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Characterizing quality traits of boiled yam: texture and taste for enhanced breeding efficiency and impact

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Abstract

BACKGROUND: Boiled yam key quality attributes typical for West African consumers are that it is crumbly, easy to break and has a sweet taste. New yam varieties are being developed but high- or medium-throughput tools to assess the required quality traits and their range of acceptance are limited. This study assessed the acceptance thresholds of these quality attributes and established predictive models for screening yam varieties that meet the required consumer preferences.

RESULTS: Overall liking was associated with sweet taste, crumbliness and easiness to break (*r*-values 0.502, 0.291 and −0.087, respectively). These parameters and selected biophysical parameters highly discriminated the boiled yam varieties. Crumbly texture and easiness to break were well predicted by penetration force and dry matter, whereas sweet taste were well predicted by dry matter and sugar intensity. A high crumbliness and sweet taste are preferred (sensory scores above 6.19 and 6.22 for crumbly and sweet taste, respectively, on a 10 cm unstructured line scale), while a too high easiness to break is disliked (sensory scores ranging from 4.72 to 7.62). Desirable biophysical targets were between 5.1 and 7.1 N for penetration force, dry matter around 39% and sugar intensity below 3.62 g 100 g^{-1}. Some improved varieties fulfilled the acceptable thresholds, and screening was improved through deviation from the optimum.

CONCLUSION: Acceptance thresholds and deviation from optimum for boiled yam assessed through the instrumental measurements are promising tools for yam breeders.

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

Keywords: yam varieties; consumer acceptability threshold; sensory attributes; varietal adoption; selection index; high-throughput phenotyping

INTRODUCTION

In West Africa, boiled yam may be either an end-product or an intermediate product in pounded yam processing. Its simple preparation involves peeling, slicing and boiling.[1] All yam varieties can be boiled but not all of them exhibit the high-quality characteristics expected by consumers. Indeed, a deviation from the acceptable crumbliness, easiness to break, sweetness and white or yellowish colour (no discoloration) could lead to rejection of a given variety.[1] Available information on these attributes is qualitative, essentially limited to consumer testing using a hedonic scale or check-all-that-apply (CATA) questions,[1] and thus not convertible into measurable criteria that breeders could use. It has been pointed out that users' varietal selections are influenced by their preferences for qualities associated with specific traits.[2]

To date, no study has generated validated relationships between sensory attributes and biophysical variables of boiled yam to be used by breeders to screen germplasm. The adoption of new varieties depends greatly on consumer acceptance. All new varieties of dessert banana reported by Bugaud *et al.*[3] had been rejected because of either visual or sensorial flaws. Preferred varieties can be readily identified if the thresholds (acceptable range) of major quality traits are available. Additionally, appropriate high- or medium-throughput phenotyping protocols are required for timely and cost-effective screening of quality traits in breeding germplasm.[4] Unfortunately, there is limited information on thresholds of boiled yam quality attributes.

In food sciences, many relationships have been established to predict either intrinsic characteristics of food products or sensory attributes as a function of biochemical/biophysical characteristics.[5,6] The difference in paste firmness in yam has been related to the extent of cell disintegration, which was more pronounced for *Dioscorea alata*.[7] Dry matter of raw and boiled yams (DMR and DMB, respectively) are closely linked.[8] The physicochemical measurements and starch functional properties do not fully explain the sensory perception of roots' and tubers' textural quality.[9] Reported correlations in yam were from studies that looked at an intermediate product for pounded yam processing,[10] instead of an end-product with a specifically targeted quality profile.

Understanding sensory attributes through robust and objective instrumental parameters with clearly defined thresholds is critical for efficient (rapid and early) screening of germplasm to ensure the adoption of new varieties. This study aimed to establish robust relations between sensory attributes and biophysical/instrumental variables and to determine the acceptance thresholds and deviation from optimum for screening and selecting yam germplasm.

MATERIAL AND METHODS

Plant materials and locations

Plant materials (landraces and improved yam varieties) were obtained from Benin and Nigeria farmers' fields, and research centres and were used in four experiments (Table 1 and Supporting Information Table S1). TDa and TDr stand for improved clones of *D. alata* and *D. rotundata*, respectively. Landraces are composed of *D. alata* (Aga, Kpètè) and *D. rotundata* (Deba, Dodo, Gnidou, Irindou, Kpaïnan, Kodjèwé, Kratchi, Laboko and Wété). Samples from Benin were grown at Dassa (7° 45′ N, 2° 10′ E) for Experiments 1 and 3. Materials from IITA-Nigeria (used for Experiment 2) were cultivated across two locations in Nigeria, namely Abuja (9° 04′ N, 7° 29′ E) and Ubiaja (7° 30′ N, 3° 54′ E), which differ in their agro-ecological conditions, such as rainfall patterns and temperature. The samples associated with each experiment and analysis are summarized in Table 1.

Experimental design

Sample preparation for sensory and biophysical analyses

Standard cooking procedures were employed to ensure consistency.[11] Yam tubers were sliced into three equal sections (proximal, middle, distal), and only the middle section was used in this study. After peeling, a punch was used to take cubic samples having 2.5 cm sides. The cubic samples (about 20 g per sample) were steam cooked for 38 min in 2 L of tap water in stainless steel saucepans using a gas cooker.

Quantitative descriptive analysis (QDA)

Three previously prioritized[1,12] sensory attributes – easiness to break, crumbliness and sweet taste (ST) – were selected using triangulation tools according to the methodology reported by Forsythe *et al.*[13] These attributes were used for the quantitative descriptive sensory analysis, with 13 and 15 trained panellists for Experiments 1 and 3, respectively (Table 1). The panellists scored the randomly coded boiled yam samples for each sensory attribute on a 0–10 cm unstructured line scale using anchor descriptors for 0 (lowest intensity of attribute) and 10 cm (highest intensity of attributes). The samples were served at around 50 ± 2 °C, and the panellists immediately assessed the texture attributes for 2–3 min and, after that, the sweetness. Sensory evaluation took approximately 5 min per sample and was replicated three times.

Consumer testing

Samples were evaluated for Experiment 1 according to Honfozo *et al.*[1] Overall liking data were collected from 113 consumers, 18–70 years old, including 54.9% males. In addition, the 3-point 'just about right' (JAR) test (1 = too weak; 2 = 'JAR: just about right' and 3 = too strong) was performed on crumbliness, easiness to break and sweetness.

Dry matter

Dry matter content was determined in triplicate by oven drying fresh (DMR) and boiled (DMB) yam tubers according to Adesokan *et al.*[14]

Sugar content

Soluble sugars were separated and measured, in duplicate, using high-performance liquid chromatography according to Mestres.[15] The sugar intensity was calculated according to Schaafsma[16] as follows:

Table 1. Yam varieties tested for each experiment, and analysis methods used

Origin	Yam variety	Experiment	Analysis	Prediction of model	Validation of model	Predicted parameter
Farmers' fields and AfricaYam – Benin	Aga†‡, Dodo,†‡ Irindou,†‡ Kodjèwé,‡ Kratchi,†‡ Laboko,†‡ Wété,†‡ TDa1, TDa2	1	QDA (crumbly, easy to break, sweet taste), penetration and compression tests, DMB and DMR, sugar intensity,† JAR test‡ and overall liking‡	Crumbly and easy to break, sweet taste† and overall liking‡		
	Kodjèwé, Gnidou, Deba, Kpètè,	3	QDA (crumbly, easy to break, sweet taste), penetration test, DMR and sugary intensity		Crumbly, easy to break and sweet taste	
IITA-Nigeria	TDa3, TDa4, TDa5, TDa6, TDa7, TDa8, TDa9	2	DMR, compression force			Penetration force, crumbly, 'easy to break', overall liking

Note: † and ‡ stand for specific analyses performed on some samples.
Abbreviation: na, not applicable; DMR, dry matter of raw yam; DMB, dry matter of boiled yam; QDA, quantitative descriptive analysis; JAR, just-about-right test.

$$\text{Saccharose} + 0.6 \times [\text{Glucose}] + 1.3 \times [\text{Fructose}] + 0.5 \times [\text{Galactose}]$$

Texture analyses

Penetration and double compression tests were performed according to Adinsi *et al*.'s[11] protocol using a texturometer (model TA-XT plus, Stable Micro Systems, Godalming, UK) on the samples collected in Benin from the same cooking batch used for quantitative descriptive analysis.

For the yam variety from IITA-Nigeria, the double compression test developed by Adinsi *et al*.[11] was slightly modified. Samples with regular shapes and sizes of 6 × 3 cm were analysed. A cylindrical compression probe of 35 mm was used at a test speed of 1.2 m s^{-1} and a load of 10 g. For each test, six replications were performed per sample.

Ethical assessment and consent for sensory evaluation and consumer testing

The research described in this article was previously and formally approved in Benin by the 'Comité National d'Ethique pour la Recherche en Santé' under approval number 16 of 6 May 2020. Written informed consent was obtained for all study participants.

Statistical analysis

Sensory (QDA and overall liking) and biophysical data were subjected to analysis of variance (ANOVA) followed by the least significant difference (LSD) Fisher post hoc test. JAR test data were analysed by counting the percentage of respondents who evaluated each boiled yam sample as JAR. Linear (simple and multiple) and partial least squares (PLS) regressions were applied to predict the sensory attributes and overall liking by the biophysical parameters. For models of sensory attributes, the number of variables was reasonably set to a maximum of two to minimize the laboratory analyses involved. In this case, a high coefficient of determination (R^2) between predicted and observed variables and the lowest root mean square error of calibration (RMSEC) were considered to assess the quality of the model. The robustness of the model validation was evaluated by the root mean square error of validation (RMSEV). Regarding the overall liking, the best model was selected using the lack-of-fit test (*F*-test) and associated *P*-value. All analyses were performed using XLSTAT (version 2016.02.28451, Addinsoft, Paris, France).

The thresholds of sensory attributes and their equivalent biophysical parameters were computed by linking the intensity of sensory attributes and biophysical parameters to their 'satisfied' level of JAR, according to the methodology developed by Bugaud *et al*.[3] but slightly modified as follows: the percentage of consumers who judged boiled yam to be JAR (2 on the scale) was linked to the intensity scored in QDA, and the relationship was fitted with a linear/quadratic function. The score of attributes at which the percentage of consumers who judged the boiled yam to be JAR was above 80% or 60% was assessed to stand for optimal and acceptable levels, respectively. The threshold of 80% of satisfied consumers was chosen because an attribute is considered optimal according to the Pareto principle.[17] The threshold of 60% of satisfied consumers (20% decrease from optimal level) was chosen as the acceptable threshold. Based on the score (optimal and acceptable) of sensory attributes determined, the optimal/ideal and acceptable levels of explicative biophysical parameters were assessed using predictive models from multiple regressions.

Table 2. Mean values of overall liking, sensory attributes and biophysical parameters of raw and derived boiled yam (Experiment 1)

Variety type	Sample name	Overall liking score (1–9 scale)	Sensory attribute scores_boiled (0–10 cm scale)			Hardness_boiled (N)		Sugar intensity_raw ($g\ 100\ g^{-1}$, dry solid, SE)	Dry matter ($g\ 100^{-1}$, wet solid)	
			Crumbly	Easy to break	Sweet taste	Penetration	Compression		Raw	Boiled
Landrace	Dodo	6.0bc	6.4abcd	7.3a	6.3ab	6.8c	58.4b	5.1	32.9b	30.0d
	Kratchi	6.6b	5.9bcd	5.8b	6.2ab	6.8c	64.0b	3.7	38.8a	34.8c
	Irindou	5.6c	5.7cde	4.6cd	6.1abc	8.5b	84.7a	2.8	39.9a	37.0b
	Kodjèwé	6.2bc	4.5e	4.4d	6.8a	9.7a	79.7a	nd	39.9a	36.0bc
	Wété	6.4b	5.3de	4.6cd	6.1abc	8.1b	81.6a	4.5	39.7a	35.2bc
	Laboko	8.0a	7.2ab	5.9bc	6.7a	6.0cde	45.6c	3.1	42.1a	39.4a
	Aga	5.7c	7.1abc	7.5a	4.6cd	5.8de	39.4cd	3.8	31.4bc	30.4d
Improved	TDa 1 520 050	nd	7.1abc	7.8a	4.8bcd	4.9e	28.5d	nd	30.3c	29.9d
	TDa 1 520 002	nd	7.8a	7.8a	3.7d	5.3e	42.0cd	nd	28.3c	27.4d

Note: Mean values with different letters in the same column are significantly different ($P < 0.001$).
Abbreviation: SE, saccharose equivalent; nd, not determined.

To screen and rank yam varieties, the selection index described by León *et al.*[18] was modified as follows: on the scale of overall liking (OL), the deviation from the ideal/optimum (DI_{OL}(obs → opt)) was determined for each variety and used as selection index. It was calculated using the regression coefficient (β) between consumers' overall liking and relating parameters. Accordingly, the deviation ($Value_{observed} - Threshold_{optimal}$) of each parameter from the optimal threshold target was standardized and DI_{OL} was calculated as follows:

$$DI_{OL} = \sum_{i=1}^{n} \left[\beta_i \times \left(Value_{observed_i} - Threshold_{optimal_i}\right)\right]$$

where i stands for each relevant parameter in the predictive models explaining consumers' overall liking.

RESULTS

Quality attributes and biophysical characteristics of boiled yam as affected by variety and harvesting location

Tables 2 and 3 present the mean values of overall liking, sensory attributes and biophysical parameters of boiled yam with varietal (Experiment 1) and harvesting location (Experiment 2) effects, respectively. For all sensory attributes, the range of variation of the scores was very large (>3.0) on the 0–10 cm unstructured linear scale. There were significant differences between yam varieties for the mean scores of crumbliness, easiness to break and sweetness (Table 2). *Dioscorea alata* genotypes (TDa 1 520 002, TDa 1 520 050 and Aga) generally showed the highest scores (>7) for crumbliness and easiness to break compared with *D. rotundata* clones, but had lower ST (<5 *vs.* >6). Laboko had a high crumbliness (7.2) for a *D. rotundata* but median easiness to break score (5.9). Overall liking of varieties varied significantly (Table 2). Laboko was the most preferred variety, while Aga and Irindou were the least.

Regarding sugars, saccharose (96.2%), glucose (2.4%), fructose (0.9%) and galactose (0.5%) were identified in the raw yam. The sugar intensity of raw yam, expressed as saccharose equivalent, varied from 2.8 $g\ 100\ g^{-1}$ in Irindou to 5.1 $g\ 100\ g^{-1}$ for Dodo (Table 2). Boiling decreased DM (Table 2) by 0.4% for TDa 1 520 050 to 4.5% for Wété.

The mean penetration (PF, 4.9–9.7 N) and compression (CF, 28.5–84.7 N) forces measured on boiled yam, and the DMR, exhibited significant varietal and harvesting location effects (Tables 2 and 3). For instance, CF was always significantly lower in Abuja than in Ubiaja (Table 3). The averages for CF (across the two locations) varied from 14.3 for TDa 1 508 044 to 30.3 N for TDa 1 515 030. The range of DMR from Ubiaja (25.5–39.5%) was wide compared to samples from Abuja (26.7–34.2%) in Nigeria (Table 3).

Comprehensive relationships within and between sensory attributes and biophysical characteristics of boiled yam

The crumbly texture was positively and significantly correlated with easiness to break but negatively with ST. A significant and positive correlation was found between PF and CF (Table 4). The linear regression equation was $PF = 0.07 \times CF + 2.62$ ($R^2 = 0.88$). Both were negatively and significantly correlated to the sensory texture attributes. Although some correlations between overall liking and any sensory attributes or instrumental texture parameters were relatively high, none reached statistical significance (Table 4). A positive and significant correlation was found

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Table 3. Key biophysical parameters and deviation from ideal of yam samples as affected by harvest location (Experiment 2)

Variety	Location	DMR (g 100 g^{-1}, wet solid)	Compression force (N)	Penetration force (N)	Predicted[a] Crumbliness (score)	Predicted[a] Easiness to break (score)	Predicted[a] Overall liking (score)	DI	Rank
TDa 0000194	Abuja	34.2a	13.9b	3.7	8.3	8.2	7.1	0.40	4
	Ubiaja	30.5b	39.0a	5.5	7.2	7.8	5.6	−0.35	12
TDa 1 508 044	Abuja	31.0a	6.7b	3.1	8.7	9.0	6.7	0.49	1
	Ubiaja	32.2a	22.0a	4.2	8.0	8.2	6.5	0.15	8
TDa 1 510 043	Abuja	26.7a	9.4b	3.3	8.5	9.5	5.8	0.27	5
	Ubiaja	34.6a	54.0a	6.6	6.5	6.6	5.9	−0.58	13
TDa 1 515 030	Abuja	27.0b	12.2b	3.5	8.4	9.4	5.8	0.21	7
	Ubiaja	39.5a	48.5a	6.2	6.8	6.1	7.0	−0.27	11
TDa 1 520 008	Abuja	33.6a	11.7b	3.5	8.4	8.4	7.0	0.45	3
	Ubiaja	31.0b	29.3a	4.8	7.6	8.1	6.0	−0.10	9
TDa 1 520 050	Abuja	31.5a	16.1b	3.8	8.2	8.5	6.5	0.27	5
	Ubiaja	25.5b	22.9a	4.3	7.9	9.2	5.2	−0.12	10
TDa 1 520 002	Abuja	32.9a	9.8b	3.4	8.5	8.6	6.9	0.46	2
	Ubiaja	35.3a	nd	nd	nd	nd	nd	nd	nd

Note: Mean values with different letters within the same column for a specific sample are significantly different ($P < 0.05$).
Abbreviation: nd, not determined.
[a] Predicted using prediction regression equations; DMR, dry matter of raw yam; DI, deviation from ideal/optimum.

between DMR and DMB (Table 4). Moreover, the easiness to break was significantly and negatively correlated with DMR and DMB. Correlations between the two dry matter and the penetration and compression forces were relatively high but non-significant (Table 4). Furthermore, a negative but not significant correlation was observed between the sugar intensity of raw yam and the sweetness of boiled yam (Table 4), while an unexpected negative correlation was found between ST and crumbliness.

Prediction of sensory attributes and overall liking of boiled yam through biophysical parameters

Sensory attributes

Multiple linear regression analyses (Experiment 1) revealed that crumbliness was properly predicted by the PF alone ($R^2 = 0.88$; RMSEC = 0.34), while easiness to break required both PF and DMR ($R^2 = 0.95$; RMSEC = 0.31; Table 5). The prediction models were validated by new independent samples (Experiment 3; Supporting Information Table S2). The robustness of the prediction was sufficient ($R^2 \geq 0.79$; $0.85 <$ RMSEV < 1.46) to score both attributes with a bias less than 1.25 points on the 0–10 cm unstructured linear scale (Table 5). Regarding ST, it was predicted (Table 5) by raw yam's sugar intensity and DMR ($R^2 = 0.73$, RMSEC = 0.34).

Overall liking

The overall liking of boiled yam was predicted (Table 5) by multiple regression analysis from PF and DMR ($R^2 = 0.79$, lack of fit = 8.11, $P < 0.05$, Supporting Information Table S3)

Table 4. Pearson correlation between sensory attributes, overall liking and biophysical data from Experiment 1

Variable	Overall liking	Crumbly	Easy to break	Sweet taste	Penetration force	Compression force	DMR	DMB	Sugar intensity_raw
Overall liking	**1**								
Crumbliness	0.291	**1**							
Easiness to break	−0.087	**0.854**	**1**						
Sweet taste	0.502	**−0.721**	**−0.754**	**1**					
Penetration force	−0.338	**−0.939**	**−0.893**	**0.694**	**1**				
Compression force	−0.328	**−0.874**	**−0.899**	0.658	**0.936**	**1**			
DMR	0.593	−0.639	**−0.852**	**0.862**	0.606	0.607	**1**		
DMB	0.631	−0.522	**−0.817**	**0.805**	0.563	0.558	**0.953**	**1**	
Sugar intensity_raw	−0.226	−0.151	0.443	−0.061	−0.086	−0.053	−0.567	−0.765	1

Abbreviation: DMR, dry matter of raw yam; DMB, dry matter of boiled yam.
Note: Numbers (>0.694) in bold represent significant correlation ($P < 0.05$).

Table 5. Multiple linear regressions between biophysical parameters, overall liking and sensory attributes

Dependent variable	Prediction regression equation	Calibration[a] R^2	Calibration[a] RMSEC	Validation R^2	Validation RMSEV	Validation Bias
Crumbliness = *f* (Lab)[b]	−0.61 × Penetration force (N) + 10.56	0.88	0.34	0.79	0.85	−0.72
Easiness to break = *f* (Lab)	15.33 − 0.54 × Penetration force (N) − 0.15 × DMR (g 100 g^{-1})	0.95	0.31	0.88	1.46	1.21
Sweet taste = *f* (Lab)	−2.4 + 0.18 × DMR (g 100 g^{-1}) + 0.43 × Sugar intensity (g 100 g^{-1})	0.73	0.34	nd	nd	nd
Overall liking = *f* (Lab)	2.4 − 0.41 × Penetration force (N) + 0.18 × DMR (g 100 g^{-1})	0.79	0.38	nd	nd	nd

[a] Calibration performed with data from Experiment 1.
[b] Model validated with data from Experiment 3.
Abbreviation: nd, not determined; DMR, dry matter of raw yam.

(Experiment 1). However, based on R^2 value (0.88), a model with three parameters (DMR + PF + ST) can also be used even if the lack-of-fit test was not significant (Supporting Information Table S3). The overall liking for seven yam varieties grown in Nigeria (Table 3) was determined using the predicted PF and DMR from Experiment 2. Irrespective of harvesting location, the overall liking varied from 5.2 (like slightly) to 7.1 (like much).

Thresholds for acceptance of key attributes of boiled yam

Texture

The thresholds of sensory attributes and their corresponding biophysical parameters were evaluated considering 60% (acceptable) and 80% (optimal) JAR levels (Experiment 1). For the crumbliness and the easiness to break, R^2 values ranged between 0.62 and 0.88, showing a strong relationship between sensory and biophysical variables (Supporting Information Table S4). Based on the sensory analysis (0–10 scale), the optimal texture of boiled yam was scored between 5 and 7 for easiness to break and above 7 for crumbliness (Table 6). Concerning easiness to break, the corresponding optimal thresholds of PF ranged between 6 and 8 N, concomitant with the DMR content between 35% and 38%, while PF below 6 N characterized the optimal crumbliness (Table 6). Thus, based on the thresholds of PF, no variety can have an optimal crumbliness and easiness to break texture simultaneously (the maximum threshold for crumbliness is below the minimum threshold for easiness to break). However, some varieties (Laboko, TDa 1 520 050 and TDa 1 520 002) were close to the optimal threshold characteristics.

The acceptable texture (60% JAR) was characterized by scores between 5 and 8 for easiness to break and above 6 for crumbliness. Acceptable (60% JAR) easiness to break was characterized by PF between 5 and 9 N and DMR between 33% and 40%. At the same time, crumbliness was judged acceptable if the PF was below 7 N.

Sweet taste

The optimal sweetness (80% JAR) of boiled yam was characterized by a sensory score of ST above 7, corresponding to a sugar intensity of raw yam below 3 g 100 g^{-1} and DMR above 45% (Table 6). In contrast, the acceptable sweetness of boiled yam (60% JAR) was associated with a sensory score above 6, a sugar intensity of raw yam below 4 g 100 g^{-1} and a DMR around 39% (Table 6).

Screening of yam varieties using texture acceptability thresholds

The seven varieties grown in Abuja and Ubiaja were screened based on the calculated acceptable thresholds (Table 6). Regardless of the harvesting location, the sensory scores of crumbliness and easiness to break (predicted using the regression equations presented in Table 5) were high (ranging between 6.1 and 9.4 on the 0–10 scale), while the predicted PF was low (3.1–6.6 N) (Table 3). Based on the sensory scores, no variety from either area had the textural characteristics of optimal boiled yam, i.e. when crumbliness and easiness to break were simultaneously considered at their optimal level (80% of satisfied consumers). However, TDa 1 510 043 and TDa 1 515 030, grown in Ubiaja, met the requirements from the acceptable threshold (60% of satisfied consumers). Furthermore, based on biophysical variables, only TDa 1 510 043 and TDa 1 515 030 grown in Ubiaja can be considered easy to break because they matched for DMR (Table 3) at

Table 6. Acceptability thresholds for sensory attributes and biophysical parameters of raw and boiled yam

Sensory attribute	JAR level (%)	Sensory score Min	Sensory score Max	Penetration force (N) Min	Penetration force (N) Max	Sugar intensity_raw (g 100 g^{-1}, dry basis)	DMR (g 100 g^{-1}_oven) Min	DMR (g 100 g^{-1}_oven) Max
Easy to break[a]	60	5 (4.72)	8 (7.62)	5 (5.1)	9 (8.6)	nd	33 (33.2)	40 (39.6)
	80	5 (5.29)	7 (7.04)	6 (5.8)	8 (7.9)	nd	35 (34.5)	38 (38.4)
Crumbly[b]	60	>6 (6.19)		<7 (7.1)		nd		
	80	>7 (7.03)		<6 (5.7)		nd		
Sweet taste[b]	60	>6 (6.22)		nd		<4 (3.62)		>39 (39.2)
	80	>7 (6.96)		nd		<3 (2.97)		>45 (44.9)

[a] Quadratic function.
[b] Linear function; nd: not determined; DMR: dry matter of raw yam.
Note: In parentheses, the observed threshold; not in parentheses, rounded value of the threshold.

acceptable level and PF at optimal level. Regarding crumbliness, all varieties can be considered crumbly at acceptable levels. Indeed, except TDa 1 510 043 and TDa 1 515 030 grown in Ubiaja that matched for PF at an acceptable level, the other samples matched at the optimal level. Similar to the sensory acceptability threshold, the screening from the biophysical variables' threshold revealed that the crumbly and easy to break samples were TDa 1 510 043 and TDa 1 515 030 grown in Ubiaja.

Use of selection index to identify promising varieties based on biophysical parameters

As previously established, the DMR and PF explained the overall liking of consumers, while the PF was predicted from CF (Table 3) (PF = 0.07 × CF + 2.62; $R^2 = 0.88$). The samples harvested in Abuja and Ubiaja areas were screened based on the deviation (DI) from the ideal/optimum on the overall liking scale (Table 3), used as selection index. Regardless of the harvesting location, DI ranged from −0.58 to 0.49. Variety × location samples with high DI values corresponded to those with high overall acceptance. DI ranked all yam varieties grown at Abuja among the top seven. In each location, TDa 1 508 044 was assigned the first rank.

Mapping of sensory attributes, biophysical parameters and yam genotypes

The PLS regression (Fig. 1) performed on data collected in Experiment 1 (Tables 2 and 3) confirmed that PF or CF explained the texture attributes (easy to break and crumbly), while ST was strongly associated with DMR and DMB. Overall liking was highly and positively correlated with DMR and DMB but weakly and negatively with sugar intensity. PLS also revealed, to a large extent, that the yam varieties were grouped into two classes with respect to species. Indeed, while 87.5% of samples from *D. alata* genotypes were on the left, varieties of *D. rotundata* were on the right. Furthermore, the *D. alata* TDa 1 510 043 and TDa 1 515 030 clones grown in Ubiaja were close to the acceptance threshold in texture attributes and related biophysical parameters. Both clones were the only *D. alata* located close to the *D. rotundata* varieties.

DISCUSSION

PF and DMR tightly explained the overall liking for boiled yam. These results show for the first time that the acceptability thresholds for boiled yam have been determined and used for yam genotype screening. However, the values calculated for the thresholds present two situations. First, for the optimal product (80% of satisfied consumers), the ranges obtained for some biophysical parameters exclude each other, thus making impossible the simultaneous satisfaction of the relevant traits. This is the case for PF associated with a crumbly texture and easiness to break or DMR related to ST and easiness to break. Second, at 60% of satisfied consumers, most thresholds widen and therefore expand the range of parameter variation. As a result, the number of yam varieties that pass through the screening is high. As a solution, the use of DI is promising and helpful to select and rank yam varieties that are close to optimal levels of overall liking simultaneously across a set of relevant traits. Consequently, the DI is highly appropriate to screen yam varieties. The effect of harvest locations observed on the DI demonstrates that it is sensitive, as it should be, to growing environmental conditions. Several selection tools are generally used by breeders to allow ranking of top varieties.[18] The use of the deviation of preferred variables from the optimum as well as the regression coefficients as weights in our study should give consistent results.

The correlations between instrumental parameters (biophysical, biochemical) and sensory attributes have been the subject of several publications,[3,5,6,8] but the profile of the ideal/optimal product[8] as well as the acceptability thresholds[3] have been poorly documented. Several studies[5,6] have provided evidence that sensory attributes' scores varied within and between genotypes and, specifically for yam, some variation between samples is expected, in agreement with Mestres *et al.*,[19] who reported a sizeable sensory score range covering the whole scale.

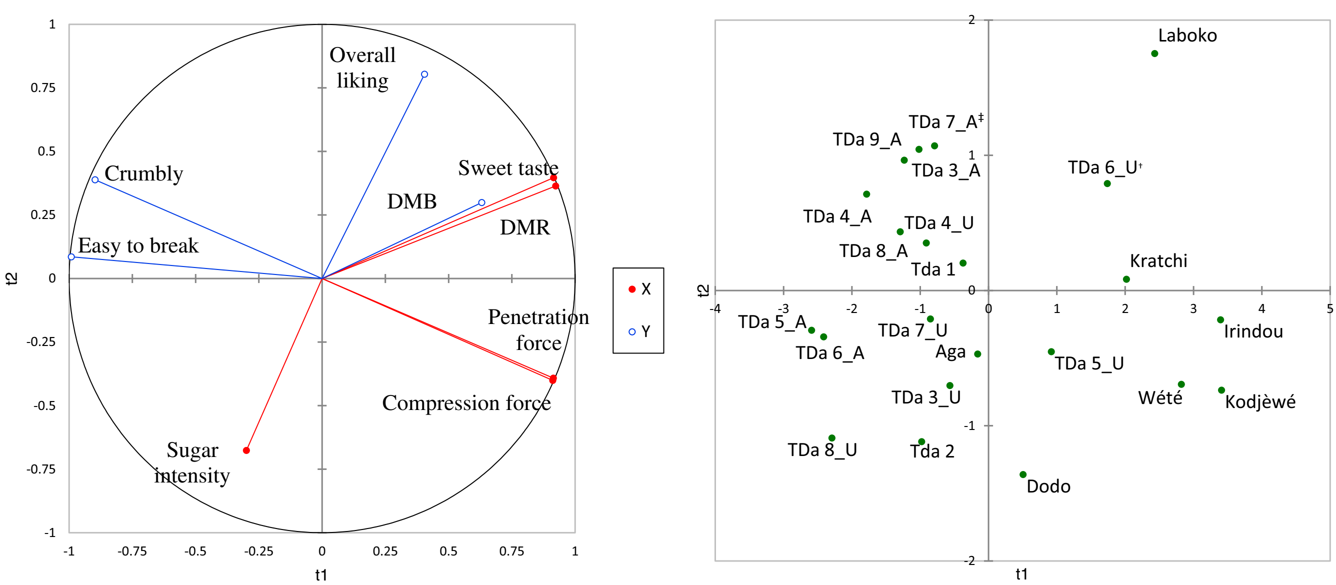

Figure 1. Partial least squares regression showing the sensory attributes (X) and the biophysical parameters (Y) (left) and yam genotypes (right). U, Ubiaja; A, Abudja; DMR, dry matter of raw yam; DMB, dry matter of boiled yam.

Dioscorea alata clones have generally lower scores of crumbliness, easiness to break and ST compared to *D. rotundata*.[1] The panellists had some difficulty in correctly assessing crumbliness, especially when the samples were very easy to break. Likewise, sweetness was difficult to score discriminately due to the narrow range of sugar in the samples. Thus, the negative association observed between crumbliness and ST (Table 4) should be considered with caution. van Oirschot *et al*.[9] reported regarding sweet potato that crumbliness is a complex organoleptic sensation that is difficult to assess. It is generally accepted that crumbliness is due to cell rupture on chewing, and crumbly varieties display more 'cell disorganization' than non-crumbly ones.[20] Therefore, the higher the instrumental cohesive force between cells, the lower is the cell disintegration[20] and the lower the crumbliness. This fact could be confirmed by the negative significant correlation between a crumbly sensory attribute and PF and CF. Favaro *et al*.[21] linked the low hardness of cooked roots and tubers to the separation of intact cells rather than the rupture due to the disintegration of middle lamellae (cells 'round off' during boiling) to become easily separable. The methods used for the penetration and compression tests could lead to the rupture of samples since they reflected more the technique used by the panellists to assess easiness to break; thus they could be linked more to the easiness to break than to the crumbliness. Furthermore, the texture parameters depend on DM, which varied between locations, which in turn are influenced by the soil carbon content[22] and/or the amount of rainfall received over the tubers' growing phases, among other possible differences.[23] DM effect on texture was also highlighted by Gibert *et al*.,[24] who reported a positive correlation between the DM of raw banana and the hardness of boiled banana, while Hongbété *et al*.[23] reported a negative correlation for cassava. Consequently, the role of starch, as the main component of roots and tubers, is complex and variable in textural behaviour of the end-products, and thus in PF and CF measured. Given that the crumbly samples were also easy to break, their prediction by PF could be due to collinearity between these sensory traits, as reported by Kouassi *et al*.[6] for boiled plantain.

Sugar content should be another criterion for yam breeders for phenotyping. However, the relationship between sugar intensity and ST of boiled yam is negligible, in agreement with Laurie *et al*.[25] for sweet potato. This is probably due to the observed narrow range in sugar content and the presence of bitter molecules such as polyphenols, which could mask the ST and lead to wrong and incoherent detection of sweetness differences in the mouth by assessors. Kouassi *et al*.[6] reported that an increase in the soluble solid content of 4 °Brix was sufficient for the panellists to perceive a significant and coherent difference. This led to a 2-point increase in the sweetness of boiled plantain. Mestres *et al*.[19] reported antagonistic roles of sweet and bitter molecules such as phenol and proanthocyanin in the paste from yam chip flour expressed by positive and negative correlations with bitterness and sweetness, respectively. Furthermore, during cooking, starch degradation occurred and allowed an increase in sugars, as pointed out by Chan *et al*.,[26] who observed that maltose formed during baking of sweet potato contributed to the final sweet sensation of the cooked root. This phenomenon of starch saccharification can be suspected in our study, given the sugar content and the scores obtained by some varieties. Accordingly, the ST of boiled yam should be interpreted with caution or through other deepened mechanisms/models. Bugaud *et al*.[27] reported that the sweetness of dessert banana was predicted to a lesser extent by saccharose, confirming that other biophysical parameters play a prominent role in predicting ST.

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CONFLICT OF INTEREST

None.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in https://collaboratif.cirad.fr/share/page/site/RTBfoods/docum at https://collaboratif.cirad.fr/share/page/user/akissoe/user-notifications.

SUPPORTING INFORMATION

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

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