Research Article

Received: 27 January 2023 Revised: 7 May 2023 Accepted article published: 1 June 2023

(wileyonlinelibrary.com) DOI 10.1002/jsfa.12723

Combined use of sensory methods for the selection of root, tuber and banana varieties acceptable to end-users

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Abstract

BACKGROUND: The assessment of user acceptability in relation to crop quality traits should be a full part of breeding selection programs. Our methodology is based on a combination of sensory approaches aiming to evaluate the sensory characteristics and user acceptability of root, tuber and banana (RTB) varieties.

RESULTS: The four-stepped approach links sensory characteristics to physicochemical properties and end-user acceptance. It starts with the development of key quality traits using qualitative approaches (surveys and ranking) and it applies a range of sensory tests such as Quantitative Descriptive Analysis with a trained panel, Check-All-That-apply, nine-point hedonic scale and Just-About-Right with consumers. Results obtained on the same samples from the consumer acceptance, sensory testing and physicochemical testing are combined to explore correlations and develop acceptability thresholds.

CONCLUSION: A combined qualitative and quantitative approach involving different sensory techniques is necessary to capture sensory acceptance of products from new RTB clones. Some sensory traits can be correlated with physicochemical characteristics and could be evaluated using laboratory instruments (e.g. texture). Other traits (e.g. aroma and mealiness) are more difficult to predict, and the use of a sensory panel is still necessary. For these latter traits, more advanced

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physicochemical methods that could accelerate the breeding selection through high throughput phenotyping are still to be developed.

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

Keywords: sensory analysis; instrumental methods; user acceptability; root crops and bananas; breeding; high-throughput phenotyping

INTRODUCTION

Roots, tubers and bananas (RTBs) are important food security crops in low-middle income countries. However, there is little understanding of the factors determining their acceptability by various value chain actors in those countries. Research work linking RTB sensory properties to consumer acceptance has been sparse and, to our knowledge, only started at the beginning of the 21st century.[1] Initially, the sensory properties and acceptability of sweet potato[2,3] and cassava[4] were investigated in sub-Saharan Africa. With the development of biofortified clones of root and tuber crops, in particular, there was an enhanced need to assess their acceptability by local consumers compared to common landraces. Later, other researchers[5-7] tested the acceptance of roots such as biofortified cassava.

The sensory and consumer methodologies were standard methodologies in sensory science but they were not yet common in sub-Saharan Africa until the early 2000s. Those methods were later applied in traditional African products such as hibiscus drinks in the European Union-funded AFTER project (2011-14) that benefited from the collaboration among researchers from the Natural Resources Institute and the University of Porto. The University of Porto introduced Check-All-That Apply (CATA) and Just-About-Right (JAR) tests for use with African food products.[8,9] The enhanced methodology includes qualitative interviews with various stakeholders of the value chain, including producers, processors and consumers.[10] The RTBfoods project (https://rtbfoods.cirad.fr) further built on those methodologies as described in various recent publications.[11-14]

A major problem in current breeding selection is that sensory properties and consumer acceptance of new clones are rarely considered.[15] A key challenge is assessing consumer acceptability using quicker and more efficient methods because a sensory panel and consumer tests require considerable efforts, time and money. The sensory properties of food are influenced by factors such as environment, including agronomic and processing conditions, and genetics. Developing reliable and objective instrumental methods that correlate with sensory characteristics and user acceptance of RTB products is desirable so that phenotypic characteristics can be traced back to their genetics and breeders can develop more acceptable varieties for users.

The possibility of using analytical chemistry methods for flavor selection in sweet potato breeding has been demonstrated previously in a study[16] suggesting a process to follow when developing sensory-based chemical tools for breeding selection. The relationships between sensory, physicochemical properties, genetics and consumer acceptance for cassava have been explored in a review.[6] The present study describes the step-by-step procedure applied in the RTBfoods project to develop breeding selection criteria for various RTB crops based on sensory approaches. The procedure described (based on selected examples from different crops) could help breeders with the selection of varieties acceptable to various stakeholders along the value chain.

MATERIALS AND METHODS

Consumer, sensory and physicochemical methods

The sensory methods described in RTBfoods reports[17,18] include ranking as part of qualitative participatory methods as well as hedonic approaches such as Overall Liking (nine-point-scale), JAR (three-point scale) and CATA. The Triadic Comparison of Technologies (TRICOT) is a relatively simple comparative approach (i.e. the consumer simply choses the best and the worst sample) rather than a rating approach using a Likert scale. It employs an incomplete block design where each participant compares only three samples. TRICOT was developed by the Consultative Group on International Agricultural Research (CGIAR) for farmer breeding selection and adapted to RTBfoods.[19,20] It is generally applied when more than seven samples were tested by consumers, but its applicability should be determined on a case-by-case basis.[21] Quantitative Descriptive Analysis (QDA), also called sensory profiling, has been described in a guidance document[22] that explains how to train a panel in sensory analysis and implement descriptive tests.

Biophysical properties such as texture were examined by Texture Profile Analysis (penetration, or penetration combined with compression) and hardness, penetration, compression, extrusion tests.[23,24] Biochemical properties were analysed following standard laboratory methods, such as dry matter (DMC), sugar content, Total Soluble Solids, Total Titrable Acidity (TTA), Cyanogenic potential.[24,25] Color was measured using a Hunter chromameter, including L^* (lightness or whiteness), a^* (redness) and b^* (yellowness).[24]

General approach

The steps of the methodology are outlined below.

Step 1: Identification of the key quality traits (KQTs). This is achieved through qualitative surveys with different stakeholders of the crop value chain, on RTB products that have contrasting sensory properties, aiming to develop a lexicon. Triangulation of results from the different surveys is carried out to select KQTs that drive end-user preferences.[11]

Step 2: Assessment of the sensory profile, consumer acceptance, and physicochemical properties of various RTB products. Numerous RTB products from highly contrasting clones (in terms of sensory properties), including new hybrids from breeding programs and common/local landraces, are characterized using KQTs from Step 1. Sensory testing is conducted on the ready-to-eat RTB products using QDA with a trained panel. Consumer testing is performed on the same prepared products using hedonic testing (i.e. nine-point hedonic scale and JAR) or TRICOT with consumers recruited *ad hoc*. Physicochemical (biophysical and biochemical) properties are measured on raw material or/and ready-to-eat products using laboratory methods. To develop meaningful correlations (translatable to measurable criteria that could be used by breeders), it is critical to ensure that the same samples are tested by the sensory panel, consumers and physicochemical means. All tests should be on edible (processed) products. However, some instrumental analyses (e.g. DMC, sugars and starch) and visual observations (e.g., color, absence of pests and diseases) can additionally be carried out on raw materials because these could generate more discriminating indicators and eliminate time allocated to product processing. In addition, high throughput methods such as near-infrared spectroscopy (NIRS)[26] and hyperspectral imaging[27] have been applied to develop correlations with physicochemical characteristics of RTB products (e.g. for DMC, pectin, starch and texture).

Step 3: Establishing correlations between sensory, consumer and instrumental measurements to determine thresholds. Once all the data are collected, relationships between sensory profile, consumer acceptance, and instrumental properties are explored. Non-linear (e.g. bell shape curve) or linear relationships could be obtained, and thresholds of acceptability linked to sensory and instrumental measurements can be obtained.

Step 4: Validation and scaling up of the method. The thresholds defined in Step 3 are then used to screen new RTB clones using instrumental measurements (if sensory traits can be predicted by physicochemical parameters) or a trained panel (for sensory traits that are not easily predicted by instrumental measurements, such as aroma). The clones that meet the acceptability thresholds are then validated using consumer testing (Overall Liking or JAR). To generalize the findings, the consumer tests should be performed in different regions or countries and new hybrids compared to local and preferred landraces.

The steps of the approach are summarized in Fig. 1. In theory, the methodology is a linear approach from Steps 1 to 4. However in practice, it is often a feedback loop process. Although steady forward progress is most desirable, sometimes there may be a need to go back a step to improve data collected earlier.

Case studies

The 11 products considered in the present study are those relevant to the RTBfoods project, with selected examples from local research institutions:

- Boiled: plantain, yam, cassava
- Steamed: matoke, sweet potato
- Dough-like: fufu, pounded yam
- Granulated: gari/eba, attieke
- Fried: plantain, sweet potato

RESULTS

Selected examples (not an exhaustive list) from different RTB crops are used here to illustrate the different steps of the process, identify commonalities and challenges and draw relevant conclusions.

Step 1: Identification of the KQTs of RTB products

The initial step concerns the development of a full lexicon of quality traits to identify KQTs using field interviews. Initially, RTB quality traits were identified through various qualitative interviews (state of knowledge, gendered food mapping and process diagnostics with expert processors).[10,11] KQTs were then selected by the country teams using a triangulation approach and a ranking system. Traits were divided into *desirable* and *undesirable* characteristics and listed for each RTB product (see Supporting information, Table S1). KQTs were applied with four to five crop varieties using CATA and JAR tests as part of preliminary consumer studies, as described in the examples of boiled yam in Benin[14] or sweet potato in Uganda.[28] Terms were further refined into a list of KQTs (see Supporting information, Table S1), which were part of a product profile exercise conducted with the various country teams. There were many similarities between different RTB quality traits: color should be homogeneous, either yellow, cream or white, (or all of them); the aroma should be typical of the crop (e.g. sweet potato, cassava), but actual descriptive terms for aroma were missing. Firmness should be optimal (neither too soft nor too hard, in the hand or the mouth). Stickiness was either a desirable or undesirable characteristic, depending on the product or the country. Mealiness was mostly seen as a desirable attribute. Taste should be sweet (=sugary) and non-bitter.

Step 2: Assessment of the sensory profile, consumer acceptance, and physicochemical properties of various RTB products

The second step assesses the sensory diversity, acceptability and physicochemical characteristics of RTB products. A few examples are presented below.

Steamed and mashed cooking banana (matoke) is a traditional dish in Uganda. similar to the vast majority of RTBs, it had never been sensorily characterized using QDA. Procedures for sensory analysis (product processing and sensory testing by the panel) are reported in Standard Operating Procedures (SOPs) (https://doi.org/10.18167/agritrop/00593). To explore the sensory diversity of matoke, a wide range of genotypes ($n = 32$) from local (13 landraces) and breeding programs (19 hybrids) germplasm were made into matoke and served to the panellists. The sensory traits of 68 matoke samples (from different bunches) from those

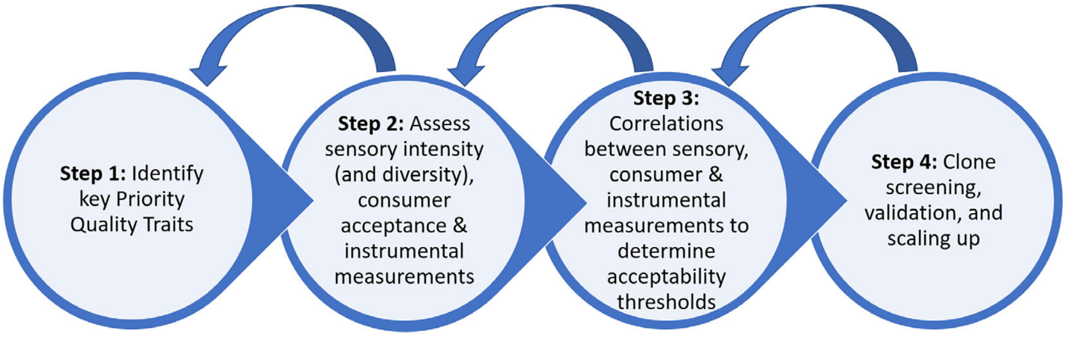

Figure 1. Workflow summarizing the RTB approach for sensory methods.

genotypes are described via principal components analysis using the covariance as the index of similarity (Fig. 2).

The first two axes explain 85% of the sensory variability. Hardness (handfeel) was positively correlated with firmness in the mouth ($r^2 = 0.85$) and negatively correlated with moldability, smoothness and moisture ($r^2 > 0.60$). Homogeneity of color and intensity of yellow color were strongly correlated ($r^2 = 0.85$). Stickiness was independent of the other attributes and sweetness was weakly represented. Replicated products were close to each other in distance, which demonstrates that the panel was well trained and consistent in their sensory assessments. Greater variabilities were observed between biological replicates (matooke prepared from different bunches), which was expected because of intra-varietal variability. Landraces had a more intense and more homogeneous yellow color, higher moisture, and more desirable smoothness, moldability and matooke aroma than hybrids. Landraces also felt softer in the mouth and in the hand compared to hybrids. Hybrids were divided into three groups: a first group presenting sensory characteristics close to landraces (N7, N17, N24), a second group of *firm* products (N2, N6, N15, 27914S-18) and a third group of products with lower intensity of yellow color and of matooke aroma (N8, N21, 17914S-24). In summary, sensory mapping of matooke allowed the identification of contrasting genotypes and some promising hybrids with sensory characteristics close to the landraces, which are appreciated by consumers.

The sensory diversity was also evaluated on cassava fufu samples from Nigeria. Eleven cassava genotypes (eight Nextgen elite clones and four landraces) were harvested from NRCRI-Umudike germplasm and processed into fufu. QDA of fufu was carried out at NRCRI, as reported in the SOPs (https://doi.org/10.18167/agritrop/00593). Fufu sensory properties are significantly affected by variety (Fig. 3).

Principal components analysis explained 72% of variation and showed that genotypes *Chenke* (preferred landrace), *Wonono* (intermediate landrace) and *0505* (good elite variety) were linked with smoothness, whereas *Genotype 1368* (poor elite clone) was associated with high adhesiveness, *F24(P001)* was associated with sticky texture, and *F3P017* was associated with hardness. The varieties *F1304(P0003)*, *F1160(P0004)* and TMEB419 were judged cohesive, resilient, springy, stretchable and chewy. The data generated from the study were correlated with data from texture analysis using the same genotypes, as described in SOPs (https://agritrop.cirad.fr/602118).

Consumer testing of boiled plantain was carried out with 123 consumers in two localities (*Njombe* and *Mbanga*) with four plantain accessions, namely: *Batard* and *Big ebanga* (landraces) and *CARBAP 969* and *CARBAP K74* (hybrids). JAR data were recorded for the four most important sensory attributes of the product (Table 1).

Most consumers (> 50% JAR) were satisfied with the sensory characteristics; namely, color, sweet taste, firmness and wetness – of *Batard* and *Big ebanga* boiled plantain samples. By contrast, *CARBAP K74* and *CARBAP 969* hybrids were *not yellow enough* for most respondents. Hybrids were also *not sweet enough* and *CARBAP K74* sample was *not firm enough* and *too wet*.

Physicochemical properties as well as sensory QDA data were recorded. *Batard* had the highest acidity, sugar and DMC levels, and was the most firm. Although *Big ebanga* was also appreciated by consumers, it was not as acidic and sweet as *Batard*. *CARBAP 969* and *K74* hybrids exhibited similar physicochemical properties.

Step 3: Establishing correlations between sensory, consumer and instrumental measurements to determine thresholds

This step is adapted from a stepwise method described by Bugaud *et al.*[30] Initially, correlations between data from sensory, consumer testing and physicochemical measurements are explored, usually using a linear (simple and multiple) regressions. Then, the percentage of consumers who judge products not satisfying (i.e. *too much* and *too little*; not JAR) is related to the intensity

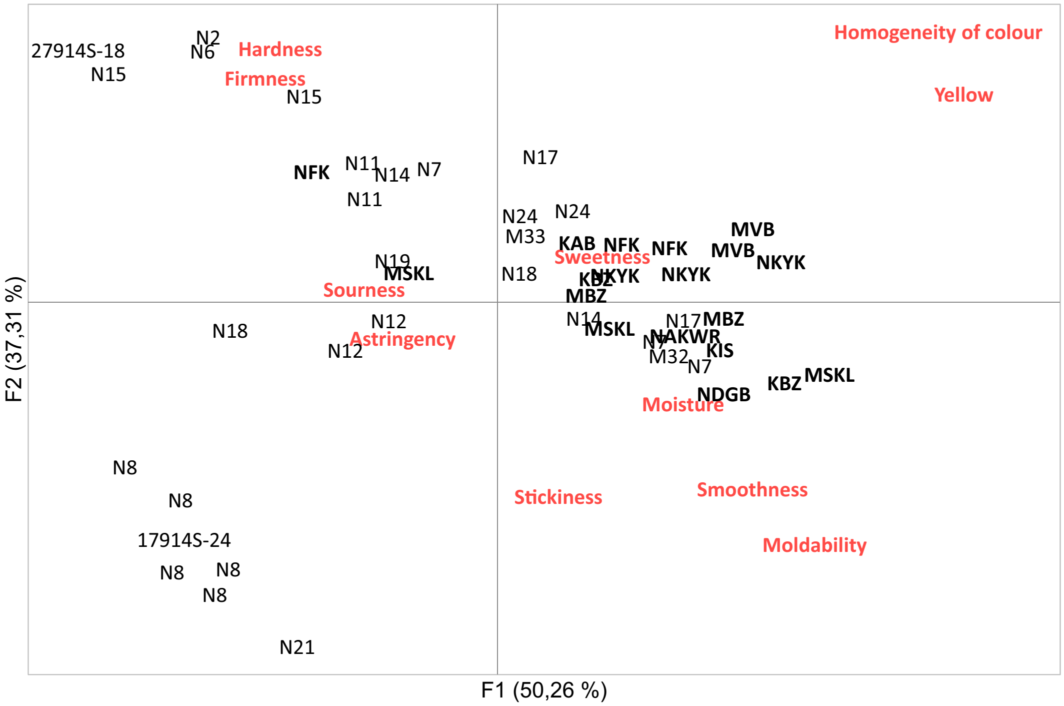

Figure 2. Principal components analysis illustrating the sensory diversity of matooke products from 32 genotypes [source: Khakasa *et al.*[29] ; NARO, Uganda]. In bold: landrace cultivars.

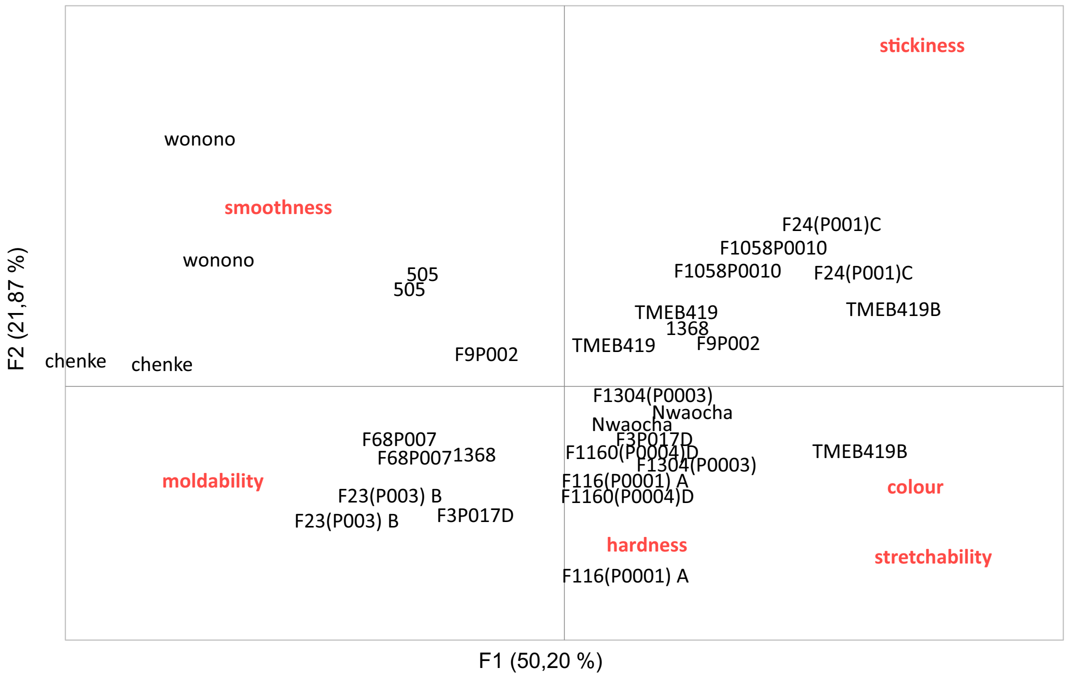

Figure 3. Principal components analysis illustrating the sensory diversity of fufu products from 12 cassava genotypes (source: NRCRI, Nigeria).

Table 1. Consumer Just-About-Right (JAR), Quantitative Descriptive analysis (QDA) and physicochemical data for boiled plantain

Variety of boiled plantain		CARBAP 969	CARBAP K74	Batard	Big ebanga
JAR data (% of consumers satisfied)	**Firmness**	44.7	33.3	65.0	52.9
	Wetness	53.7	37.2	53.6	52.9
	Sweetness	54.8	29.3	53.7	48.8
	Color	26.0	17.9	65.0	59.3
QDA intensity score (0–10) (evaluated by a trained sensory panel)	Firmness	5.4	4.7	6.7	5.6
	Wetness	5.4	5.4	3.6	4.2
	Sweetness	4.0	1.8	1.8	1.8
	Color	4.3	4.8	5.0	5.2
Physicochemical data (instrumental analysis)	**TTA (mEq/100 g)**	5.1	5.1	6. 7	4.4
	TSS (°Brix)	10	13	16	13
	Dry matter (%)	30	31	34	33
	Hardness (N)	67	75	108	89
	b*	37	33	33	37

Source: CARBAP, Cameroon.

of each QDA attribute or physicochemical indicator. On this basis, acceptable range of consumer acceptability scores are set by researchers. Thus, the method allows development of acceptability thresholds for each sensory trait or physicochemical indicator.

Physicochemical characteristics of seven boiled cassava samples in Benin were related to sensory characteristics measured by a sensory panel (Table 2). Pearson correlation revealed that DMC, whiteness (L^*) and total cyanide released from boiled cassava were not significantly correlated with any sensory attribute (Table 2a). With lower total sugar content, there was greater crumbliness and sweetness/'coolness' of boiled cassava ($-0.90 < r < -0.80$). This appears to be counterintuitive; however, a negative relationship between 'sweetness/coolness' or lack of bitterness perceived by consumers and sugar content has been shown in cassava products. Some studies have demonstrated that 'bitter varieties' tend to have higher sugar content than the sweet cassava varieties and this may explain those results.[31]

High forces of penetration, compression, and extrusion were positively associated ($t > 0.85$) with *hard to break* and negatively with *crumbly* and *easy to chew* ($-1 < r < -0.90$). Low forces of extrusion and penetration were significantly associated with higher scores for white color ($r = -0.85$) and sweet taste ($r = -0.94$).

The adequacy of these physicochemical variables to explain sensory profiling of boiled cassava was studied through a lack of fit test (F-test) and r^2 values (Table 2b). Based on the lack of fit test and associated P-value (< 0.05), lack of yellowness (b^*) and DMC of boiled cassava should be considered as the best model for white color, explaining about 96% of the phenotypic variation.

Table 2. Relationship between key sensory attributes and physicochemical parameters for boiled cassava in Benin, showing Pearson correlations and lack of fit (*F*-test)

	White color	Hard to break	Crumbly	Easy to chew	Sweet or ‘cool’ taste
Dry matter	−0.38	0.44	−0.59	−0.56	−0.53
*L**	−0.03	0.00	0.10	0.12	−0.26
*b**	**−0.85**[a]	0.76	−0.68	−0.69	−0.48
Cyanogencic potential	−0.42	0.65	−0.47	−0.52	−0.52
Total sugar	−0.63	0.79	**−0.85**	−0.81	**−0.87**
Penetration force	−0.78	**0.95**	**−0.92**	**−0.92**	**−0.94**
Compression force	−0.79	**0.96**	**−0.98**	**−0.97**	−0.74
Extrusion force	**−0.85**	**0.86**	**−0.94**	**−0.91**	−0.64

Sensory attributes	Model	Parameter (s)	r^2	*F*-test value	*P*-value
White color	1	b*	0.73		
	2	b* and dry matter	0.96	16.46	< 0.05
Hard to break	1	Compression force	0.92		
	2	Compression force and cyanogenic potential	0.96	3.78	> 0.10
Crumbly	1	Compression force	0.97		
	2	Compression force and L*	0.98	2.28	> 0.10
Easy to chew	1	Compression force	0.95		
	2	Compression force and L*	0.97	1.85	> 0.10
Sweet or ‘cool’ taste	1	Total sugar	0.75		
	2	Total sugar and cyanogenic potential	0.84	1.61	> 0.10

Source: Faculté des Sciences Agronomiques, Université d'Abomey-Calavi, Benin.
[a] Numbers in bold represent a significant correlation ($P \leq 0.05$); *r* is the Pearson correlation coefficient.

Lack of fit results suggest also that cyanogenic potential and whiteness (L^*) do not have predictive value for *hard to break, crumbly* and *easy to break*’. In other words, the appropriate biophysical variable to explain these three textural sensory attributes would be compression force ($r^2 = 0.92$–0.97). With sweet taste, an r^2 value of 0.84 suggests that total sugar content and cyanogenic potential explain most of the correlation, whereas, based on the lack of fit test, total sugar content may be sufficient to predict sweetness.

Correlations between sensory and physicochemical data were reported on various RTBfoods products, especially for texture. Texture Profile Analysis tests (penetration, or penetration combined with compression) were performed in steamed sweet potato,[32] boiled plantain,[33] gari and eba,[34] and fufu flour[35] and were significantly correlated with QDA data.

For boiled plantain, relationships between the percentage of satisfied consumers (JAR) and the QDA intensity of these attributes were explored (Table 3). The results showed that well-accepted varieties (with more than 50% consumers satisfied on average) such as *Batard* and *Big ebanga* are characterized by high scores for firmness and color (> 5.0), medium scores for wetness (3.0 < < 5.0) and low scores for sweetness (< 3.0). No acceptable color was found for *CARBAP 969*, whereas, for *CARBAP K74*, no acceptable firmness, wetness, sweetness and colour were found in relation with QDA. These observations confirm positive correlations between QDA and JAR data for the varieties *Batard* and *Big ebanga*, whereas, for the *CARBAP* plantain-like hybrids, these correlations were negative.

It was further shown that boiled plantain best accepted levels of sugar level were between 11.2 and 19.6 °Brix and that color parameters should be $L^* = 48$–55; $a^* = -0.7 - 2.9$ and $b^* = 30$–40. The sweetness and color acceptability threshold values above are based on values obtained from *Batard* and *Big ebanga* clones, which were rated ‘liked very much’ (score of 8) by consumers.

A threshold for firmness was established for steamed sweet potato in a recent publication[32] (Fig. 4).

Table 3. Sensory intensity (QDA) of boiled plantain key quality traits (KQTs) and corresponding consumer satisfaction (‘Just About Right’; JAR)

	CARBAP 969		CARBAP K74		Batard		Big ebanga	
KQTs	QDA	%JAR	QDA	% JAR	QDA	% JAR	QDA	% JAR
Firmness	≥ 5	< 50	3–5	< 40	≥ 5	> 60	≥ 5	> 50
Wetness	≥ 5	≈ 50	≥ 5	< 40	3–5	> 50	3–5	> 50
Sweetness	3–5	≈ 50	< 3	< 30	< 3	> 50	< 3	≈ 50
Color	3–5	< 30	3–5	< 30	≥ 5	> 60	≥ 5	> 50

High QDA score ≥ 5; Medium QDA score 3 ≤ *x* < 5; Low QDA score < 3.
Source: CARBAP, Cameroon.

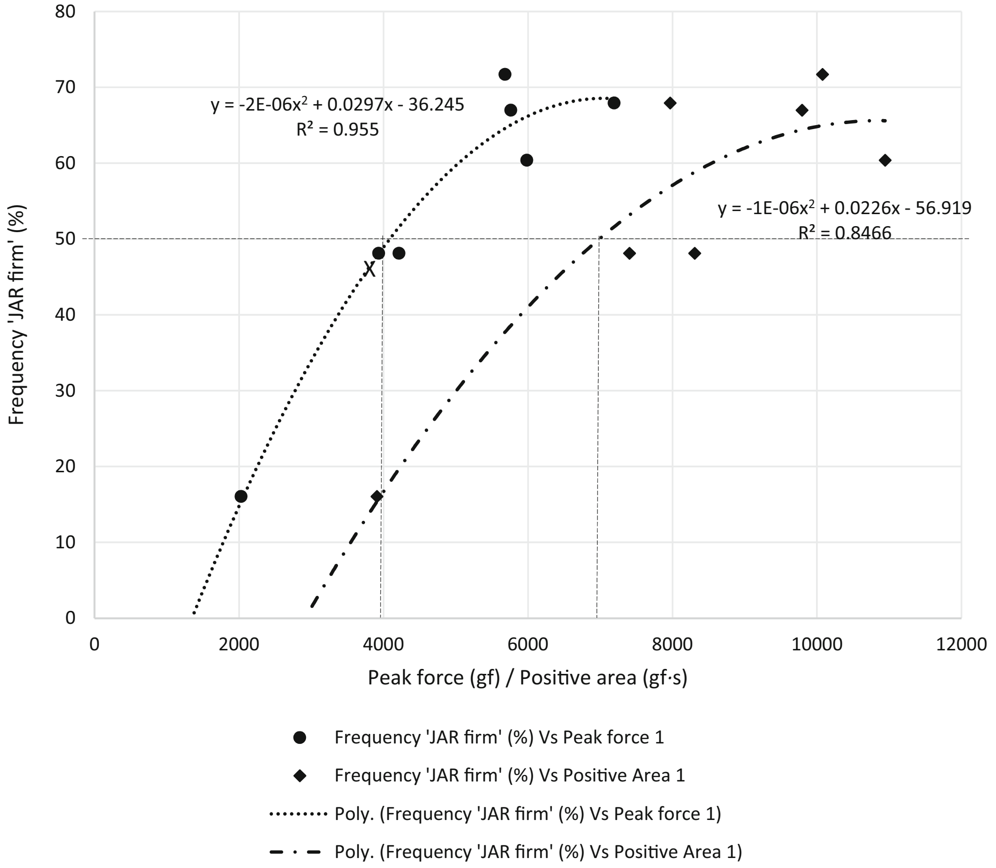

Figure 4. Firmness threshold for steamed sweet potato. (Source: Nakitto *et al.*[32]; CIP, Uganda).

The approach used for sweet potato was different from that for boiled plantain presented earlier. In the case of steamed sweet potato, an acceptable product with at least 50% consumers satisfied (indicated as 'JAR') for a sensory modality was identified. For boiled plantain, the two best varieties were considered the acceptable product and only four varieties were assessed in total. The analytical values associated with this product were adopted as the 'threshold' values. On the other hand, for boiled sweet potato, the thresholds of biophysical parameters were evaluated considering 50% (acceptable) 'JAR' level. The acceptable firmness was characterized by peak force and positive area above 4000 and 7000 g, respectively.

Step 4: Validation and scaling up of the method

Similar to Step 3, Step 4 is also inspired from the stepwise method.[30] In this approach, for example, the acceptability thresholds were used to screen banana dessert hybrids (Table 4).

Despite a large number of hybrids screened ($n = 172$), a limited number ($n = 7$) met acceptable sensory characteristics for all the KQTs. Acceptability thresholds in this example were calculated when a maximum of 66% of consumers satisfied (who judged bananas for example to be Just-About-Right). Those seven hybrids were then 'validated' using consumer testing to confirm their acceptability as follows: an overall liking test was carried out for each of these 'promising' hybrids by consumers. If the hedonic score was equal to or higher than 6 (like slightly), the hybrid was considered 'validated'.

With boiled yam, there was an attempt to translate results for Step 3 obtained in Benin to IITA, Nigeria for Step 4. A consumer satisfaction of 60% and above (JAR test) corresponded to QDA scores of between 4.7 and 7.6 for the 'easy to break' trait and this equated to a penetration force in the range 5.5–8.5 N. Seven improved varieties of boiled yam from IITA, grown in two Nigerian locations (Abuja and Ubiaja) were screened using the penetration force criteria and ranked according to their acceptability threshold. The rankings in Abudja (1–7) and Ubiaja (8–14), respectively (i.e. from the best to worst the variety), were: TDa1508044 (ranks 1 & 8) > TDa1520002 (ranks 2 & 8) > TDa1520008 (ranks 3 & 9) > TDa0000194 (ranks 4 & 12) > TDa1510043 (ranks 5 & 13) > TDa1520050 (ranks 6 & 10) > TDa1515030 (ranks 7 & 11).

Table 4. Screening of hybrids matching acceptability thresholds for key quality traits (KQTs) in banana dessert

KQTs	Acceptability threshold (on a scale 0–9)*	Number of acceptable hybrids
Sweetness	4.7–9.0	116
Sourness	1.1–4.6	125
Firmness	2.3–5.4	99
Mealiness	0.0–4.2	100
Banana aroma	4.8–9	18
All attributes		**7**

Source: Interpretation of Bugaud *et al.*[30] CIRAD breeding program, Martinique.

The results showed that the ranking widely differed with regards to the growing site (with Abuja producing the better yam products compared to Ubiaja) and therefore acceptability for 'easy to break' is linked to location rather than variety. These initial results underline the need (and the potential) for translation of threshold data to different contexts and countries.

DISCUSSION

We have proposed a formal four-staged approach to integrate sensory quality traits into RTB varietal selection programs. To our knowledge, breeding selection based on KQTs has been rarely reported with the exceptions of dessert banana[30,36,37] and sweet potato.[16] Such an approach should not in any case undermine the selection of other traits equally important for breeding such as yield, disease resistance, gender considerations (associated do drudgery), processing ability and shelf-life.

The results indicate that some traits are easier to predict using physicochemical methods than others. For example, hardness of boiled yam was well predicted by penetration (using texture analysis) and DMC. In raw and cooked matrices, color was well predicted by chroma metric measurements and is associated with carotenoid contents,[38] sweetness by sugar content[39] and acidity by organic acid contents.[39] On the other hand, mealiness in boiled yam was weakly correlated with penetration, or penetration combined with compression measured by Texture Profile Analysis. Criteria such as mealiness and fibrousness,[32] stickiness, fermented smell or aroma are currently difficult to predict using standard instrumental tools and the use of a trained sensory panel is still required.

We observed various challenges in the implementation of our approach. First, the method is cumbersome and has a low throughput because it is an iterative process. The use of a sensory panel requires training and time. Preparation of samples can also be lengthy, especially those requiring several steps of processing such as gari and fufu. Strong logistics is essential to organize all the different activities, including (i) processing, (ii) consumer testing, (iii) sensory panel testing and (iv) physicochemical analyses, which should be all conducted on the same samples to achieve meaningful and robust statistical comparisons. With climacteric crops such as plantain, there is an additional obstacle as a result of the difficulty of obtaining sufficient bunches from the various clones within a specific time frame because varieties have different flowering and harvesting dates even for those from the same location and planted the same day. Unstable textural properties of RTB products is another hurdle. For example, matooke texture may vary according to temperature, meaning that its viscosity differs if served hot or cold. Another challenge is that consumer preferences may differ in different areas because of different food habits, as well as tribal or cultural customs.

Most RTBfoods research teams did not manage to achieve all four steps of the method for all the products. A major difficulty for the teams was the development of acceptability thresholds because this required a sufficient number of varieties/clones and robust data. A challenge was the need for *trial and error* (feedback loop) (Fig. 1), perhaps necessary to test and perfect the method. With the experience described in the present study, the method will be faster to implement in the future.

The experience to date illustrates a number of critical considerations. It is crucial to identify all KQTs in Step 1. Missing some of the KQTs will lead to biased screening and incorrect selection of clones in Step 4. To establish a robust threshold (Step 3), a minimum of 10 sensorily contrasting varieties/clones is recommended in Step 2.[29] In our examples, we observed in Step 3 that steamed sweet potato showed a more robust response to the method than did boiled plantain: thresholds were calculated based on percentage of consumers satisfied with a sample product (JAR) rather than a comparison with acceptance score of local landraces. This percentage (high or low) is chosen based on participatory consultations with breeders and food scientists of the research team because it should be adapted to the specific context: selecting a high percentage (e.g. 66% JAR on dessert banana) would lead to an ideal product but with the risk of being too restrictive, as well as discarding potentially promising clones. Conversely, a low percentage (e.g. 50% JAR on sweet potato) leads to the selection of too many clones with only an average liking. To evaluate product samples with a panel (for sensory attributes that cannot be measured instrumentally), it is possible to work with a reduced panel of experts (3–5 tasters).[29] This could allow breeders to phenotype a large number of clones using a simplified list of KQTs. Finally, the screening stage (Step 4) should reduce the number of hybrids/varieties to an achievable number to be checked using consumer testing. Once high throughput methods such as NIRS and hyperspectral analysis are calibrated on sensory traits, this could greatly improve efficiency of the approach.

ACKNOWLEDGMENTS

This research was supported by the grant opportunity INV-008567 (formerly OPP1178942): Breeding RTB Products for End User Preferences (RTBfoods) funded by the Bill and Melinda Gates Foundation (BMGF). The opinions expressed in this paper do not necessarily reflect the views of our donor or partners. We thank Dr Michael Adezokans, Emmanuel Alamu and Bussie Mazyia Dixon for providing information about boiled yam in Step 4 through Laurent Adinsi, as well as Syvie N'Diby for providing traits of fried plantain in the Supporting information (Table S1). The editorial comments by Hernán Ceballos as well as the final proofreading of the manuscript by Clair Hershey greatly improved the quality of the manuscript. The article is dedicated to the memory of our dear colleague, Dr Genevieve Fliedel.

AUTHOR CONTRIBUTIONS

AB, CB, LA, GNN and DD were responsible for conceptualization. AB was responsible for data curation. AB was responsible for formal analysis. DD was responsible for funding acquisition. AB, CB, LA, GNN and MN were responsible for methodology. AB was responsible for writing the original draft. All authors were responsible for writing, reviewing and editing.

ETHICAL STATEMENT

The research described in this manuscript (from laboratory through consumer preferences interviews and surveys) has been previously and formally approved by the competent authority(es) within each country. Written informed consent was obtained for all study participants and can be made available.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

SUPPORTING INFORMATION

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

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