diameter), then boiled for 55 min in banana leaf wraps.[20] The boiled samples were characterized by sensory QDA and instrumental hardness using a penetrometer.

In Benin, seven cassava landraces named Agric, Alanmandou, Attinwéwé, Dossi, Hombété, Koléahonmè and Ofégué were harvested from two rural districts named Bonou (6° 53′ N, 2° 27′ E) and Dangbo (6° 34′ N, 2° 33′ E) at different physiological stages. The roots were harvested at 6 MAP (Alanmandou 6, Attinwéwé 6 and Koléahonmè 6), at 8 MAP (Hombété 8 and Ofégué 8), and at 9 and 12 MAP (Agric 9, Agric 12, Dossi 9 and Dossi 12). Nine and 12 months represent optimum and late harvesting time, respectively. Samples were collected at different maturity stages and from different growing areas, and thus were considered as independent samples. Roots were cut into half cylinders (5 cm long and 5 cm in diameter) and processed as boiled cassava by steam cooking for 45 min.[13] The boiled samples were characterized by QDA, penetration, compression and texture–extrusion, DM after boiling and cyanide.

In Colombia, 15 cassava varieties with contrasted cooking behaviours were grown at CIAT (Palmira) in 2021–2022 and harvested at 9, 10 and 12 MAP (45 samples in total). For each sample, 12 roots of suitable dimensions (minimum 25 cm long and 5.5 cm in diameter) were collected from four to six plants, cut into half-cylinders (6 cm long and 5–5.5 cm diameter) and boiled in excess water.[2] The boiled samples were characterized by QDA, texture–extrusion, water absorption after 30 min (WA30) and dry matter after 30 min (DM30). In the three countries, dry matter of all the fresh roots samples was also measured.

Statistical analyses

Sensory and biophysical data were subjected to analysis of variance (ANOVA) followed by the least significant difference (LSD) Fisher post hoc tests. Pearson correlation, principal component analysis (PCA) and multifactorial analyses were performed to identify the relationship between and within sensory attributes and biophysical parameters. All analyses were performed using XLSTAT (version 2016.02.28451, Addinsoft, Paris, France).

RESULTS

Product profile of boiled cassava

Among several quality attributes generated during interviews and focus groups with end users in Uganda, seven were classified as high-priority or value-added for acceptability of boiled cassava (Table 1), and can be included in the boiled cassava product profile. Three were related to fresh roots and root processing: white colour of the flesh; sweet taste (meaning not bitter, which is related to low content of cyanogenic compounds); and ease of peeling. Four were related to sensory perception during consumption: cassava aroma; white colour of the flesh after boiling; not hard/easy to break; and mealiness. Additionally, cassava varieties from the NaCRRI collection that possess these preferred attributes were identified and could be used as benchmark varieties or progenitors during development of new varieties (Table 1). The assessment from G+ product profile tools[21] revealed that each of the identified attributes either had positive benefits or did no harm to youth, men and women or any other social category included in the study. The detailed product profile and gendered impact assessment can be found at https://doi.org/10.18167/DVN1/AJNOH8.

Sensory mapping of boiled cassava

Descriptive statistics of QDA data were comparable across Benin, Uganda and Colombia. For most attributes, the whole scale was used (minimum 0.5–3.8; maximum 5–8.5), confirming that the genotypes selected for the study had contrasted properties and covered a wide range of cooking behaviours. Pooling together the datasets showed a significant and negative correlation between the attributes mealiness and hardness, common to the three countries ($R^2 = 0.63$; Fig. 1). Two other attributes – sweetness and stickiness – were common to Uganda and Benin and to Colombia and Benin, respectively, but could not be interpreted due to the limited variations among samples in Uganda (range 0.4–2.8 for sweetness) and Benin (range 2.1–5 for stickiness).

QDA data from Uganda were well correlated with overall liking scores, with consumers preferring mealy and less hard samples (Supporting Information, Table S1 and Fig. 2; $R^2 = 0.80$ and 0.70, respectively). We defined thresholds of acceptability as the mean of the minimum and maximum scores used by consumers (Table 2). Using the linear regression equations between overall liking and QDA scores (Fig. 2), the corresponding ranges of acceptability on the QDA scale were 5.8–10 for mealiness and 0–4.9 for hardness.

QDA in Benin showed significant differences ($P < 0.05$) in sensory attributes among landraces, except for sticky and cassava aroma (Supporting Information, Table S2). Three genotypes – Agric 12, Dossi 9 and Dossi 12 – met the thresholds of acceptability for mealiness (≥5.8) and hardness (≤4.9), and thus were identified as good candidate varieties for breeding for cooking quality. Sweet taste (i.e., non-bitter) was scored highest in Dossi 12, Agric 12 and Attinwéwé 6, and lowest in Koléahonmè 6, which appeared markedly different, with a sweetness score of only 0.7 (Table S2).

Among the 15 genotypes analysed in Colombia, two met the thresholds of acceptability for mealiness and hardness (COL1516, VEN77) and two nearly met them (CR63, PER368), based on the average QDA scores over the three harvests (9, 10 and 12 MAP). Younger plants tended to cook better than older ones, with 6, 5 and 0 genotypes meeting the two thresholds of acceptability at 9, 10 and 12 MAP, respectively (Supporting Information, Table S3). Thus, under the growing conditions in Colombia, 9–10 MAP seems to be optimum harvest time for cooking quality, after which roots became less desirable. The main change was in mealiness, with all genotypes failing to meet the 5.8 acceptability threshold at 12 MAP, while some genotypes remained below the 4.9 threshold for hardness.

A PCA of the sensory QDA data from Colombia and Benin revealed a similar structure of the sensory attributes space: hardness and mealiness were opposite (negative correlation $r = -0.85$ and -0.98, respectively) (Fig. 3), also in line with the Uganda dataset (Table 4); while stickiness was independent. According to the Benin dataset, softness/easy to chew attribute was used by panellists in the same way as mealiness ($r = 0.95$); and stickiness was correlated with sweetness ($r = 0.74$) (Table 6). The attribute hardness/hard to break was strongly and negatively correlated with mealiness and soft/easy to chew ($r = -0.98$ and

Table 1. Key attributes of boiled cassava food product along with examples of Ugandan varieties that possess such attributes

Attribute category	High-quality attributes	Indicator of the attribute	End-user group(s)	Priority	Key benchmark varieties
1. Raw cassava roots	Sweet taste	Break the root and taste. It is sweet but not like sugar	Farmer, Processor, Retailer, Consumer	Must-have	Bao, TME 14, NASE 14, Njule, NAROCASS 1, NASE 19, Alanyo Der
	Colour (white flesh)	White like paper when fresh root is cut	Farmer, Processor, Retailer, Consumer	Value added	Bwanjule, Alanyo Der, Nabwangu, Bao
2. Processing	Ease of peeling	Self-retracting peel. Outer peel is soft	Processor, Retailer, Consumer	Value added	Bao, NAROCASS 1, NASE 14
3. Final cooked product	Nice aroma	Cassava aroma	Processor, Retailer, Consumer	Must-have	Bwanjule
	Colour (white flesh)	Boiled cassava is white like paper or paracetamol tablet	Processor, Retailer, Consumer	Value added	Bao, TME 14, NASE 14, Njule, NAROCASS 1, NASE 19, Alanyo Der
	Soft (not hard, easy to break)	Boiled cassava can easily be broken. The finger can easily go through when pressed. Soft as one chews	Processor, Retailer, Consumer	Must-have	Bwanjule, Bao
	Mealy	Boiled cassava is cracked. When chewing, it feels powdery in the mouth	Processor, Retailer, Consumer	Must-have	Bwanjule, Nabwangu

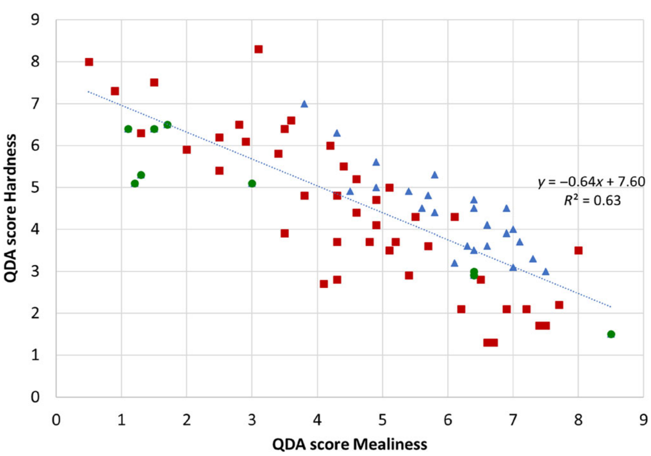

Figure 1. Correlation between sensory attributes mealiness and hardness of boiled cassava. Triangles, circles and squares represent the QDA datasets from Uganda, Benin and Colombia, respectively.

− 0.96, respectively). White colour was associated with more mealy samples, although the reason for this connection between a visual and a textural attribute is not clear. According to the Colombia dataset, the attributes moisture and glassiness were also closely correlated ($r = 0.904$, Table 3). On the PCA biplot, this translated as a distribution of the five sensory variables over the four quadrants with moisture and glassiness together, then hardness, stickiness and mealiness (Fig. 3). The right-hand side of the biplot represented samples perceived as having a harder texture and in some cases as more glassy/moist; and the left-hand side represented samples perceived as mealy and/or sticky. A typical mealy genotype was CR63, which is one of the main varieties produced in Costa Rica for its good cooking quality and exported in large quantities as fresh, wax-coated roots. On the other hand, the glassiness attribute was associated with poor-cooking samples which take on a translucid appearance after boiling, as opposed to the more opaque appearance of other samples. Glassy samples (e.g., VEN177B, CM6370-2) tended to absorb less water, as indicated by lower DM30 (Supporting Information, Table S3). Nevertheless, and apparently contradictorily, they were also perceived as more moist. Glassy samples were also among the hardest (Table 3) and tended to break under the tooth into pieces that retained perceptible edges, in contrast to softer samples, which tended to produce rounder pieces under the tooth, or even melt into a paste without producing noticeable pieces. Results from Uganda also revealed strong positive correlations among various sensory attributes such as mealiness in the mouth with mealiness by touch ($r = 0.95$, Table 4).

Instrumental characterizations of boiled cassava

Phenotyping data from Benin, Uganda and Colombia illustrated the variability of biochemical and biophysical parameters in boiled cassava samples (Supporting Information, Tables S1, S2 and S3). DM ranges were 41.4–45.3%, 31.0–40.3%, 30.7–41.3% (wet basis, wb), respectively, among the three countries, with no significant difference among samples. Texture–extrusion parameters (maximum force and area under the texture–extrusion curve) were also comparable in samples from Uganda, Benin and Colombia (ranges 5126–11 937 g and 44 554–106 640 g mm; 5737–10 845 g and 63 372–125 169 g mm; 7514–29 198 g and 82 966–291 010 g mm, respectively), confirming the reproducibility of the method across different laboratories. In all three countries texture measurements evidenced statistically significant differences among cassava genotypes, which enabled discriminating between genotypes with good and poor cooking quality.

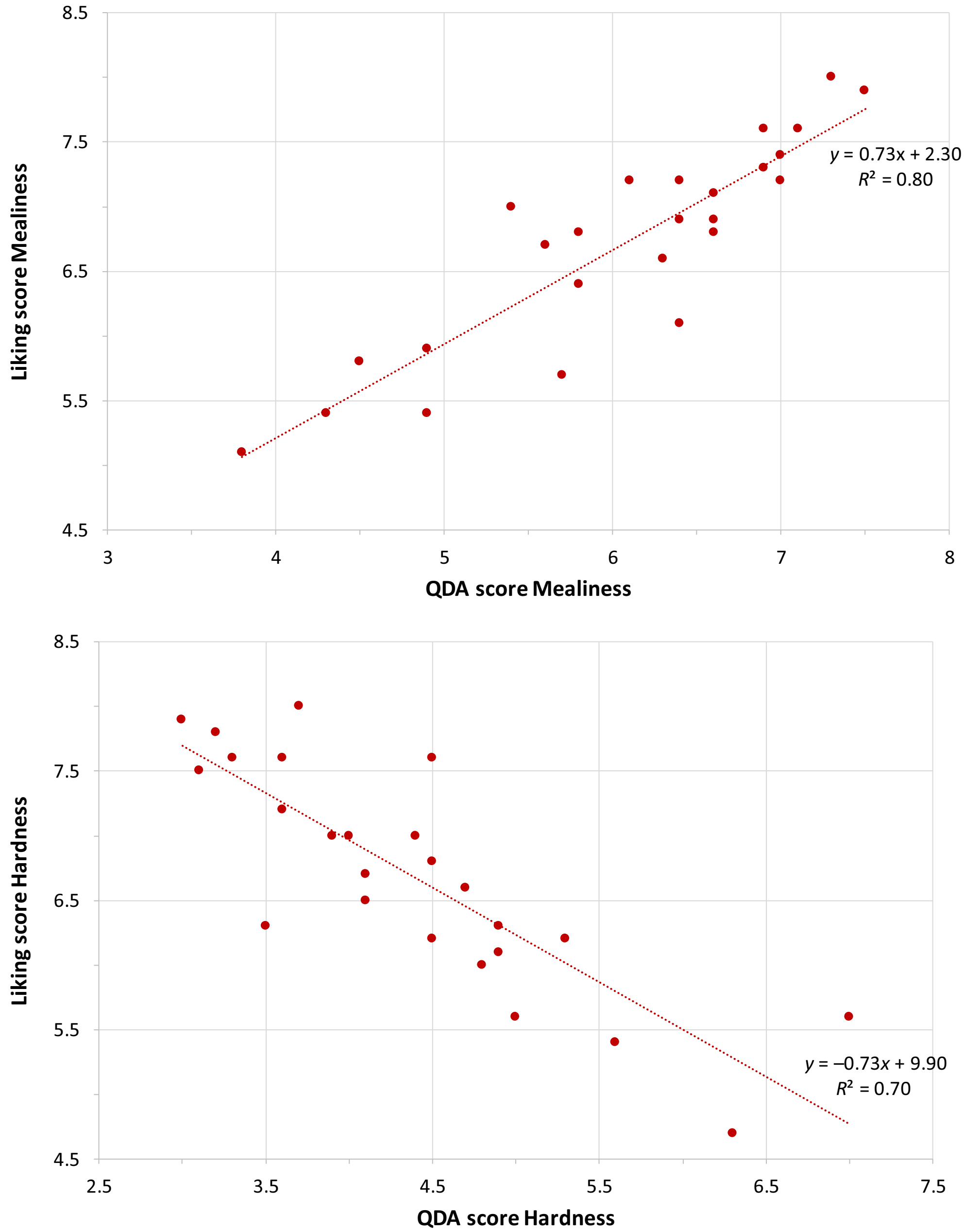

Figure 2. Correlation between overall liking and QDA scores of mealiness and hardness of boiled cassava (Uganda dataset).

A PCA of the biophysical data from Colombia indicated significant correlations among several parameters (Table 5), in particular between WA30 and gradient ($r = -0.744$, Fig. 4) and distance at maximum force ($r = 0.571$), indicating that WA30 may be used to predict texture parameters. Several texture parameters were also strongly correlated, indicating that they give similar information on hardness of boiled cassava samples (Table 5): maximum force, area, linear distance, end force and, to a smaller extent, gradient. In the same way, the parameters distance at maximum force and end force:maximum force ratio were also strongly correlated. In Benin, the three texture methods (compression, penetration and extrusion) gave equivalent results, as indicated by positive correlations (r from 0.65, (P-value = 0.057) to 0.80 (P-value = 0.009), Table 6) among maximum forces.

Prediction of cassava sensory attributes and acceptability using biophysical measurements

Compression force for phenotyping hardness of boiled cassava in Uganda was positively correlated with sensory hardness ($r = 0.60$). Similarly, maximum force data from compression and penetrometer in Benin were significantly and positively correlated with the sensory attribute hardness/hard to break ($r > 0.82$), and negatively with mealiness and easy to chew ($r < -0.80$) (Table 6). Regarding data from Colombia, the gradient (initial slope of the texture–extrusion curve) was also related to sensory hardness ($r = 0.544$) (Table 7, Fig. 6). These results imply that different texture methods (penetrometer, compression, texture–extrusion) can equally be used to predict sensory hardness of boiled cassava roots.

In addition to hardness, mealiness is a key parameter for consumer acceptability of boiled cassava. Water absorption (WA30) and gradient (texture–extrusion method) were good candidates for instrumental evaluation of mealiness, with correlations $r = 0.594$ and -0.608, respectively (Table 7, Fig. 6). Distance at maximum force may also be an appropriate indicator of mealiness ($r = 0.491$; Table 7); however, a larger dataset would be needed to confirm these correlations. WA30 is of particular interest as an indicator of overall cooking quality of boiled cassava because, in addition to mealiness, WA30 is also correlated with texture parameters (gradient, distance at maximum force) and optimum cooking time;[2] besides, WA30 is suitable as a medium-throughput phenotyping (MTPP) method, faster and simpler to implement than texture analysis.

Pearson correlation analysis of the combined sensory and biophysical data of boiled cassava samples from Benin revealed additional associations (Table 6). Sensory hardness was significantly and positively correlated with two of the instrumental texture parameters for hardness: penetration and compression forces ($r = 0.82$ and 0.87, respectively), indicating that sensory hardness can accurately be evaluated by instrumental texture. Sensory mealiness and whiteness scores showed a negative correlation with all instrumental parameters (except L^*), with significant correlations in the range $-0.85 < r < -0.62$ and $-0.74 < r < -0.40$, respectively. For instance, lower dry matter after boiling and lower penetration and compression forces were all linked with higher mealiness ($r = -0.69$, -0.80 and -0.85, respectively), indicating that sensory mealiness may be predicted by these instrumental parameters. A multifactorial analysis (Fig. 5) indicated that

Table 2. Translation of overall liking scores for mealiness and hardness into sensory and instrumental thresholds of acceptability

	Mealiness	Hardness
Minimum overall liking score used by consumers	5.1	4.7
Maximum overall liking score used by consumers	8	8
Range of overall liking scores	2.9	3.3
Threshold of acceptability at 50% of the range of liking scores	≥6.6	≤6.4
Threshold of acceptability in terms of QDA scores	≥5.8	≤4.9
Threshold of acceptability in terms of WA30 (%)	≥36	—
Threshold of acceptability in terms of gradient (g mm)	≤302	≤794

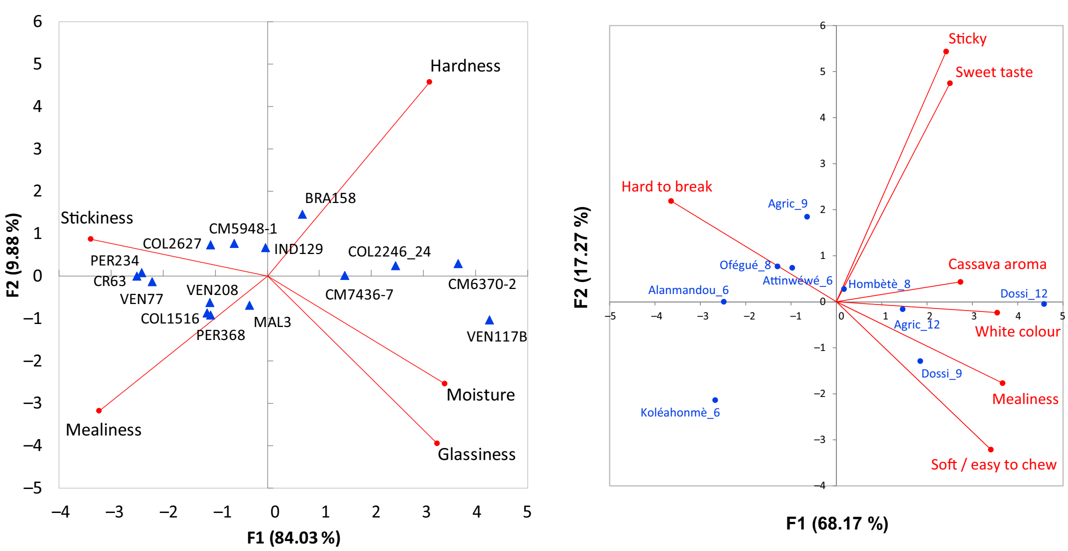

Figure 3. Biplot of PCA of sensory variables and observations of boiled cassava, Colombia (left) and Benin (right).

Table 3. Pearson correlations among sensory attributes of boiled cassava, Colombia

Variable	Friability/mealiness	Glassiness	Hardness	Moisture	Stickiness
Friability / mealiness	1				
Glassiness	−0.700	1			
Hardness	−0.853*	0.660	1		
Moisture	−0.705*	0.904	0.723	1	
Stickiness	0.789	−0.804	−0.845*	−0.828*	1

The attribute Moisture means the perception of moistness of the sample by panellists during tasting.
*$P < 0.05$.

Table 4. Pearson correlations among sensory attributes of boiled cassava, Uganda

	Yellow	White	Hardness_M	Smoothness_M	Mealiness_M	Stickiness_M	Mealiness_T	Stickiness_T	Sweetness	Cassava_aroma
Yellow	1									
White	−0.75**	1								
Hardness_M	0.51	−0.27*	1							
Smoothness_M	−0.62	0.25	−0.56**	1						
Mealiness_M	−0.68	0.51	−0.69**	0.76**	1					
Stickiness_M	−0.14	0.14	−0.47**	0.22**	0.44	1				
Mealiness_T	−0.71	0.52	−0.67**	0.72**	0.95**	0.53**	1			
Stickiness_T	−0.02	0.12	−0.38	−0.21	0.09	0.49**	0.22*	1		
Sweetness	−0.22	0.07	−0.09	0.65	0.57*	0.24	0.46*	−0.5	1	
Cassava_aroma	−0.03**	0.06	0.02	0.39	0.28	−0.09	0.2**	−0.29	0.41	1

_M and _T indicate sensory attributes evaluated by mouth and by touch, respectively.
*$P < 0.05$.
**$P < 0.01$.

Table 5. Pearson correlations among biophysical parameters of boiled cassava, Colombia

Variable	DM fresh (% wb)	WA30 (%)	OCT (min)	DM30 (% wb)	Gradient (g mm^{-1})	Max. force (g)	Distance at max. force (mm)	Area (g mm)
WA30 (%)	0.164	1						
OCT (min)	−0.222	−0.602*	1					
DM30 (% wb)	0.470*	−0.730*	0.406*	1				
Gradient (g mm^{-1})	−0.079	−0.744*	0.593*	0.545*	1			
Max force (g)	0.124	−0.394*	0.299*	0.419*	0.531*	1		
Distance at max. force (mm)	0.433*	0.571*	−0.501*	−0.128	−0.615*	−0.245	1	
Area (g mm)	−0.023	−0.668*	0.514*	0.559*	0.821*	0.833*	−0.585*	1

*$P < 0.05$.

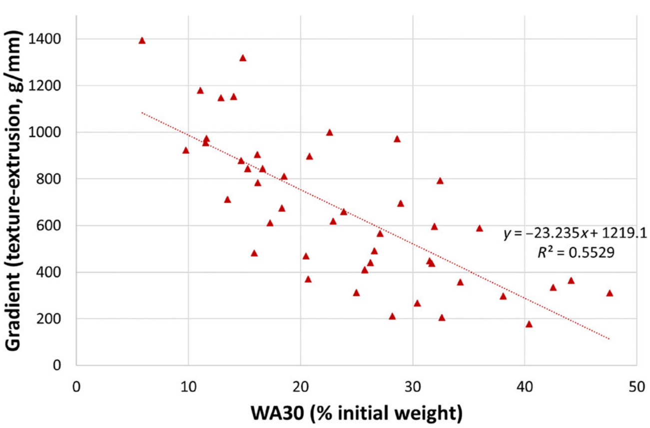

Figure 4. Linear regression between instrumental parameters WA30 and gradient (boiled cassava, Colombia).

samples with high sensory hardness were characterized by high penetration and compression forces, confirming the correlation observed in Table 6. An opposite trend was observed for samples described by QDA as mealy, easy to chew, sticky and white. The varieties identified as meeting the thresholds of sensory acceptability (Agric 12, Dossi 9, Dossi 12; section on 'Sensory mapping of boiled cassava', above) all belonged to this second group of samples, while the other varieties were associated with the first.

Using the QDA thresholds of acceptability for mealiness (≥5.8) and hardness (≤4.9) defined in the section on 'Sensory mapping of boiled cassava section', above (Table 2) and the linear regression equations linking sensory QDA scores with gradient and WA30 (Fig. 6), the following instrumental thresholds of acceptability can be defined (Table 2): WA30 ≥ 36% and gradient ≤ 302 g mm. As gradient is correlated with both sensory mealiness and hardness, resulting in two possible acceptability thresholds (302 and 794 g mm, respectively), we selected the most stringent criteria (302 g mm) as threshold. These thresholds can then be integrated into the target product profile of boiled cassava and used by breeders as selection criteria for screening cooking quality in candidate cassava genotypes, in addition to well-established agronomic criteria such as yield, plant architecture and tolerance to pests and diseases. These WA30 and gradient criteria for boiled cassava are quite stringent, as only 13.3% and 11.1% (six and five genotypes out of 45, respectively) of the cassava population (Colombia) characterized in the present study would pass the selection. This may reflect the high expectations by consumers regarding mealiness of boiled cassava, and underlines the importance of using mealiness among the criteria used for screening new cassava genotypes.

Table 6. Pearson correlations among sensory attributes, biochemical and biophysical parameters of boiled cassava (Benin)

	Sensory attributes						Biochemical parameters					Biophysical parameters		
Variable	White colour	Stickiness	Hardness/ Hard to break	Mealiness	Soft/ easy to chew	Cassava aroma	Sweet taste	Dry matter after boiling	*L**	*b**	Cyanide	Penetration force	Compression force	Extrusion max. force
White colour	**1**													
Stickiness	0.525	**1**												
Hardness/hard to break	**−0.855**	−0.375	**1**											
Mealiness	**0.861**	0.445	**−0.981**	**1**										
Soft/easy to chew	**0.816**	0.274	**−0.964**	**0.954**	**1**									
Cassava aroma	0.566	0.544	−0.631	0.592	0.527	**1**								
Sweet taste	0.603	**0.739***	−0.477	0.500	0.338	0.292	**1**							
Dry matter after boiling	−0.509	−0.459	0.582	**−0.694***	−0.623	−0.178	−0.368	**1**						
*L**	0.103	−0.140	−0.027	0.110	0.038	−0.455	0.296	−0.458	**1**					
*b**	**−0.774***	−0.241	**0.723***	**−0.693***	−0.609	−0.521	−0.330	0.134	0.133	**1**				
Cyanide	−0.478	−0.176	0.484	−0.367	−0.369	−0.210	−0.655	−0.149	0.007	0.469	**1**			
Penetration force	**−0.704***	−0.253	**0.819**	**−0.798***	**−0.861**	−0.314	−0.252	0.457	0.189	0.648	0.410	**1**		
Compression force	**−0.743***	−0.175	**0.874**	**−0.852**	**−0.963**	−0.475	−0.228	0.526	0.008	0.466	0.327	**0.804**	**1**	
Extrusion force	−0.401	−0.191	0.514	−0.616	−0.659	0.071	−0.146	**0.738***	−0.268	0.123	−0.109	0.652	0.662	**1**

Significance: **P* < 0.05; ***P* < 0.01. Correlations with high Pearson coefficient values are highlighted in bold.

Table 7. Pearson correlations among sensory attributes and instrumental measurements of boiled cassava, Colombia

Variable	Friability/mealiness	Glassiness	Hardness	Moisture	Stickiness
DM fresh (% wb)	0.374*	−0.567*	−0.169	−0.536*	0.424*
WA30 (%)	0.594*	−0.210	−0.492*	−0.323*	0.300*
OCT (min)	−0.433*	0.082	0.445*	0.157	−0.307*
DM30 (% wb)	−0.249	−0.205	0.255	−0.089	0.063
Gradient (g mm^{-1})	−0.608*	0.207	0.544*	0.231	−0.435*
Max force (g)	−0.112	−0.015	0.157	−0.011	−0.041
Distance at max. force (mm)	0.491*	−0.326*	−0.394*	−0.391*	0.495*
Area (g mm)	−0.393*	0.070	0.364*	0.136	−0.245
Linear distance (mm)	−0.271	0.065	0.294*	0.106	−0.193
End force (g)	−0.066	−0.034	0.119	−0.041	0.011
End force: max. force (%)	0.294	−0.163	−0.233	−0.210	0.295*

*$P < 0.05$.

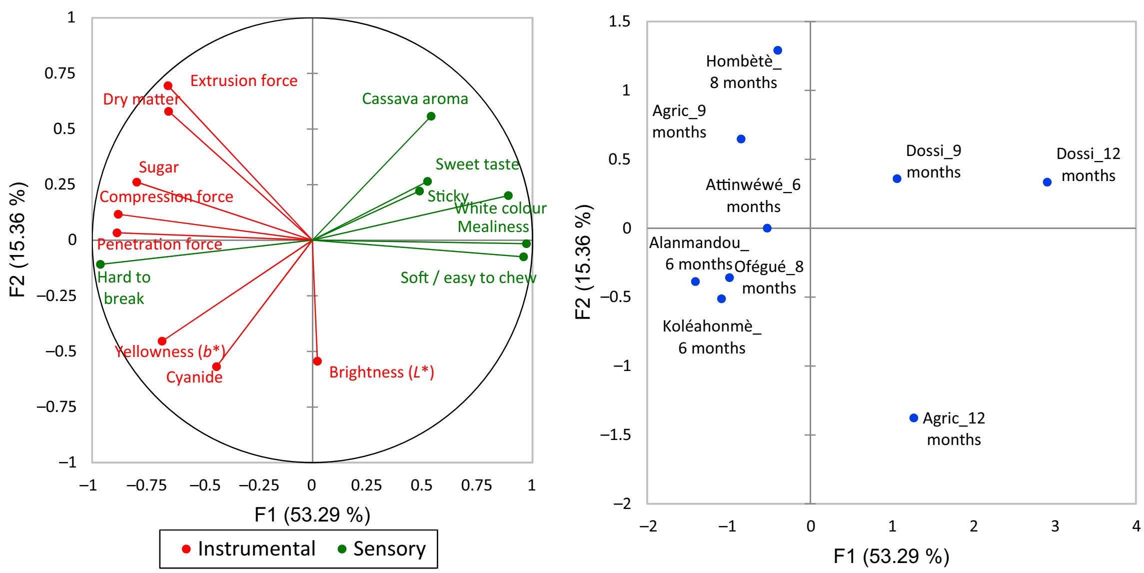

Figure 5. Multifactorial analysis of sensory attributes, biochemical and biophysical parameters of boiled cassava samples.

DISCUSSION

Hedonic scores and QDA for key sensory traits describing boiled cassava (hardness, mealiness and taste) can guide breeders in breeding varieties with sensory properties above the minimum acceptability thresholds of end users and consumers. Thanks to a standardized operating protocol for QDA, it was possible to produce comparable sensory datasets on boiled cassava from Uganda, Benin and Colombia, and to identify similar correlations between sensory and instrumental measurements in the three countries, in particular regarding the evaluation of textural attributes. Previous research works established correlations between sensory attributes and instrumental measurements of boiled cassava in Benin,[9,10] in Nigeria[3] and in Cameroon[11] but, to our knowledge, this is the first time datasets from different countries have been combined to draw robust conclusions on sensory and instrumental characterization of boiled cassava. The present study brings together hedonic, QDA and instrumental methods (WA30, texture analysis) as a demonstration of the complete approach to define acceptability thresholds for MTPP laboratory methods. A similar experimental approach had previously been applied to dessert banana.[22]

Seven key attributes for consumer acceptability of boiled cassava were identified: white colour of the flesh of fresh cassava root; sweet taste (not bitter); ease of peeling; cassava aroma; white colour of the flesh after boiling; not hard/easy to break; and mealy. Most of the attributes of boiled cassava in this study matched up with those of previous works that reported them as the major quality characteristics of boiled cassava.[8,23] In addition, easiness of peeling was reported for yam as one of the main purchasing criteria of fresh tubers,[24] and is also important in the case of cassava as it strongly impacts drudgery and productivity during processing.[25] A glassy sensory attribute evaluated in Colombia revealed additional information: glassiness was associated with moistness as perceived by sensory panellists, but at the same time with

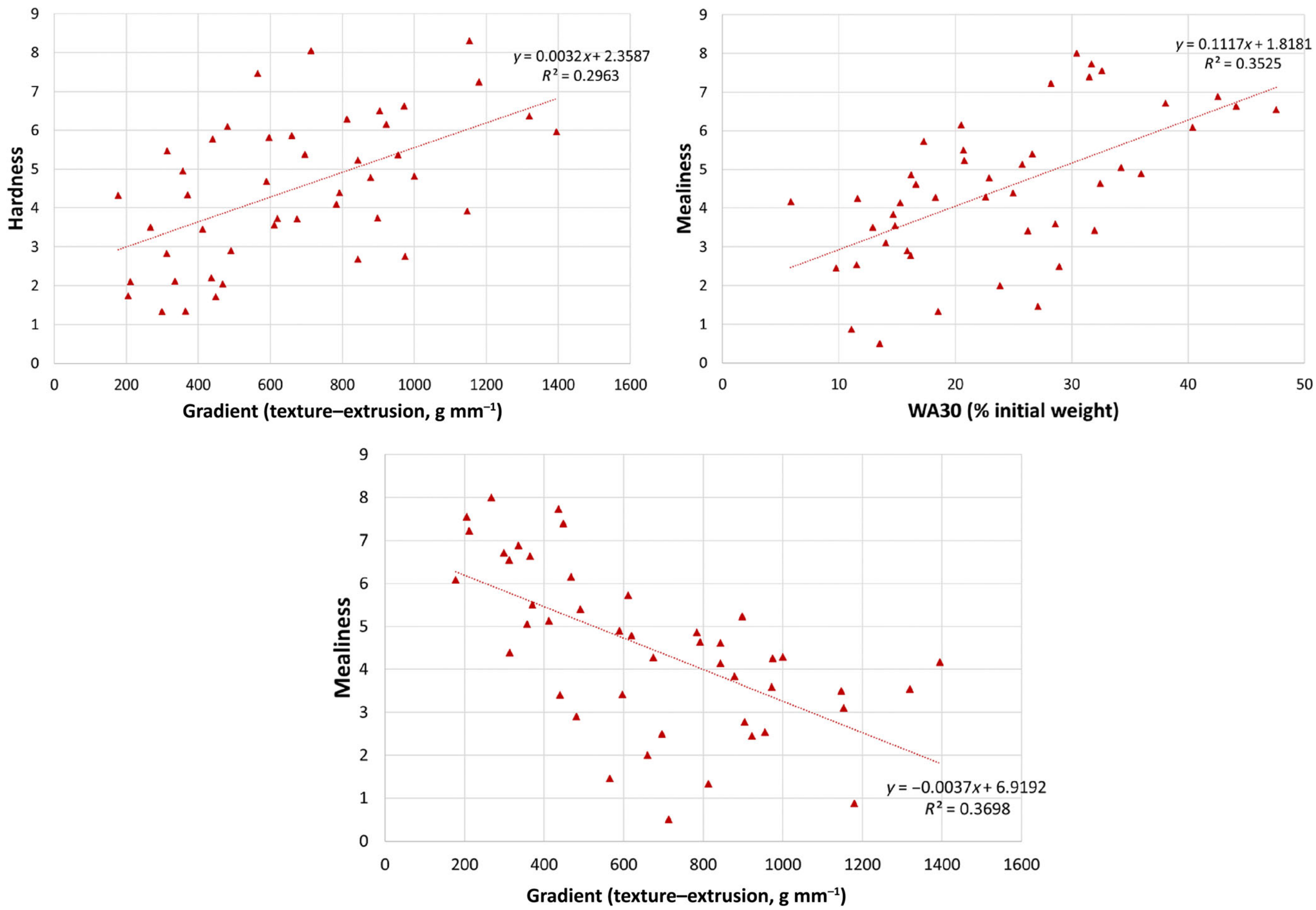

Figure 6. Linear regression among key sensory attributes and instrumental parameters describing boiled cassava (Colombia).

lower water absorption. This is likely because the water that was present in the samples after cooking was not fully absorbed by the starch fraction and instead remained on the surface and in the interstitial spaces, resulting in quicker release into the mouth upon biting, and hence a more moist perception. Combining results from consumer preference tests and sensory QDA, thresholds of acceptability were defined for the attributes of texture mealiness and hardness, while thresholds for the other attributes are still being investigated. To improve adoption rates of new cassava varieties, the sensory attributes and their acceptability thresholds can be included in the target product profile of boiled cassava alongside agronomic selection criteria such as yield, plant architecture and tolerance to pests and diseases. This is in agreement with the findings of Bechoff *et al.*[7] and Alene *et al.*,[26] who pointed out consumer liking as a driver or inhibitor of varietal adoption, and potentially the main constraint to stimulate the adoption of cassava varieties.

As sensory QDA is slow and requires large quantities of materials, instrumental methods for faster characterization of cooking quality of boiled cassava were developed. In the present study, water absorption (WA30) and texture analysis proved suitable to evaluate the texture attributes mealiness and hardness; and the acceptability thresholds of these sensory attributes were translated into instrumental acceptability thresholds (Table 2). Mealiness being a key quality trait for consumer adoption, identifying this relationship between mealiness and instrumental measurements implies that large-scale rapid and accurate phenotyping of mealiness of boiled cassava roots is no longer a major limitation for the effective development of varieties with adequate mealiness. This is a significant progress achieved over the course of the RTBfoods project, made possible by a multidisciplinary approach involving consumer preference scientists, food scientists and breeders.

These methods can be considered MTPP, allowing screening of 40–60 clones per day. For a full integration of cooking quality criteria in the screening of large progeny populations, further methodological developments are needed to increase the screening rate to several hundreds of clones per day (high-throughput phenotyping). To this end, prediction of cooking quality by near-infrared spectroscopy (NIRS) is being explored, as NIRS has proven successful in predicting various compositional traits of cassava such as dry matter, carotenoids and starch,[27-29] with an analysis time 1–2 min per sample.

The information generated is important for breeders to develop target product profiles (TPP) that integrate robust, evidence-based consumer acceptability traits. There remains a need to collect more data (sensory and instrumental) in order to obtain more robust correlations, and thus increase the accuracy and reliability of the instrumental thresholds of acceptability. The MTPP laboratory methods presented in this paper with their associated acceptability thresholds can then be applied by breeders for varietal selection integrating both agronomic and consumer preference criteria. Ultimately, these criteria can be normalized and combined into a joint selection index, leading to a more integrated and effective varietal selection process.

AUTHOR CONTRIBUTIONS

Conceptualization: Iragaba, Nuwamanya, Adinsi, Akissoé, Dufour, Tran. Data curation: Iragaba, Nanyonjo, Adinsi, Hotegni, Tran. Formal analysis: Iragaba, Nuwamanya, Djibril-Moussa, Adinsi, Akissoe, Tran. Funding acquisition: Dufour. Investigation: Iragaba, Nanyonjo, Nuwamanya, Wembabazi, Kanaabi, Honfozo, Djibril-Moussa, Hotegni, Adinsi, Delgado, Londoño. Methodology: Iragaba, Nanyonjo, Adinsi, Bugaud, Delgado, Londoño, Tran. Project administration: Dufour, Akissoé, Nuwamanya, Tran. Resources: Iragaba, Adinsi, Nanyonjo, Londoño. Supervision: Kawuki, Akissoé, Tran. Writing – original draft: Iragaba, Djibril-Moussa, Adinsi, Londoño, Tran. Writing – review and editing: Adinsi, Akissoé, Tran.

ACKNOWLEDGEMENTS

The authors are grateful to the CGIAR Research Program RTB (Roots Tubers and Bananas) and the grant opportunity INV-008567 (formerly OPP1178942): Breeding RTB Products for End User Preferences (RTBfoods), coordinated by the French Agricultural Research Centre for International Development (CIRAD), Montpellier, France, by the Bill & Melinda Gates Foundation (BMGF): https://rtbfoods.cirad.fr. Several members of the Cassava Program at the Alliance Bioversity – CIAT contributed to this work, in particular Sandra Salazar and the field agronomy team, and Jhon Larry Moreno, Maria Alejandra Ospina, Jorge Luna, Cristian Duarte, Juan Morera, Paola Ramos and Cristian Salazar for the Post-harvest Quality Laboratory. Previous versions of this paper and the ideas in it benefited greatly from suggestions and comments by Xiaofei Zhang and Hernan Ceballos.

CONFLICT OF INTEREST

The authors declare no conflict of interest in the execution of the present study.

DATA AVAILABILITY STATEMENT

Averaged data supporting the findings of this study are available in the supplementary materials. The raw data that support the findings of this study are available from the authors upon reasonable request.

ETHICS STATEMENT

Research described in this manuscript (from laboratory through consumer preference interviews and surveys) has been previously and formally approved by the competent authority (or authorities) within each country (UAC-FSA in Benin, NaCRRI in Uganda, Alliance Bioversity – CIAT in Colombia). Written informed consent was obtained for all study participants and is available.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

REFERENCES

1 Lebot V ed, *Tropical Root and Tuber Crops: Cassava, Sweet Potato, Yams and Aroids*, 2nd edn. CABI, Wallingford (2020).
2 Tran T, Zhang X, Ceballos H, Moreno JL, Luna J, Escobar A *et al.*, Correlation of cooking time with water absorption and changes in relative density during boiling of cassava roots. *Int J Food Sci Technol* **56**: 1193–1205 (2021).
3 Uchendu K, Njoku ND, Ikeogu NU, Dzidzienyo D, Tongoona P, Offei S *et al.*, Genotype-by-environment interaction and stability of root mealiness and other organoleptic properties of boiled cassava roots. *Sci Rep* **12**:20909 (2022).
4 Akinwale MG, Akinyele BO, Odiyi AC and Dixon AGO, Genotype × environment interaction and yield performance of 43 improved cassava (*Manihot esculenta* Crantz) genotypes at three agro-climatic zones in Nigeria. *Br Biotechnol J* **1**:68–84 (2011).
5 Jiwuba L, Danquah A, Asante I, Blay E, Onyeka J, Danquah E *et al.*, Genotype by environment interaction on resistance to cassava green mite associated traits and effects on yield performance of cassava genotypes in Nigeria. *Front Plant Sci* **11**:572200 (2020).
6 Thiele T, Dufour D, Vernier P, Mwanga ROM, Parker ML, Schulte Geldermann E *et al.*, A review of varietal change in roots, tubers and bananas: consumer preferences and other drivers of adoption and implications for breeding. *Int J Food Sci Technol* **56**:1076–1092 (2021).
7 Bechoff A, Tomlins K, Fliedel G, Lopez-Lavalle AB, Westby A, Hershey C *et al.*, Cassava traits and end-user preference: relating traits to consumer liking, sensory perception, and genetics. *Crit Rev Food Sci* **58**:547–567 (2017).
8 Iragaba P, Hamba S, Nuwamanya E, Kanaabi M, Nanyonjo AR, Mpamire D *et al.*, Identification of cassava quality attributes preferred by Ugandan users along the food chain. *Int J Food Sci Technol* **56**:1184–1192 (2021).
9 Hongbété F, Mestres C, Akissoé N, Pons B, Hounhouigan DJ, Cornet D *et al.*, Effects of cultivar and harvesting conditions (age, season) on the texture and taste of boiled cassava roots. *Food Chem* **126**:127–133 (2011).
10 Padonou W, Mestres C and Nago MC, The quality of boiled cassava roots: instrumental characterization and relationship with physicochemical properties and sensorial properties. *Food Chem* **89**:261–270 (2005).
11 Ngeve JM, Cassava root yields and culinary qualities as affected by harvest age and test environment. *J Sci Food Agr* **83**:249–257 (2003).
12 Forsythe L, Tufan HA, Bouniol A, Kleih U and Fliedel G, An interdisciplinary and participatory methodology to improve user acceptability of root, tuber and banana varieties. *Int J Food Sci Technol* **56**:1115–1123 (2021).
13 Adinsi L and Akissoé N, *Sensory evaluation of boiled cassava, RTBfoods Laboratory Standard Operating Procedure*. University of Abomey-Calavi, Abomey-Calavi, Benin (2020) Available: https://doi.org/10.18167/agritrop/00598 [2 February 2024].
14 Meilgaard MC, Civille GV and Carr BT eds, *Sensory Evaluation Techniques*, 5th edn. CRC Press, Boca Raton, FL (2015).
15 Tomlins K, Owori C, Bechoff A, Menya G and Westby A, Relationship among the carotenoid content, dry matter content and sensory attributes of sweet potato. *Food Chem* **131**:14–21 (2012).
16 Adesokan M, Alamu E and Maziya-Dixon B, *SOP for Determination of Dry Matter Content, RTBfoods Project Report*. IITA, Ibadan, Nigeria (2020) Available: https://mel.cgiar.org/reporting/download/report_file_id/17813 [2 February 2024].
17 Essers AJA, Bosveld M, van der Grift RM and Voragen AGJ, Studies on the quantification of specific cyanogens in cassava products and introduction of a new chromogen. *J Sci Food Agric* **63**:287–296 (1993).
18 Adinsi L, Honfozo L, Hotegni F, Djibril Moussa IM, Akissoé N, Mestres C *et al.*, *Standard Operating Protocol for Sample Preparation, Determination of Instrumental Texture of Steam-Cooked Cassava. RTBfoods Laboratory Standard Operating Procedure*. University of Abomey-Calavi, Abomey-Calavi, Benin (2023) Available: https://doi.org/10.18167/agritrop/00723 [2 February 2024].
19 Tran T, Escobar A, Dahdouh L, Ayetigbo O and Mestres C, *SOP for Characterization of Extrusion-Texture of Boiled Cassava. RTBfoods Laboratory Standard Operating Procedure*. Alliance Bioversity-CIAT Cali, Colombia (2023) Available: https://doi.org/10.18167/agritrop/00594 [2 February 2024].
20 Nuwamanya E, Iragaba P, Kawuki R, Nanyonjo AR, Kanaabi M, Khakasa E *et al.*, *Sensory characterization of boiled cassava. RTBfoods Laboratory Standard Operating Procedure*. NaCRRI Kampala, Uganda (2020) Available: https://doi.org/10.18167/agritrop/00599 [2 February 2024].

21 Ashby JA and Polar V, User Guide to the G+ Product Profile Query Tool (G+PP) CGIAR Research Program on Roots, Tubers and Bananas, CIP, Lima, Peru (2021). Available: https://cgspace.cgiar.org/bitstream/handle/10568/113167/9789290605959.pdf [2 February 2024].
22 Bugaud C, Maraval I, Daribo M-O, Leclerc N and Salmon F, Optimal and acceptable levels of sweetness, sourness, firmness, mealiness and banana aroma in dessert banana (Musa sp). *Sci Hortic* **211**: 399–409 (2016).
23 Favaro SP, Beléia A, Junior NDSF and Waldron KW, The roles of cell wall polymers and intracellular components in the thermal softening of cassava roots. *Food Chem* **108**:220–227 (2008).
24 Barlagne C, Cornet D, Blazy JM, Diman JL and Ozier-Lafontaine H, Consumers' preferences for fresh yam: a focus group study. *Food Sci Nutr* **5**:54–66 (2017).
25 Bouniol A, Ceballos H, Bello A, Teeken B, Olaosebikan DO, Owoade D *et al*., Varietal impact on women's labour, workload and related drudgery in processing root, ruber and banana crops: focus on cassava in sub-Saharan Africa. *J Sci Food Agr* (2023). https://doi.org/10.1002/jsfa.12936.
26 Alene AD, Abdoulaye T, Rusike J, Manyong V and Walker TS, The effectiveness of crop improvement programmes from the perspectives of varietal output and adoption: cassava, cowpea, soybean and yam in Sub-Saharan Africa and maize in west and Central Africa, in *Crop Improvement, Adoption and Impact of Improved Varieties in Food Crops in Sub-Saharan Africa*, ed. by Walker TS and Alwang J. CABI, Wallingford, pp. 74–122 (2015).
27 Bantadjan Y, Rittiron R, Malithong K and Narongwongwattana S, Establishment of an accurate starch content analysis system for fresh cassava roots using short-wavelength near infrared spectroscopy. *ACS Omega* **5**:15468–15475 (2020).
28 Jaramillo AM, Londoño LF, Orozco JC, Patiño G, Belalcazar J, Davrieux F *et al*., A comparison study of five different methods to measure carotenoids in biofortified yellow cassava (*Manihot esculenta*). *PloS One* **13**:e0209702 (2018).
29 Sánchez T, Ceballos H, Dufour D, Ortiz D, Morante N, Calle F *et al*., Prediction of carotenoids, cyanide and dry matter contents in fresh cassava root using NIRS and hunter colour techniques. *Food Chem* **151**: 444–451 (2014).

