Research Article

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Establishing the linkage between eba's instrumental and sensory descriptive profiles and their correlation with consumer preferences: implications for cassava breeding

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Abstract

BACKGROUND: Gari and eba, forms of cassava semolina, are mainly consumed in Nigeria and other West African countries. This study aimed to define the critical quality traits of gari and eba, to measure their heritability, to define medium and high throughput instrumental methods for use by breeders, and to link the traits with consumer preferences. The definition of a food product's profiles, including its biophysical, sensory, and textural qualities, and the identification of the characteristics that determine its acceptability, are important if new genotypes are to be adopted successfully.

RESULTS: Eighty cassava genotypes and varieties (three different sets) from the International Institute of Tropical Agriculture (IITA) research farm were used for the study. Participatory processing and consumer testing data on different types of gari and eba products were integrated to prioritize the traits preferred by processors and consumers. The color, sensory, and instrumental textural properties of these products were determined using standard analytical methods, and standard operating protocols (SOPs) developed by the RTBfoods project (Breeding Roots, Tubers, and Banana Products for End-user Preferences, https://rtbfoods.cirad.fr). There were significant ($P < 0.05$) correlations between instrumental hardness and sensory hardness and between adhesiveness and sensory moldability. Principal component analysis showed broad discrimination amongst the cassava genotypes and the association of the genotypes concerning the color and textural properties.

CONCLUSIONS: The color properties of gari and eba, together with instrumental measures of hardness and cohesiveness, are important quantitative discriminants of cassava genotypes.

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

Keywords: biophysical traits; textural properties; genotypes; consumer acceptability; quality traits

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INTRODUCTION

Gari, an important cassava product in West Africa, is a dry, crispy, and granular precooked food product.[1,2] It is produced by peeling, washing, grating, pressing, fermenting (optional), sieving, and roasting cassava roots.[3] Its versatility is reflected by the various ways it is consumed, such as dispersing the dry form in cold water and drinking it directly with sweeteners, groundnut, and fish, or preparing it into a dough. The dough, popularly called eba, is the most widely eaten form of gari in Nigeria.[4,5] Eba is made by briefly cooking and stirring the gari granules until a homogeneous gelatinous dough is formed.

For breeders to develop varieties that cassava users will adopt, it is important to characterize the food product profile that determines the acceptability of the cassava genotypes and to link it to genetically controlled traits. Food quality criteria that inform demand-led breeding, which could benefit crop users, have been identified by Teeken *et al.*[6] Farmer-processors assessed diverse genotypes, including landraces and improved varieties, using a participatory variety selection 'mother-baby trial' approach to understand the criteria for food quality preferences. Color, bulk density, swelling power, solubility, and water absorption capacity were identified as crucial quality parameters of gari and eba that drove the choices of women processors, who most often market the product and are expected to reflect the preferences of consumers.[6]

The end users' preferred quality traits in gari and eba were also evaluated in Cameroon and Nigeria through focus group discussions (FGDs) and individual interviews (IIs).[7] The study revealed that color, attractive appearance, uniform granules, and taste were the preferred end-user traits for gari and eba quality, characterized by sensory textural attributes such as smoothness, firmness, and moldability.[7]

Breeding cassava for the shininess/gloss of gari and textural attributes like moldability and stretchability of eba has been recommended for cassava breeding programs.[7] The authors also suggested developing high-throughput selection methods for these essential quality traits. The RTBfoods project (RTBfoods: Breeding Roots, Tubers, and Banana Products for End-User Preferences, https://rtbfoods.cirad.fr) delivered standard operating protocols (SOPs) for color and textural attributes for RTB crops. These SOPs can be adopted by breeding programs to select cassava genotypes effectively for end users' preferred quality characteristics.[8] Awoyale *et al.*,[9] in their review, established that several parameters like water absorption capacity, starch properties, and particle sizes contribute to the texture and result in variations in gari quality in different regions.

Sensory evaluation has also been reported to be a significant determinant of the acceptability of any cassava variety and its subsequent adoption and use for making different products.[2] The acceptability of eba by consumers has been reported to be driven by sensory attributes such as appearance, color, taste, aroma, and other textural parameters such as smoothness, moldability, hardness, and stretchability.[1,7,10] Vital sensory textural attributes, such as hardness, adhesiveness, cohesiveness, springiness, chewiness, gumminess, and resilience, can be measured by the texture analyzer. The relationship between Eba's instrumental and sensory texture has been reviewed.[1] However, little information is available on the link between each attribute's instrumental and quantitative descriptive sensory scores. The present study aimed to define and measure the eba critical quality traits (color and texture) and link the traits with consumer testing.

MATERIALS AND METHODS

Source of genetic materials

Three sets of cassava genotypes, comprising 30, 40, and 10 genotypes respectively, from advanced lines, released elite genotypes, and farmer varieties (used as checks) were used for the three experiments reported in this study. These genotypes were harvested 12 months after planting from the IITA experimental plots at three locations in Nigeria during the 2019–2020 (sets of 30 and 40) and 2020–2021 (set 10) cropping seasons.

Experiment 1

The set of 30 genotypes (26 advanced lines and 4 landraces) coded A1 to A30 (supporting information, Table S1) was planted at Ibadan (7° 30.0854' N, 3° 54.5952' E) following a replicated randomized complete block design (RCBD) with four replications. Plot size was 5.6 m by 6 m, spaced 1 m between rows and 0.8 m within rows. The whole set was used for an initial evaluation of root pulp color, and a subset of 13 contrasting genotypes was then selected for instrumental and sensory textural properties.

Experiment 2

The second set of 40 genotypes (35 advanced lines and 5 released elite genotypes) coded B01 to B40 (supporting information, Table S1) was planted using the same location and experimental design as in Experiment 1 above. Genotypes were evaluated to assess the genetic variability in the texture and color of eba and gari. The released elite genotypes used as checks in this study were *Game changer*, *Baba70*, *IITA-30572*, *TME 419*, and *Dixon*, and healthy harvested fresh roots were selected and visually sorted by size, weight, and shape.

Experiment 3

In Experiment 3, ten different genotypes were utilized (coded C1 to C10). The set included three advanced lines, three released varieties, two regional varieties (as informed by the Cassava Monitoring Study, Wossen *et al.*[25,11]), and two local varieties (best varieties as chosen by the processors) (supporting information, Table S2). They were planted in Osun (7° 30.0854' N, 3° 54.5952' E) and Benue states (7° 21.0496' N, 8° 50.1766' E) using the same experimental design as in Experiment 1. All the genotypes were processed into food products (following regionally dominant traditional methods) by three experienced 'champion' processors in the state for the biophysical traits (gari) and consumer testing (eba).

Production of gari

Production of gari followed the SOP developed by the RTBfoods project (https://mel.cgiar.org/reporting/download/report_file_id/). Roots (50 kg) from each variety were peeled, washed, drained, and grated using a mechanical grater (Dandrea Agriport Grater, Maquinas d' Andrea, Brazil). The grated mash was loaded into jute bags and tied with a string. The bagged cassava mash was left to ferment at ambient temperature before pressing out the juice using a hydraulic press (Dandrea Agriport Grater, Maquinas d' Andrea, Brazil). The typical gari for each ethnic group (see below) was produced in a centralized facility. Depending on the preferences for sourness at each location, fermentation times ranged from 2–3 days, and dewatering process took 36 h. The pressed cake was manually crushed and sieved with a mesh size of 1.50 mm to remove the fibrous materials. The starchy granules obtained were processed into gari (garification) using a standard laboratory scale approach where all unit operations were controlled, such as roasting temperature (68 to 70 °C), roasting time (20 min), the thickness of the pan (33.7 cm), and quantity of starch granule used for frying. It is important to standardize these steps due to varying processing conditions.

Instrumental and sensory texture profile analysis of eba

Instrumental texture profile analysis (ITPA) of eba made from gari with the 13 selected genotypes (Experiment 1) followed an SOP[12] to determine hardness, adhesiveness, cohesiveness, springiness, gumminess, chewiness, and resilience using the texture analyzer (TA.XT, Stable Micro Systems, Ltd, Godalming GU7 1YL, UK). The texturometer was coupled with a standard compression cylindrical platen of 30 mm diameter for a double compression test. Eba samples were presented in a uniform shape with dimensions of 2.2 cm long and 3.6 cm in diameter using an opened cylindrical plastic adapted for sample collection. A test speed of 1.75 mm/s and a trigger force of 5 g were used as the test conditions. Two cooking replicates per genotype were considered, with two measurements per cooking replicate. A sensory texture profile analysis (STPA) was conducted for the same varieties in duplicate sessions by 16 trained panelists following an SOP.[13] The sensory attributes of moldability, adhesiveness, hardness, and stretchability were assessed using 16 trained panelists, and samples were scored on a scale of 0 (lowest attribute score) to 10 (highest attribute score). The performance of the panelists was tested statistically, assessing the repeatability of each panelist and agreement with other panelists on the same sample. Panelists with inconsistent responses with high standard deviation were eliminated from the analysis.[13] The ITPA of eba made from gari from selected genotypes/varieties for Experiments 2 and 3 was carried out as described for Experiment 1.

Color measurements

The color properties of gari (Experiments 1, 2, and 3) and eba samples (Experiments 1, 2 and 3) were determined using the RTBfoods SOP[14] for color analysis and color meter (Chroma meter CR-400, Konica Minolta, Inc., Chiyoda-ku, Tokyo, Japan). Gari and eba samples from each variety were transferred into a transparent plastic container for color measurements and were processed in duplicate. There were three dimensions: a light to dark dimension (L*), a red to green dimension (a*), and a blue to yellow dimension (b)*. The total color difference, ΔE*, was calculated using the L*, a*, and b* values. The ΔE* is a single value that considers the differences between the sample and standard L*, a*, and b*.[14] The color meter was calibrated (L* = 93.24, a* = 00.96, b* = 02.75) with a sheet of business Xerox 80 gm^{-2} white paper with 136 CIE whiteness D65.

Near infrared reflectance spectroscopy spectral collection and model development

A near infrared reflectance spectroscopy (NIRS) calibration model was developed for color parameters (L*, a* b*) and key textural attributes of eba (Experiment 1). The genotypes in Experiment 1 were used as the training set. In contrast, an independent group of ten genotypes was randomly selected from Experiment 2 to validate the model developed using Experiment 1 data. Texture analysis of the eba was carried out using a texture analyzer (TA. XT, Stable Microsystem, Ltd) by molding the samples into uniform thickness and shape with an open-end cylindrical plastic mold with a dimension of 2.2 cm long × 3.6 cm diameter. Spectra data of eba were collected using the adapted SOP[14] by scanning two times at a wavelength range of 400 to 2498 nm, registering the absorbance values log (I/R) at 0.5 nm intervals for each sample using a NIRS monochromator (model FOSS XDS, solid module Munkedal, Sweden) and a stationary cell. The reference values for the color parameters used for the calibration development were obtained using the Chroma meter (CR-400, Konica Minolta, Inc., Chioyoda-ku, Tokyo, Japan).

Genetic components of color and texture analyses

Descriptive statistics for 15 traits grouped in two broad categories (color and ITPA from Experiment 2) were used to analyze the genetic components of color and texture attributes. Subsequently, data curation of the 40 genotypes (Experiment 1) was done by adjusting the genotypic means using the Best Linear Unbiased Estimates before further analysis for genotype variance, means and genotype fixed effects. However, the genotype variance components, adjusted means, and genotype fixed effects were obtained after fitting a single trait mixed linear model using the lme4 R package, as shown in Eqn (1):

$$y = X\beta + Zd + Wa + \varepsilon \tag{1}$$

where y is the vector of adjusted means, β is the vector of fixed effects attributed to the clonal genotypes, d is a vector of random factors related to the design effects, where replications (also referred to as blocks) were independent and identically distributed, W is the vector of fixed additive genetic effects, and ε is the vector of random residual effects that followed a normal distribution. Hence, broad-sense heritability (H^2) for all traits was derived following the method in Eqn (2)

$$H^2 = \frac{Vg}{Vg + \frac{Ve}{k}} \tag{2}$$

where Vg is genotypic variance, Ve is the residual, and k is the number of replications. The correlations between traits were determined using the 'cor' R package, and data were visualized using the ggplot2 package[15] in R.

Crowd-sourced consumer testing

The consumer testing of eba was carried out with 600 consumers from rural and urban areas in Osun and Benue states, Nigeria, using the tricot approach[16] developed for consumer testing.[17] Participants in this experiment received three samples (out of ten) as part of an incomplete block design to evaluate overall liking, taste, moldability, smoothness, and stretchability, indicating which sample had the best and worst characteristics for each trait. The trial was designed, and data were collected and managed using the ClimMob platform (https://climmob.net/). Demographics on the consumers' gender, age, ethnicity (Hausa, Ibo, Igbira, Tiv, Idoma, Igede, and Yoruba), region, and frequency of eba consumption were collected during the consumer testing sessions, as these parameters could influence consumer preferences.

Statistical analysis to establish the relationship between the biophysical traits and consumer preferences

Consumers' appreciation of genotypes (for taste, moldability, stretchability, and smoothness) was assessed using the Plackett–

Luce model.[18,19] We applied Luce's axiom, which estimates the probability that a given genotype outperforms all the other genotypes in a set. To account for the effects of gender, age, ethnicity, occupation, and frequency of eba consumption on eba preference, we applied a model-based recursive partitioning approach.[20] To account for the effect of biophysical features of gari and eba from the different genotypes (texture profile and color spectrum) on eba preference, we applied the alternating directions method of multipliers (ADMM) algorithm,[20] which estimates the linear predictor for log-worth by genotype features. This method helps explain how the traits of the genotypes affect what consumers want.

RESULTS

Color properties of Gari

Chromametric color parameters ranged from 91.48 to 105.42, −1.24 to 1.24, and 19.96 to 28.26 for L*, a*, and b*, respectively, for the gari samples from Experiment 1. Rhe eba *samples* (from Experiment 1) had L* values ranging from 89.48 to 101.44, b* ranged from 1.5 to 2.32, and a* ranged between 21.34 and 31.80. In the principal component analysis (PCA) for the color of gari samples, PC1 and PC2 explained 86.50% of the observed variability in the L, a*, and b* values (Fig. 1). The PCA shows wide discrimination amongst the cassava genotypes. The genotypes were classified into three clusters. L* values explained the association of cluster 1 genotypes (A2, A6, A4, A3, and A1). However, the genotypes A1, A10, A9, A14, A12, A4, A11, A8, A26, and A7 (cluster 2) were associated with the positive quadrant of PC1 and characterized by a* (redness). Genotypes A30, A29, A20, A23, A18, A28, A24, A27, A19, A25, A22, A16 and A21 (cluster 3) were in the same group with the check sample (A17). They were associated with the positive section of PC2 and mainly characterized by low negative L* values. Genotypes A5, A26, A1, A10, A7, and A8, were described by a* and b*, but there was an overlap between L* and a* for a few genotypes (A3 and A11), which occupied the opposite side of b*. The results highlight the discriminants among the genotypes and the protocol's effectiveness.

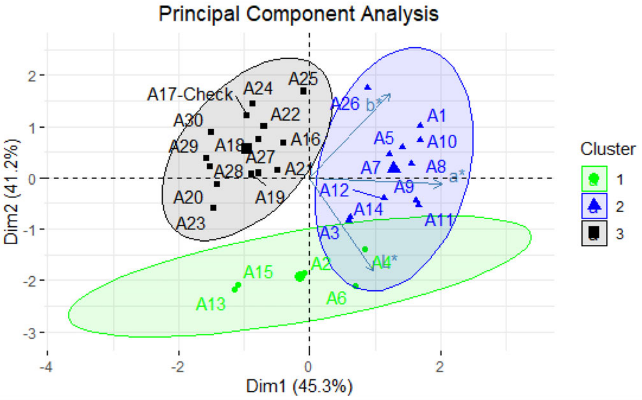

Figure 1. Principal components analysis showing variation in color parameters (L*, a*, b*) for the gari samples.

Near infrared reflectance spectroscopy prediction models for color and textural properties of eba

Table 1 shows the NIRS prediction model statistics for the color and textural properties of eba (Experiment 1) and prediction performances using a set of ten genotypes selected from Experiment 2 as a validation set. Because NIRS can predict multiple constituents at the same time, the color and texture of Eba could be determined simultaneously using a single sampling workflow, saving the additional time of using the Chromameter and Texture Analyzer. The result shows that cohesiveness had an excellent coefficient of determination in calibration (R^2_{cal}) of 0.94, followed by hardness and chewiness, which had average R^2_{cal} of 0.79 and 0.50, respectively. The model also showed a promising prediction capacity with R^2_{pred} of 0.54, 0.40, and 0.59 for hardness, adhesiveness, and chewiness, respectively.

Sensory and instrumental textural profile analysis

Table 2 shows the ANOVA of the instrumental texture of eba prepared from gari of 13 genotypes of cassava. There was a

Table 1. Prediction models for color and texture of eba using NIRS

	Training set (N = 30)				Validation set (10)	
Parameter	R^2_{cal}	RSMSEC	SEL	R^2_{pred}	SEP	Bias
Color of gari						
L	0.72	1.18	2.05	0.07	0.85	−0.74
a*	0.74	0.43	0.45	0.21	0.38	−0.01
b*	0.88	0.95	1.64	0.55	1.25	0.64
Color of eba						
L	0.80	1.7	1.14	0.64	2.22	−0.13
a*	0.66	0.56	0.65	0.35	0.57	−0.22
b*	0.35	1.44	1.44	0.27	1.23	1.14
Texture of eba						
Hardness	0.79	36.36	1.15	0.54	40.73	21.63
Cohesiveness	0.94	0.01	1.42	0.23	0.20	−0.19
Adhesiveness	0.33	52.69	2.20	0.40	67.72	7.18
Gumminess	0.21	23.14	2.18	0.30	54.66	−51.43
Chewiness	0.50	10.23	1.82	0.59	48.06	−45.86

Abbreviations: R^2_{cal}, coefficient of determination in calibration; R^2_{pred}, coefficient of determination in prediction; RSMSEC, Root means a square error in calibration; SEL, standard error laboratory; SEP, Standard error prediction; WB, wet basis.

Table 2. Analysis of variance of the instrumental texture of eba prepared from gari of 13 genotypes of cassava

Source of variation	DF	Hardness	Adhesiveness	Cohesiveness	Springiness	Gumminess	Chewiness	Resilience
Genotype	12	107249***	36038***	0.113***	1731***	19720***	8823***	407***
Cooking replicate	1	889	9909*	0.0052	88	1295	955	0.21
Genotype × cooking replicate	12	483	17 599	0.012	410	1155	1646	8.4

*** $P < 0.0001$.
*$P < 0.05$.
ns = $P > 0.05$.

significant difference ($P < 0.05$) among the genotypes for all the instrumental texture traits measured. On the other hand, the cooking replicates were not significantly ($P > 0.05$) different, except for adhesiveness. The non-significance of the cooking replicate signifies that the instrumental texture protocol used was repeatable for all the attributes (except adhesiveness). At the same time, the protocol can discriminate between the genotypes. The genotype-by-replicate interaction had no significant ($P > 0.05$) influence on the instrumental textural attributes, further indicating that the protocol is reliable. Based on the F-ratios, the most discriminant textural attributes were resilience, hardness, gumminess, and cohesiveness (Table 2).

Discrimination between genotypes based on instrumental textural profile – PCA

Based on the textural qualities of eba made from gari produced from 13 selected cassava genotypes (Experiment 1), the first two components of the PCA explained 85.3% of the data variation in the texture of eba. The PCA shows that the genotypes A7, A30, and A4 were associated in the same component space and were not associated with any ITPA attribute (Fig. 2). Genotypes A3, A16, A13, A28, A6, A26, and A11 were grouped in components space associated with the hardness, gumminess, and chewiness attributes; A17 – Check, A24, and A3 were grouped in the component associated with cohesiveness, springiness, and resilience and may be considered close to genotype A17 – Check, which is the best released elite clone for quality gari and eba.

Correlations between instrumental and sensory textural attributes

There were significant ($P < 0.05$) correlations between instrumental hardness and sensory hardness and between adhesiveness and sensory moldability (this being negative) (Table 3). Cohesiveness was significantly related to adhesiveness and moldability; any non-cohesive genotype will not likely be moldable. Stretchability, however, was not significantly correlated with any instrumental texture. Linear fit relationships between the instrumental and sensory texture can be used to estimate sensorial texture (Fig. 3). Linear regression coefficients of sensorial hardness and moldability on instrumental hardness were positive (R^2 values 0.616 and 0.563, respectively), as was the correlation coefficient between sensory adhesiveness and instrumental resilience (R^2 value 0.490). On the other hand, the regression of moldability on instrumental cohesiveness was negative ($R^2 = 0.474$).

Genetic component of textural and color traits

Figure 4 shows the distribution of color and ITPA traits of gari and eba from Experiment 2. The evaluated gari and eba quality traits showed varying magnitudes of genotypic and residual variance and broad-sense heritability (Table 4). Most gari and eba color traits followed a similar pattern to each other and were normally distributed, with a few slightly skewed (Fig. 4). Furthermore, the distribution patterns associated with eba ITPA traits were mainly skewed, with a few normally distributed, specifically gumminess and hardness (Fig. 4). A twofold difference was recorded between the minimum and maximum phenotypic observations for the evaluated traits (Table 4). The mean for gari brightness (L*_gari = 86.26) was higher than eba brightness (L*_eba = 64.48), demonstrating a change in brightness during the conversion process, which is expected going from a dry product to a wet product.

The population had moderate to low H^2 estimates for color traits and eba ITPA traits. Most eba textural (ITPA) traits, including gumminess, hardness, adhesiveness, chewiness, and cohesiveness, had low H^2 estimates (less than 10%) in comparison with the gari and eba color-related traits, which were greater than 30%. The highest estimates of H^2 were recorded for a*_eba (59%), b*_gari (42%), and b*_eba (32%), whereas other traits, including a*_gari (0.00%), L*_gari (0.00%), gumminess (0.00%) were not heritable in this population. We estimated the genotypic and residual variances to explain the extent of the genetic contribution to the observed phenotypic values. Pairwise phenotypic correlations across 15 gari and eba color and eba textural traits uncovered potential relationships and directions of expected changes among attributes (Fig. 5). Highly significant positive correlations were recorded between color traits from the two products except for L*. In contrast, the total color difference (ΔE) for gari is explained by a* (green-redness), confirming findings by Teeken *et al.*[16], while the ΔE of eba is highly correlated with b* (blue-yellowness). The phenotypic correlation between color and textural traits ranged from weak significant negative to weak positive correlation estimates.

Relationship between biophysical traits and consumer testing

Table 5 shows the estimates of the effect of genotypes' biophysical features on the consumers' preference for eba samples. Overall, consumers participating in the trial strongly prefer eba obtained from gari samples with higher L* and a* but lower b* values and eba with higher cohesiveness ($P < 0.001$, Table 5). Significant cohesiveness is necessary to achieve moldability. When looking at the effect of combined consumers' characteristics (gender, age, ethnic group, region, and consumption pattern) on the relation with biophysical traits, we found significant differences ($P < 0.001$) between consumers from different ethnic groups (Fig. 5). Participants from Hausa, Ibo, Igbira, and Tiv groups prefer the eba derived from genotypes of Experiment 3 C10_LC (TMEB3),

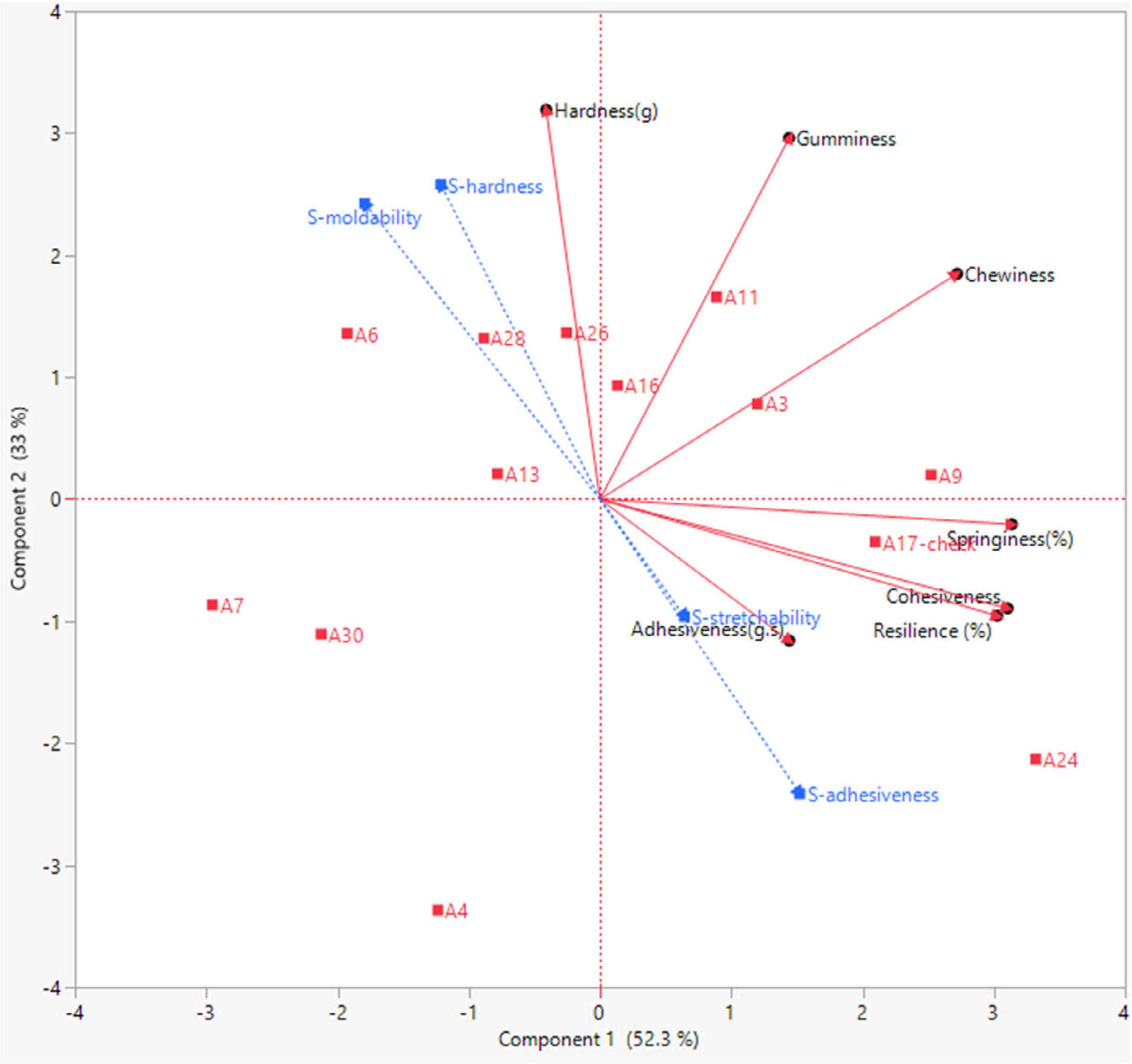

Figure 2. Principal components analysis and sensory texture profile parameters of eba, showing relationships between the texture of eba made from 13 cassava genotypes used for evaluation of textural quality (Experiment 1).

Table 3. Correlation between the instrumental (columns) and sensory (rows) texture of eba obtained from 13 cassava genotypes

	Coefficient						
	Hardness(g)	Adhesiveness (g.s)	Cohesiveness	Springiness (%)	Gumminess	Chewiness	Resilience (%)
S-hardness	0.7846**	−0.4049	−0.5337	−0.3996	0.5451	0.1361	−0.5885**
S-stretchability	−0.4024	−0.0994	0.3347	0.3041	−0.2079	0.0454	0.1713
S-adhesiveness	−0.7031**	0.6010**	0.5554**	0.4254	−0.4358	−0.0491	0.7000**
S-moldability	0.7505**	−0.5196	−0.6884**	−0.5266	0.4084	−0.0198	−0.7446**

** $P < 0.001$.
Abbreviations: S-adhesiveness, sensory adhesiveness; S-hardness, sensory hardness; S-moldability, sensory moldability; S-stretchability, sensory stretchability.

C6_BC (TMS30572), and C3 (Obasanjo 2). For that group, the ADMM estimates showed significant importance of lower gari solubility and relatively higher a* ($P < 0.05$) on eba preference (Table 6). The Idoma, Igede, and Yoruba participants preferred the eba from the genotypes C6_BC, C9_RC(TMB1_MS6), and C3. Participants in this group (node 3, Fig. 5) also liked genotypes with lower solubility and higher a* but higher L* and lower b*, higher cohesiveness, and higher hardness. However, C6_BC remains

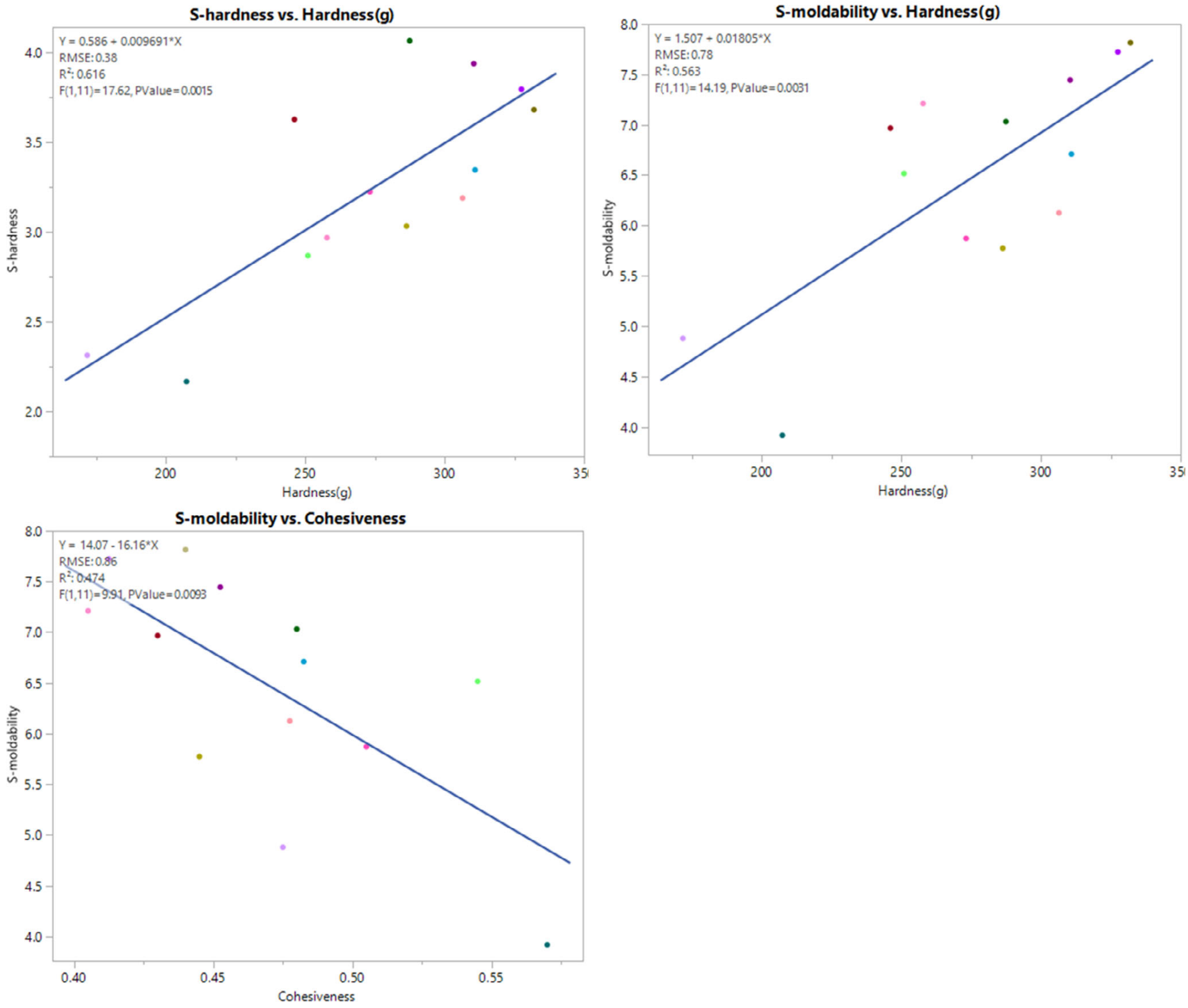

Figure 3. Selected linear model fit of instrumental and sensory texture of eba obtained from 13 cassava genotypes.

the best within the nodes, followed by the regional varieties C9_RC and C3 (node 3) and the local varieties C10_LC and C3 (Obasanjo 2) (node 2). The local variety C7_LC (Apku) performed the worst, together with C4 (TMS13F1343P00440) the breeder-advnaced line. This shows a good mix of recently improved and local and breeder checks performing relatively well. By far, the best is an improved variety (C6_BC), confirming its choice as the best breeder control variety because of its food product quality.

DISCUSSION

Near infrared reflectance spectroscopy prediction models for color and textural properties of eba

The prediction performance was reasonably good for most textural traits, and chewiness, hardness, and adhesiveness had an R^2_{pred} of 0.59, 0.54, and 0.40, respectively (Table 1). These models could be used for screening purposes in the breeding program because there are currently no other method except instrumental methods for the texture of gari and eba that are not cost effective. However, the prediction models still have room for improvement by adding new genotypes with a broader variation of textural properties to the training data sets for calibration development. Generally, for the NIRS prediction to be suitable for rapid screening, the coefficient of determination in prediction should be at least 0.50.[21]

Color parameters such as L*, a*, and b* were identified as the most critical criteria for consumer preference and have the advantage of significant heritability.[22] Color measurement using a chromameter has nonetheless been considered a mid-throughput approach in terms of the number of samples that could be analysed per day. Color and textural property measurements also appeared feasible through the NIRS prediction models reported in this study. Further calibration of NIRS looks promising and would allow breeders to simultaneously predict the texture and color of Eba from a single spectrum.

The coefficient of determination in calibrations for L*, a*, and b* for eba was moderately good for L* (0.80) and a* (0.66), whereas b* had a low R^2_{cal} of 0.35. For the color parameters, the standard error in calibration (SEC) and SEP are close and with lower values,

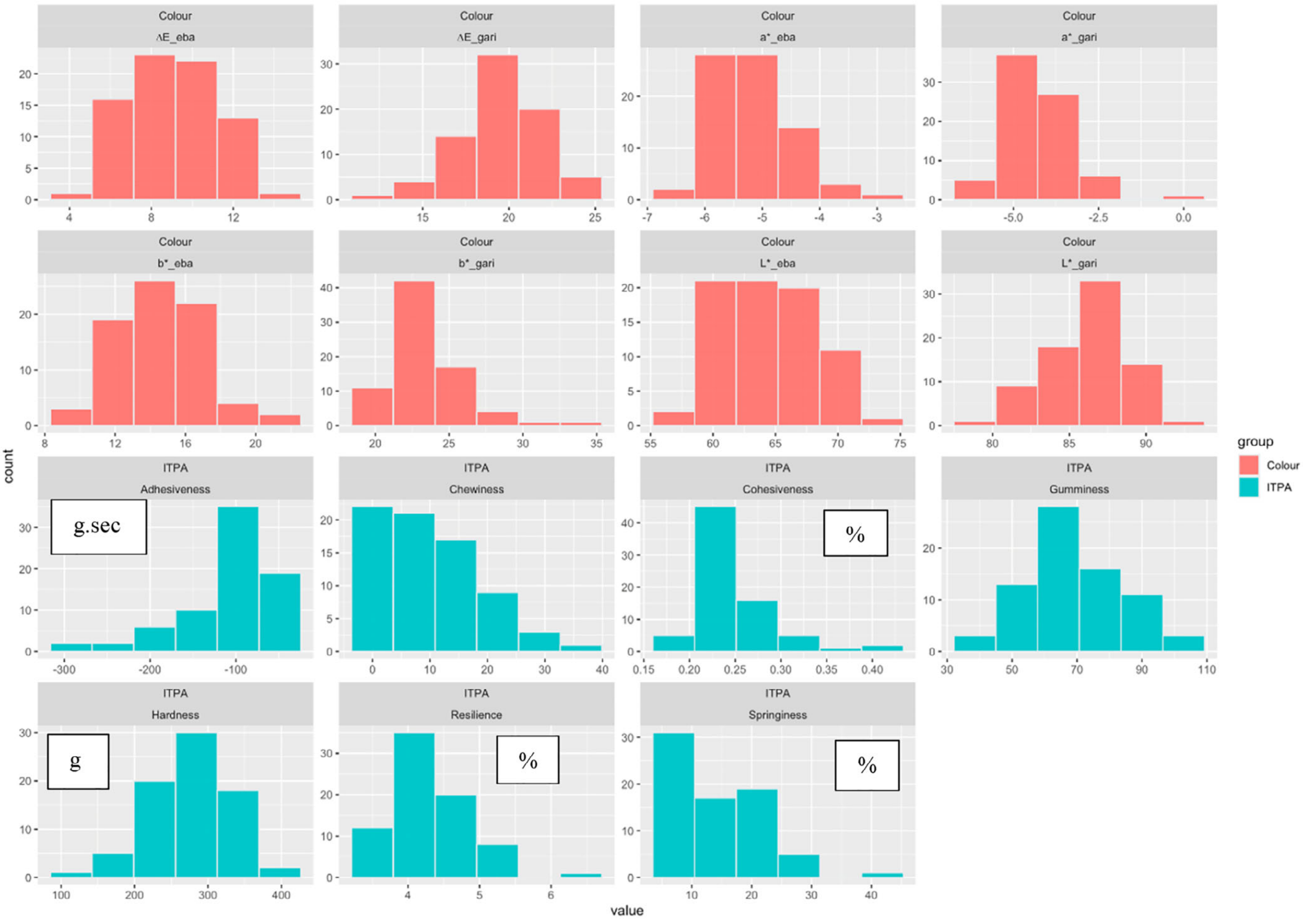

Figure 4. Distribution of color and instrumental texture profile analysis traits of gari and eba from 40 genotypes of cassava. *Δ*E (total color difference) is calculated from the L*, a*, and b* color parameters.

Table 4. Genetic variance components and broad-sense heritability (H^2) table for color and instrumental texture profile analysis (ITPA) traits of eba based on 40 cassava genotypes (Experiment 2)

Traits	H^2	Variance_genotype	Variance_error	Mean	SD	Min	Max	Median	Range
a*_eba	0.59	0.18	0.26	−5.14	0.66	−6.51	−2.88	−5.25	3.64
a*_gari	0.00	0.00	0.92	−4.33	0.96	−6.00	0.14	−4.38	6.13
b*_eba	0.32	1.00	4.35	14.63	2.32	10.27	22.15	14.35	11.88
b*_gari	0.42	1.59	4.47	23.43	2.49	18.72	32.87	23.11	14.15
ΔE_eba	0.07	0.18	4.47	9.00	2.15	3.69	13.89	8.83	10.20
ΔE _gari	0.00	0.00	5.83	19.54	2.46	12.41	24.50	19.88	12.09
L*_eba	0.29	2.56	12.47	64.48	3.87	58.28	75.00	64.34	16.72
L*_gari	0.00	0.00	6.38	86.26	2.58	77.78	91.38	86.50	13.60
Gumminess	0.00	0.00	180.70	68.43	15.30	37.39	103.74	67.10	66.35
Hardness	0.03	43.59	2901.45	277.57	54.28	140.14	424.42	281.48	284.28
Adhesiveness	0.08	127.03	2835.31	−115.23	64.86	−381.70	−47.72	−98.78	333.98
Resilience	0.29	0.05	0.23	4.30	0.53	3.30	6.22	4.23	2.92
Chewiness	0.05	1.48	51.39	10.42	8.40	1.65	38.09	8.85	36.45
Cohesiveness	0.08	0.00	0.00	0.25	0.04	0.18	0.42	0.24	0.24
Springiness	0.24	7.62	49.23	13.36	8.64	3.67	38.89	11.74	35.22

Abbreviation: *Δ*E, total color difference; SD, standard deviations.

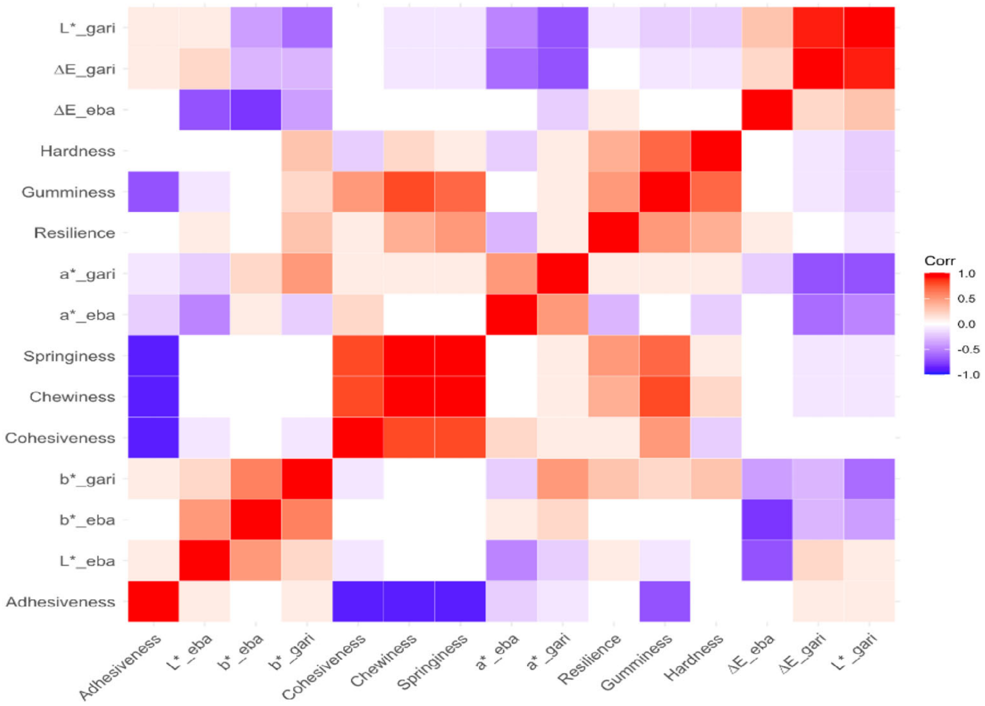

Figure 5. Correlation heatmap distribution of color of Gari and Eba and instrumental texture of eba from 40 genotypes of cassava.

Table 5. Effect of genotypes' biophysical features on the consumers' preference for eba samples

Feature	Estimate	Std. Error	z value	Pr (>|z|)	
(Intercept)	0.000	NA	NA	NA	
Solubility	−1.586	1.110	−1.429	1.53E-01	
L* gari	0.484	0.137	3.547	3.90E-04	***
a* gari	0.705	0.203	3.467	5.26E-04	***
b* gari	−0.080	0.012	−6.552	5.69E-11	***
Cohesiveness	15.380	3.978	3.867	1.10E-04	***
Gumminess	−0.006	0.034	−0.180	8.58E-01	
Chewiness	−0.012	0.041	−0.293	7.70E-01	
Hardness	0.011	0.009	1.192	2.33E-01	
Adhesiveness	0.001	0.014	0.056	9.55E-01	

Note: Values are estimated for the whole dataset without including consumers' covariates.
*** Significant at $P < 0.0001$. Pr = Probability.

which indicates that the model could be improved by increasing the training data set (Table 1). Gari samples equally had good R^2_{cal} for L*(0.72) and a* (0.74) and a value of 0.88 for b*; the R^2_{pred} for L* seems good with a value of 0.61, which implies that the models could be used for color property measurements. However, the model could be improved for all the color parameters as SEC and SEP values were relatively low. The two methods (chromametric and spectroscopic) used for color measurements are available for the breeders. However, the ultimate choice of measuring color (chromameter vs NIRs) should be based on how well it can predict the human perception of the complex color/shininess aspect of the appearance of eba and gari products through a set of panelists' or consumers' evaluations. It is recommended that the chromametric and spectroscopic methods be further investigated for accurate prediction and measurement of predicting human perception in terms of gari and eba colour to propose the best method. The NIRS prediction models are also available for screening genotypes for key biophysical trait descriptors for gari and textural traits descriptors for eba (e.g., hardness, adhesiveness, and chewiness). However, these prediction models have room to improve their robustness and accuracy.

Sensory and instrumental textural profile analysis

Instrumental and sensory textural components (Fig. 2) (instrumental-hardness, chewiness, gumminess, springiness, cohesiveness, resilience, adhesiveness, and sensory-hardness, moldability, stretchability, and adhesiveness) were closely related in a component space. Instrumental adhesiveness, cohesiveness, and resilience were closely associated with sensory adhesiveness within a component space. No instrumental attribute had a good relationship with sensory stretchability; therefore, it may be necessary to consider

Table 6. Effect of genotypes' biophysical features on the consumers' preference for eba samples and consumers' ethnic groups

Node[a]	Feature	Estimate	Standard error	z value	Pr (>|z|)	
2	(Intercept)	0.000	NA	NA	NA	
	Solubility	−16.156	5.414	−2.984	2.84E-03	**
	L* gari	0.335	2.016	0.166	8.68E-01	
	a* gari	1.482	0.596	2.487	1.29E-02	*
	b* gari	0.076	0.255	0.298	7.65E-01	
	Cohesiveness	−43.119	130.407	−0.331	7.41E-01	
	Gumminess	0.096	0.793	0.121	9.04E-01	
	Chewiness	0.130	0.467	0.279	7.81E-01	
	Hardness	−0.078	0.281	−0.276	7.83E-01	
	Adhesiveness	−0.019	0.165	−0.117	9.07E-01	
3	(Intercept)	0.000	NA	NA	NA	
	Solubility	−3.611	1.591	−2.269	2.32E-02	*
	L*gari	1.037	0.204	5.079	3.79E-07	***
	a* gari	1.699	0.322	5.271	1.35E-07	***
	b* gari	−0.096	0.015	−6.198	5.72E-10	***
	Cohesiveness	31.817	5.951	5.346	8.98E-08	***
	Gumminess	−0.068	0.044	−1.568	1.17E-01	
	Chewiness	−0.094	0.067	−1.398	1.62E-01	
	Hardness	0.026	0.012	2.289	2.21E-02	*
	Adhesiveness	−0.030	0.021	−1.441	1.50E-01	

[a] Node 2 includes participants from Hausa, Ibo, Igbira, and Tiv groups. Node 3 has participants from the groups Idoma, Igede, and Yoruba. Pr = Probability.

other protocols for instrumental measurement of stretchability, as it is a key texture attribute for eba.[23]

The genotypes were well discriminated in textural attributes and clustered in classes considered to have closely related textural attributes (supporting information, Fig. S1). The most discriminating attributes were resilience, hardness, gumminess, and cohesiveness. However, the linear fit relationships between the instrumental and sensory texture (Fig. 3) study showed that sensory textural traits could be measured using the medium throughput technique (e.g., texture analyzer equipment). This would help breeders screen for textural qualities without laborious sensory tests. The ITPA proved to be a reliable, repeatable, and discriminating instrumental texture protocol for eba. It is essential to determine the most discriminating ITPA attributes, and there was a significant effect for genotypes and a non-significant effect of cooking replicate on the ITPA attributes (Table 2). The significant correlations between ITPA and STPA (Table 3) demonstrate that the sensory characteristics of eba can be estimated reliably from instrumental measurements of eba. Thus it could provide a medium-throughput protocol for more rapid screening of cassava genotypes for breeding consumer-preferred products.

Genetic component of textural and color traits

The functional genetic variation for desired traits in a breeding population facilitates the successful selection and advancement of superior genotypes. Determining the extent of the variability available therefore helps determine the extent of potential improvements achieved over a series of population improvement cycles. The relative magnitude of the standard deviation and average coefficient of variability was significant for adhesiveness (56.3%), chewiness (80.6%), and cohesiveness (64.5%), suggesting large dispersion of the averages of individual genotypes from the overall average for each trait (Table 4). This is a prerequisite for genetic variances to be significant. However, the relative magnitude of the experimental error in most cases was large; therefore, the heritability values for ITPA traits were very low except for resilience and springiness. Two strategies can be implemented (hopefully simultaneously) to improve the heritability values for these traits: identify germplasm with more contrasting traits (e.g., increase genetic variances) and improve the experimental protocols (e.g., reduce error and thus the phenotypic variance).

With regard to the chromameter measurements, the high heritability value of a*_eba is notable. Teeken *et al.*[24] demonstrated that a*_gari and eba values are critical for consumer acceptability, and a*_gari was determined as a proxy for browning. In our current study, however, a*_gari had a negligible heritability.

There was a correlation between color properties measured for gari and eba, except for L* (Fig. 5). Accordingly, it is expected that consumers would like eba from gari samples with lower redness, while the contrary is the case. This result shows that a more detailed analysis is recommended on how gari's redness contributes to eba's overall liking. Details observed by processors might also be interpreted differently further along the value chain, for instance among consumers. Processors often are very much focused on the discoloration of the product, from grated mash to the toasting of gari, unlike the consumer, who is more focused on the consumption experience.

Heritability for the a* value for eba was high but not for gari, whereas b* values show heritability of practical levels for breeding for both gari and eba. L* only shows heritability on the eba. This requires a better understanding of what the a* and L* values signify when measured for eba. When working with processors, color differences often become more pronounced when making eba from gari,[24] so the color values for eba could be an essential manifestation of the quality attributes of eba related to consumer acceptability. Our findings point toward implementing continuous population improvement strategies, for example, targeted closed hybridization and early testing and selection for these traits. Heritable phenotypic variability for at least a few traits is essential in determining their routine utility in breeding programs to support selection and advancement decisions.

Relationship between biophysical traits and consumer testing

Linking the traits with consumer testing, the gari color chromameter value, solubility, and cohesiveness of the eba are most highly correlated with consumers' overall liking. Color screening on gari and eba will be the most critical quality traits to operationalize within breeding. As color was not measured on the eba samples made in the laboratory from the gari used for consumer testing, it will be crucial to investigate further how consumers' liking of eba color and overall preference is related to the eba color chromameter measurements. An essential change in appreciation occurs when the gari is turned into eba. This study identified positive correlations between gari and eba color (except for L), and a* and b* on the gari and eba are promising quality indicators. However, this study contradicts the preferences of processors (not consumers), who liked eba from gari with a lower a*[24]. Further work on consumer testing studies should be carried out using a larger number and more contrasting varieties. It will help to determine the parameters for focus because if the parameters measured in the lab are not related to the consumer testing likings, it will be of little use to include them in a breeding program.

The ethnic division between nodes 3 and 2 (Fig. 6) can be considered a division between the southwest (Osun state, dominated by Yoruba) and the southeast (Benue state, dominated by Tiv). Interestingly, ethnic group is more important than region, stressing that the culinary culture of the different ethnic groups primarily influences preferences. However, the Idoma live in the western part of the southeast, and their preferences are grouped with those of the Yoruba in the southwest. Part of the observed difference can be explained by the use of palm oil in the production of eba (which turns the gari and eba yellow) among the ethnic groups associated with the north central and southeast areas, which is very uncommon in the Yoruba-dominated southwest. It makes people linked to the Southwest tradition prefer a less yellow gari, indicated by the lower b* value, which was correlated with the overall liking (Table 6, node 3), while this was not the case for node 2.

Furthermore, people in the southwest (especially the Yoruba) like an eba product with a grainier structure, which is less homogeneous and integrated (and that still shows the gari particles in the eba) and therefore stretches less. It was reported that such a texture could be achieved by lower solubility coupled with a preparation method in which the gari is cooked with less prolonged contact with hot water.[24] Shorter cooking time is more common in communities closer to the southwest.[7] This practice also explains why respondents in node 3 (Yoruba dominated) tend to describe ‘hardness’ as being related to non-integrated, more grainy, less stretchable eba. To ensure good shape and moldability, ethnic groups preferring a grainier eba would prefer an eba that is somewhat cohesive and thus relatively harder.

In conclusion, this study has shown that eba's chromameter color measurements, eba cohesiveness and gari solubility are crucial quality characteristics. Near infrared reflectance spectroscopy has demonstrated strong potential as a high throughput technique for the measurement of color and texture of eba, such as hardness, adhesiveness, and cohesiveness, which are the key textural attributes that positively relate to consumer preferences, most especially cohesiveness (which, unfortunately, had a low R^2_{pred} for the validation set). Near infrared reflectance spectroscopy was also found to be helpful in predicting chewiness. The most influential traits that breeders can already incorporate in their routine selection could be a*_eba, b*_eba, b*_gari, L*_eba, resilience, and springiness.

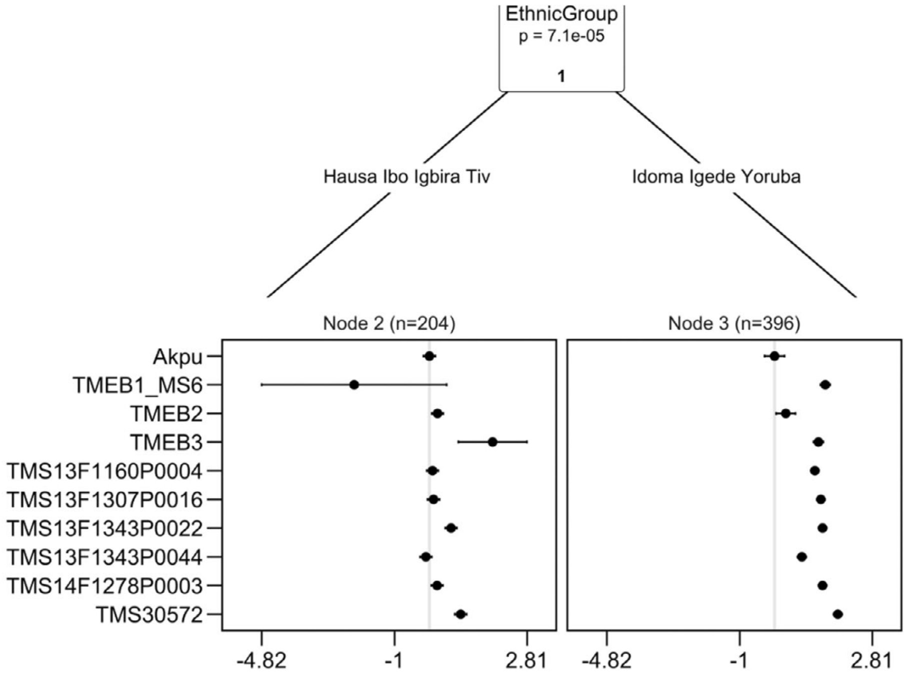

Figure 6. Plackett–Luce tree of consumers' preference for Eba samples derived from ten cassava genotypes (Experiment 3). Splitting covariate selected by the model-based recursive partitioning approach applied to ethnic group. The *x* axis shows log-worth with genotype Akpu as reference (log-worth set to 0). Intervals are based on quasi-variance estimates.

The ITPA traits proved to be a reliable, repeatable, discriminant texture protocol for eba and essential in determining the most discriminant ITPA attributes. Significant correlations between ITPA and STPA (Table 3) demonstrate that the sensory characteristics of eba can be reliably estimated from instrumental measurements of eba. Incorporating these screening protocols in breeding may allow breeders to identify broader phenotypic variability in cassava for these traits. The combination of broader phenotypic variability and the reduced experimental error should lead to more accurate identification of genetic variability and thus increased heritabilities for the characteristics the breeder needs to target. Future work will focus on defining the thresholds for these critical characteristics.

Editorial policies and ethical considerations

The consumer testing activities were approved by the International Institute of Tropical Agriculture (IITA) internal ethical review board (IRB) and implemented according to the IITA IRB policy (https://www.iita.org/wp-content/uploads/2019/06/IITA-IRB-Policy-June2016.pdfe). The IITA is mandated to conduct research in the country where this consumer testing occurred (Nigeria). Written informed consent was obtained for all study participants.

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CONFLICT OF INTEREST

The authors declare no conflict 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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