








Food quality profile of pounded yam and implications for yam breeding

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Abstract

BACKGROUND: Assessment of the key preferred quality traits in pounded yam, a popularly consumed yam food product in West Africa, is often done through sensory evaluation. Such assessment is time-consuming and results may be biased. Therefore, there is a need to develop objective, high-throughput methods to predict the quality of consumer-preferred traits in pounded yam. This study focused on how key quality traits in pounded yam proposed to yam breeders were determined, measured by biophysical and biochemical methods, in order to shorten the breeding selection cycle through adoption of these methods by breeders.

RESULTS: Consumer tests and sensory quantitative descriptive analysis (QDA) validated that preferred priority quality traits in pounded yam were related to textural quality (smooth, stretchable, moldable, slightly sticky and moderately hard) and color (white, cream or light yellow). There were significant correlations between sensory textural quality attributes cohesiveness/moldability, hardness, and adhesiveness/stickiness, with textural quality measurements from instrumental texture profile analysis (TPA). Color measurement parameters (L^* , a^* , and b^*) with chromameter agreed with that of sensory evaluation and can replace the sensory panel approach. The smoothness ($R^2 = 1.00$), stickiness ($R^2 = 1.00$), stretchability ($R^2 = 1.00$), hardness ($R^2 = 0.99$), and moldability ($R^2 = 0.53$) of pounded yam samples can be predicted by the starch, amylose, and protein contents of yam tubers estimated by near-infrared spectroscopy.

CONCLUSION: TPA and Hunter colorimeter can be used as medium-high throughput methods to evaluate the textural quality and color of pounded yam in place of the sensory panelists.

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INTRODUCTION

Yam, *Dioscorea* (spp.) is one of the most important non-cereal staple foods in West Africa.¹ There are many species widely cultivated in Central and West Africa, especially the yam zone of West Africa, which includes Nigeria, Ghana, Togo, Côte d'Ivoire and the Republic of Benin.²⁻⁴ In Nigeria, it is an integral component of food consumption and agricultural sales.⁵

Yam is consumed in various forms, such as roasted, boiled, pounded, chips, flour and fried in the yam zone of West Africa, but pounded yam is the predominant traditional way of consuming it in the region. Pounded yam is made traditionally by peeling the yam tubers, cutting them into small pieces, and boiling, followed by pounding into a glutinous dough with mortar and pestle.⁶⁻⁸ The quality of raw yam tubers is vital for the acceptability of yam food products by farmers, processors and consumers.⁴ A consumer of pounded yam will usually examine the product for palatability by assessing the hand feel and color before considering the taste or aroma of the product. Any defect in these attributes may negatively impact the acceptability of the product by the consumer.^{7,9-11}

A study¹² identified textural quality and color as the critical user-preferred quality traits for pounded yam acceptability by the stakeholders, including farmers, processors, and consumers. Key textural quality attributes identified were hardness cohesiveness, adhesiveness, stretchability, and smoothness.¹² These attributes can provide potential selection metrics in breeding programs for yam varieties targeting consumers' expectations for good pound quality.

Assessment of food quality of pounded yam in the past, to feed back to breeders, has relied mainly on evaluation by sensory panels. Sensory evaluation, though subjective, has been the most critical aspect of varietal development after all the essential agronomic features have been established.¹³ Sensory evaluation is a significant determinant of consumers' acceptability and subsequent adoption of new yam varieties; however, apart from being somewhat subjective it is time-consuming and expensive. Hence there is a need to develop high-throughput methods to characterize the quality indicators in yam tubers that can reliably predict the quality traits of preferred pounded yam.

In this study, we present the perception of consumers on key preferred quality traits in pounded yam from Nigeria and the Republic of Benin and link them to laboratory methods that can be used to predict these traits. This will help speed up the selection decision in the yam breeding cycle and enable yam breeders to breed for end-user preferences efficiently (a major objective of the RTBfoods project). Hence this is an index study that focuses on what and how key quality traits in pounded yam (color and textural quality) proposed to breeders were determined, measured by high or mid-throughput methods to shorten the breeding selection cycle and the perception and adoption of these methods by yam breeders.

MATERIALS AND METHODS

Materials

A total of 28 yam genotypes representing white Guinea yam (*Dioscorea rotundata*) and water or greater yam (*Dioscorea alata*) were used for this study. Seventeen breeding lines (eight *D. alata* genotypes and nine *D. rotundata* genotypes) were obtained from yam breeding programs of the International Institute of Tropical Agriculture (IITA) and National Root Crop Research

Institute (NRCRI), Nigeria, and 11 landrace cultivars. Four of these [three *D. rotundata* (Lasinrin, Awana, Gbongi-Kamilu) and one *D. alata* (Ewura)] were collected from a contact farmer's field from Iwo, Osun state, Nigeria. The remaining seven [six *D. rotundata* varieties (Laboko, Kratchi, Kodjèwé, Wété, Dodo, Irindou) and one *D. alata* variety (Aga)] were obtained from an experimental plot at the AfricaYam project, Benin station, Republic of Benin. Out of the total 28 yam genotypes, 15 cultivars were used for consumer studies, the remaining 13 genotypes were used for sensory quantitative descriptive analysis (QDA) and other biophysical analyses reported in the study – *D. rotundata*: TDr1401593, TDr1000048, TDr1400359, TDr0900067, TDr1100180, TDr1401419, TDr IGN 21 (Ilgangan) and *D. alata*: TDa1400301, TDa1100224, TDa1215201, TDa1100432, TDa1100201, TDa1100316. In southwest Nigeria, pounded yam samples that were used for consumer testing were prepared from the four landraces – *D. rotundata*: Lasinrin, Awana, Gbongi-Kamilu and *D. alata*: Ewura. In southeast Nigeria – *D. rotundata*: TDr11/0010 TDr1100497 and *D. alata*: TDa1100477, TDa1100203 were used and in the Republic of Benin six *D. rotundata* varieties (Laboko, Kratchi, Kodjèwé, Wété, Dodo, Irindou) and one *D. alata* variety (Aga) were used.

Methods

Pounded yam sample preparation

Pounded yam samples were prepared as reported in RTBfoods standard operating procedure.¹⁴

Yam flour sample preparation

The yam flour samples for biochemical analyses were prepared by the method of Otegbayo *et al.*¹⁵ Tubers were peeled, washed and cut into longitudinal sections. These were diced into very small cubes and dried at 60 °C for 72 h in a hot air oven (Memmert oven). The samples were then milled to pass through a 20 mesh screen. They were then used for chemical analyses.

Consumer studies

This study aimed to understand the way consumers assess the quality characteristics of yam food products and the quality attributes associated with the consumers' preferred and non-preferred pounded yam. The consumer preference study was carried out on pounded yam samples as described by Forsythe *et al.*¹⁶ in two pounded yam consuming countries; Nigeria and Republic of Benin. In Nigeria: southwest – Osun state (174 consumers: 109 women, 65 men),¹⁷ south-east – Ebonyi state (150 consumers: 70 men, 80 women).¹⁸ In Dassa center Republic of Benin (99 consumers: 51 men, 48 women).

The three-point 'Just-About-Right' (JAR) scale and the Check-All-That-Apply (CATA) approach were used¹⁶ for each of the pounded yam samples. Some examples of the JAR scale are: 1 = 'too soft', 'too dark', 'not enough', 2 = 'Just-About-Right' and 3 = 'too hard', 'too stretchable', 'too sticky'. The three-point JAR scale showed which sensory characteristics of the product are acceptable or not, and also why the consumers liked or do not like a product. CATA approach helps to describe the pounded yam sample and indicates the sensory and perception of descriptors of each sample as presented to the respondents. In all the study regions (southwest and southeast Nigeria and Republic of Benin), pounded yam samples were prepared from yam varieties with variable food quality attributes (preferred and less-preferred).

Sensory quantitative descriptive analysis (QDA)

The QDA was carried out on pounded yam samples made from other 13 yam genotypes/breeding lines (described in the Materials and method section) from southwest Nigeria as described in RTBfoods standard operating procedure on sensory characterization¹⁴ using 12 trained panelists.

Biophysical analyses

Instrumental texture profile analysis (TPA)

This was done through a texture analyzer (TVT 6700; Perten Instruments, instrumentvagen31 Hargensten Sweden) using the texture profile analysis (TPA) method described in the RTBfoods standard operation procedure.¹⁷ The parameters measured were hardness, adhesiveness, stringiness and cohesiveness.

Color

Instrumental color evaluation (L^* , a^* and b^*) of the fresh yam samples and pounded yam was carried out by means of the Hunter colorimeter (CR410; Konica Minolta, Tokyo, Japan). The CIE (Commission Internationale de l'Eclairage) tristimulus L^* a^* b^* , where L^* (lightness) axis – 0 is black and 100 is white; a^* (red-green) axis – positive values are red while negative values are green and 0 is neutral; b^* (yellow-blue) axis – positive values are yellow, while negative values are blue and 0 is neutral. The method of Alamu *et al.*¹⁹ was adapted and color was evaluated both immediately after cutting the yam tubers (0 min) and 10 min after.

Biochemical composition

The polyphenol oxidase (PPO) enzyme activity of the yam genotypes was determined as described by Omidiji and Okpuzor.²⁰ This was done to determine the browning rate of the yam tubers. Starch, sugar, protein, dry matter, fat, phytate and tannin were determined from the yam flour using near-infrared spectroscopy (NIRS) as described by Alamu *et al.*¹⁹

Ethical consideration

This study was approved by the National Research Ethics Committee and Bowen University Research and Ethics Committee (BUREC) approval 2020 prior to fieldwork. Consent from sensory panellists and from consumers participating in this study was obtained, and the research respected the rules of voluntary participation and anonymity.

Statistical analysis

Statistical analyses consisting of one-way and two-way analysis of variance (ANOVA), bivariate correlations, discriminant analysis and hierarchical classification were conducted on the data generated, to determine: (i) the correlation between the biochemical composition of yam varieties and sensory attributes of pounded yam that may serve as intrinsic quality indicators for the textural quality of pounded yam; (ii) the correlation between TPA and QDA was established; and (iii) correlation between consumer acceptance (JAR test) and QDA of the pounded yam samples for the establishment of acceptability thresholds. Linear multiple regressions were applied to predict the sensory attributes by biophysical parameters. The best model limited to two parameters/variables was selected. In these conditions, a high coefficient of determination (R^2) between predicted and observed variables was considered to assess the quality of the model. All analyses were performed using XLSTAT (version 2016.02.28451; Addinsoft, Paris, France).

RESULTS

Consumer acceptability test

Southwest Nigeria

Principal component analysis (PCA) was used to summarize the relationships between CATA sensory characteristics of the pounded yam samples and mean overall liking of each product scored by all the consumers. The PCA plot for the consumers explained 95.4% of the variance of the sensory characteristics, with the first and second axes accounting for 72.6% and 22.8%, respectively. The loading of sensory characteristics on PCA plot for the consumers (Fig. 1) showed that Axis 1 was mainly explained positively with terms like yellow, moldable, stretchable, no lumps sweet taste, smooth, soft, cream, and good aroma which describes the most liked pounded yam samples (Lasinrin, Awana and Gbongi-Kamilu) and negatively by the terms such as 'slightly sticky', 'slightly stretchable', related to the least liked pounded yam sample (Ewura). Axis 2 was mainly explained positively by the terms such as 'white' and 'not sticky' (Awana and Gbongi-Kamilu), and negatively by the terms such as 'hard', 'lumps', 'not stretchable', 'gray', 'bland taste', 'not moldable' and 'bad aroma' (Ewura). On the right part of the PCA plot, high mean overall liking scored by consumers was related to the high-quality characteristics such as 'stretchable', 'no lumps', 'sweet taste', 'soft', 'good aroma', and 'smooth', which were associated with the most liked pounded yam samples from varieties Lasinrin, Awana, and Gbongi-Kamilu. A high mean overall liking scored by consumers was related to the high-quality characteristics such as 'white', 'not sticky', (on the left part of the PCA plot), which were associated with the most liked pounded samples, made from good yam varieties, Awana and Gbongi-Kamilu. While at the opposite, a low mean overall liking by the consumers was related to the low-quality characteristics such as 'gray', 'bitter taste', 'sticky' (as on the left part of the PCA plot), which were associated with the least liked pounded yam variety Ewura.

Pounded yam samples from different varieties were perceptibly different in terms of their food quality attributes as rated by the consumers. The textural attributes associated with a preferred pounded yam were 'stretchable', 'soft', 'smooth', 'moldable', 'not sticky', 'white/yellow' depending on the yam flesh color, 'sweet taste' and 'good aroma' (Fig. 1 and Supporting Information Fig. S1). These attributes described pounded yam varieties Lasinrin, Gbongi-Kamilu and Awana. In terms of stretchability, Awana was rated as more stretchable than Lasinrin followed by Gbongi-Kamilu. These samples were also described as being smooth and moldable. Generally, Lasinrin was rated as the most moldable. The color and hardness of pounded yam samples from Awana, Gbongi-Kamilu and Lasinrin were 'Just about right'. The least liked pounded yam sample was from Ewura (*D. alata*) as it had the lowest mean overall liking score (Table 1, Figs 1 and S1) mainly because it was 'lumpy', 'not moldable', 'too dark' in appearance and had a 'bitter' taste by consumers in the JAR test.

Southeast Nigeria

The consumer acceptability result of pounded yam from the southeast was very similar to that of the southwest. The least 'liked,' or preferred product was from the water yam clone, TDA1100477; it had the lowest mean overall liking score (Table 1) because it was described as having 'lumps', 'sticky', and 'not stretchy' by the consumers (JAR test). Favorable terms such as 'sweet taste', 'not sticky', 'no lumps', and negative terms including 'lumps', 'sticky', 'not stretchy', 'too dark', and 'not smooth' were

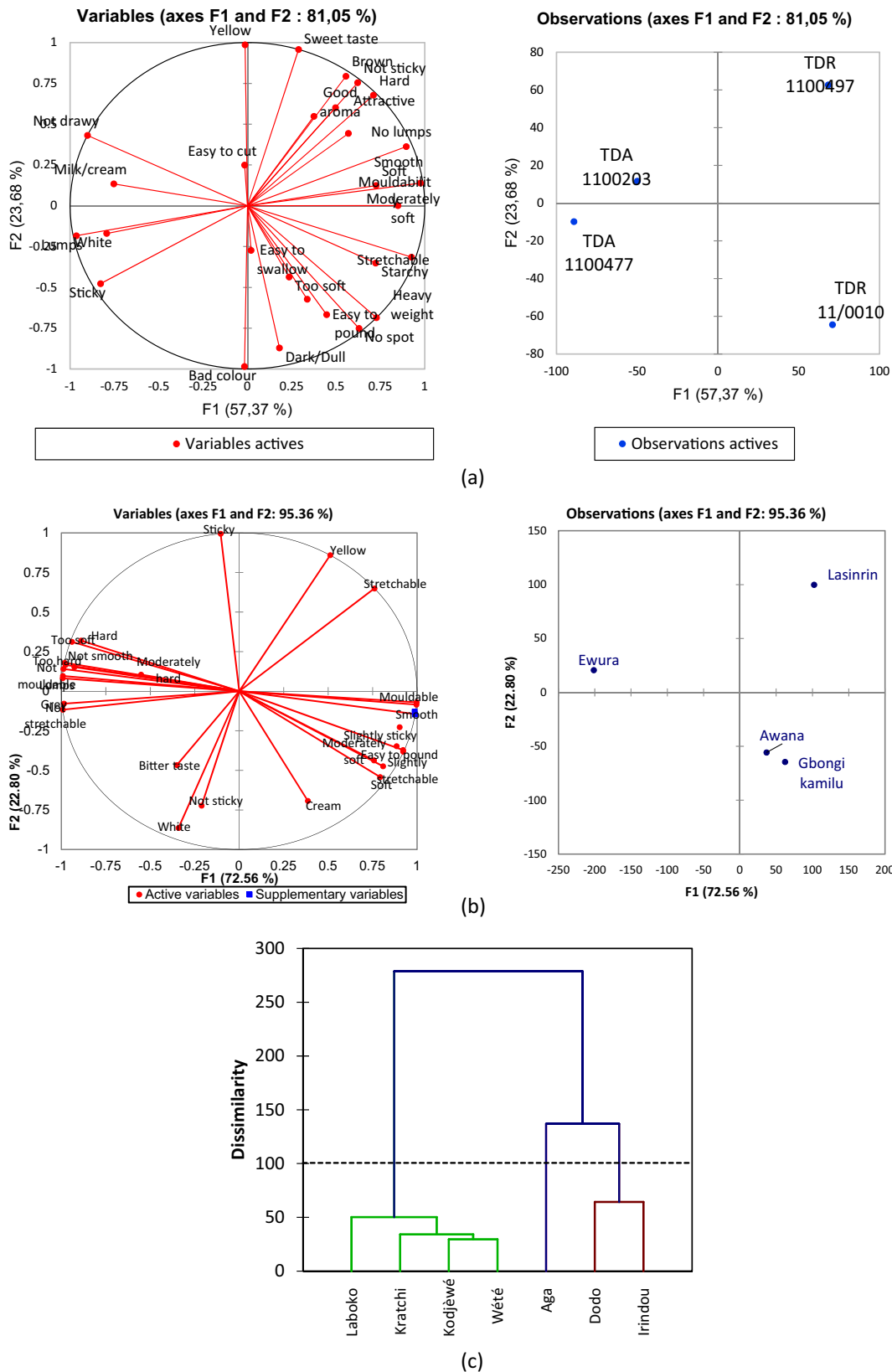


Figure 1. Mapping of the sensory characteristics and the overall liking of the product samples by consumers. (a) Consumers from southeast Nigeria; the second box represents yam genotypes associated with sensory attributes represented in the principal component analysis (PCA). (b) Consumers from southwest Nigeria; the second box represents yam genotypes associated with sensory attributes represented in the PCA. (c) Hierarchical clustering of pounded yam samples made from landraces varieties based on consumers' overall liking in Republic of Benin.

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Table 1. Overall liking scores for pounded yam samples from yam varieties

Nigeria		Republic of Benin			
Southwest varieties	Mean overall liking score	Southeast varieties	Mean overall liking score	Dassa varieties	Mean overall liking score
Ewura	4.2 ^a	TDa1100477	4.7 ^a	Aga	4.1 ^d
Awana	7.1 ^b	TDr11/0010	6.1 ^b	Dodo	6.0 ^c
Gbongi-Kamilu	7.2 ^b	TDr1100497	6.4 ^b	Irindou	6.2 ^c
Lasinrin	7.2 ^b	TDa1100203	6.6 ^b	Kodjèwé	7.4 ^b
				Kratchi	7.9 ^a
				Laboko	8.0 ^a
				Wété	7.3 ^b

Note: Means with the same superscript letter in the same column are not significantly different at $P < 0.05$.

Table 2. Descriptive sensory evaluation of pounded yam from varieties of landraces (*Dioscorea rotundata* and *Dioscorea alata* species)

Varieties	Smoothness	Adhesiveness/stickiness	Moldability/cohesiveness	Stretchability	Hardness	Color
Lasinrin (TDr)	9.83 ^a	2.72 ^b	9.39 ^a	4.83 ^a	6.17 ^{ab}	4.28 ^a
Kamilu (TDr)	9.45 ^a	2.15 ^b	7.60 ^a	1.55 ^b	7.55 ^a	3.95 ^a
Awanah (TDr)	9.35 ^a	5.00 ^a	9.15 ^a	5.60 ^a	5.35 ^a	2.35 ^b
Ewura (TDa)	3.11 ^b	2.00 ^b	3.11 ^b	0.33 ^b	5.72 ^a	4.61 ^a
Mean	7.94	2.97	7.31	3.08	6.20	3.80
Standard error	1.61	0.70	1.46	1.27	0.48	0.50

Note: Means with the same superscript letter in the same column are not significantly different at $P < 0.05$. Smoothness: no lumps, 10; small lumps, 5; big lumps, 0. Adhesiveness/stickiness: non-sticky, 0; slightly sticky, 5; sticky, 10. Moldability: not moldable, 0; slightly moldable, 5; moldable, 10. Stretchability: not stretchable, 0; slightly stretchable, 5; stretchable, 10. Hardness: very soft, 0; soft, 2; slightly soft, 4; slightly hard, 6; hard, 8; very hard, 10. Color: white, 1; off-white, 2; cream color, 3; light yellow, 4; yellow, 5; light gray, 6; gray, 7; light brown, 8; brown, 9.

Table 3. Descriptive sensory evaluation of pounded yam from varieties of *Dioscorea rotundata* and *Dioscorea alata* species

Varieties	Smoothness	Adhesiveness/stickiness	Moldability/cohesiveness	Stretchability	Hardness	Color
<i>Dioscorea rotundata</i>						
TDr1401593	0.29 ^d	3.83 ^b	2.54 ^e	1.00 ^e	5.13 ^a	4.29 ^a
TDr1000048	0.73 ^c	3.68 ^{bc}	7.23 ^d	2.95 ^d	3.82 ^{bc}	2.73 ^b
TDr1400359	0.63 ^c	3.37 ^{bc}	7.13 ^d	4.47 ^c	2.20 ^d	2.83 ^b
TDr0900067	1.27 ^a	3.13 ^c	6.93 ^d	4.40 ^c	2.60 ^d	2.43 ^b
TDr1100180	0.64 ^c	2.45 ^d	8.14 ^c	3.00 ^d	5.14 ^a	4.55 ^a
TDr1401419	1.00 ^b	2.54 ^d	9.04 ^b	6.25 ^b	4.33 ^b	1.92 ^c
TDr IGN 21	0.00 ^e	6.17 ^a	9.42 ^a	8.21 ^a	3.38 ^c	4.54 ^a
Mean	0.65 ^b	3.60 ^a	7.20 ^a	4.33 ^a	3.80 ^a	3.33 ^a
Standard error	0.16	0.47	0.86	0.89	0.44	0.42
<i>Dioscorea alata</i>						
TDa1400301	2.04 ^c	2.81 ^c	1.77 ^b	0.08 ^b	6.35 ^b	2.77 ^a
TDa1100224	1.09 ^d	6.82 ^a	2.32 ^b	0.32 ^b	1.18 ^d	1.32 ^c
TDa1215201	3.86 ^b	5.68 ^b	5.27 ^a	2.23 ^a	2.86 ^c	2.64 ^a
TDa1100432	4.53 ^a	2.97 ^c	0.73 ^c	0.27 ^b	6.70 ^b	1.27 ^c
TDa1100201	4.83 ^a	2.71 ^c	1.75 ^b	0.08 ^b	7.50 ^a	1.71 ^b
TDa1100316	1.75 ^c	2.67 ^c	2.13 ^b	0.42 ^b	6.71 ^b	1.71 ^b
Mean	3.02 ^a	3.94 ^a	2.33 ^b	0.56 ^b	5.22 ^a	1.90 ^b
Standard error	0.65	0.75	0.63	0.34	1.04	0.27

Note: Means with the same superscript letter in the same column under yam genotypes (*D. rotundata* and *D. alata*) are not significantly different at $P < 0.05$. Smoothness: no lumps, 10; small lumps, 5; big lumps, 0. Adhesiveness/stickiness: non-sticky, 0; slightly sticky, 5; sticky, 10. Moldability: not moldable, 0; slightly moldable, 5; moldable, 10. Stretchability: not stretchable, 0; slightly stretchable, 5; stretchable, 10. Hardness: very soft, 0; soft, 2; slightly soft, 4; slightly hard, 6; hard, 8; very hard, 10. Color: white, 1; off-white, 2; cream color, 3; light yellow, 4; yellow, 5; light gray, 6; gray, 7; light brown, 8; brown, 9.

related to the *D. rotundata* breeding lines TDr11/0010 and TDr1100497. Interestingly, among the *D. alata* breeding lines, TDa1100203 was the most liked (Table 1) because it was 'easy to swallow', 'easy to cut', 'moldable', and had a pleasing aroma (Fig. 1).

Republic of Benin

The overall liking of pounded yam significantly differed between the seven varieties ($P < 0.05$) (Table 1). Laboko and Kratchi were the most liked varieties by consumers (score above 7.8: like very much), while Aga scored the least (4.1: dislike slightly). A segmentation of pounded yam samples into groups of similar overall liking through an agglomerative hierarchical clustering showed that the yam varieties were clustered into three groups, as illustrated in Fig. 1. Thus, Dodo and Irindou varieties (scored around

6: like slightly) were considered as making pounded yam of intermediate quality, while Aga was defined as making poor-quality pounded yam. Pounded yam made from Laboko, Kratchi, Kodjèwé and Wété varieties (scored above 7: like) were qualified as preferred good quality.

Sensory quantitative descriptive analysis (QDA)

The trained panelists described pounded yam samples from seven clones of *D. rotundata* varieties as smoother, more moldable (cohesive) and more stretchable when compared with those of *D. alata* genotypes (six clones) (Tables 2 and 3). They were also firmer/harder than *D. alata*, in the range of soft to slightly soft. Color of *D. rotundata* varieties ranged between cream and light yellow, while those of *D. alata* species were off-white (Tables 2 and 3).

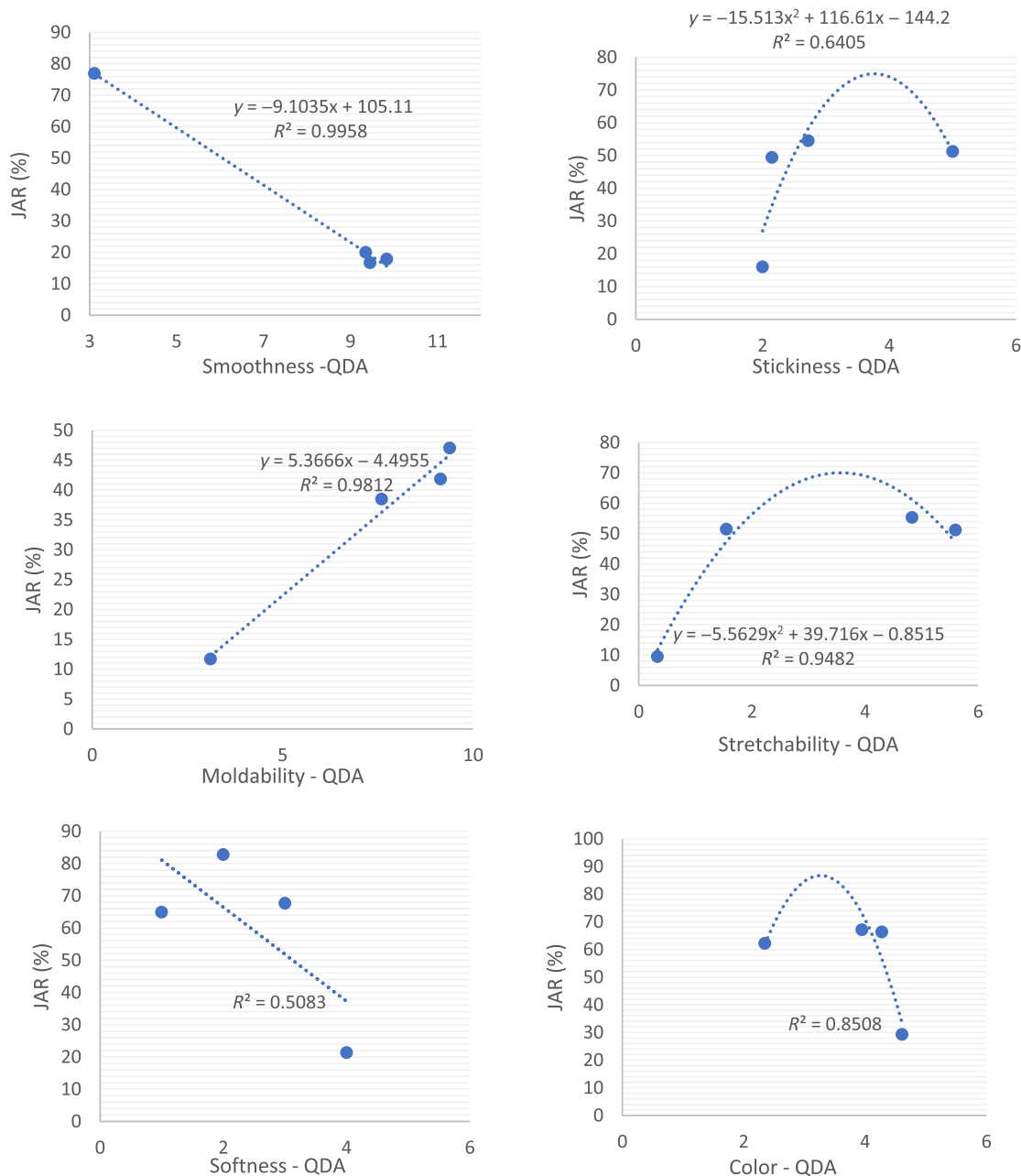


Figure 2. Correlations between consumer preferences and sensory quantitative descriptive analysis (QDA) from southwest Nigeria.

Table 4. Instrumental texture profile analysis (TPA) measurements of pounded yam samples

Varieties	Stiffness/ Hardness (g)	Adhesiveness (g.mm)	Stickiness (g)	Stringiness (mm)	Resilience	Cohesiveness	Springiness
<i>Dioscorea rotundata</i> [†]							
TDr1401593	7178 ^b	-1166 ^b	-1023 ^{bc}	0.99 ^a	0.05 ^b	0.12 ^a	0.99 ^a
TDr1000048	6734 ^b	-1513 ^{bc}	-1383 ^d	0.94 ^{abc}	0.03 ^c	0.12 ^a	0.94 ^{abc}
TDr1400359	4357 ^a	-1305 ^b	-904 ^b	0.77 ^c	0.01 ^d	0.13 ^a	0.77 ^c
TDr0900067	6397 ^b	-1833 ^c	-1181 ^{cd}	0.95 ^{ab}	0.03 ^c	0.18 ^b	0.95 ^{ab}
TDr1100180	8962 ^a	-436 ^a	-580 ^a	0.97 ^a	0.07 ^a	0.13 ^a	0.97 ^a
TDr1401419	6398 ^b	-2917 ^d	-1722 ^e	0.99 ^a	-0.01 ^e	0.18 ^b	0.99 ^a
TDr IGN 21	5091 ^a	-1920 ^c	-1230 ^{cd}	0.79 ^{bc}	0.00 ^{de}	0.20 ^a	0.79 ^{bc}
Mean	6445 ^a	-1584 ^a	-1146 ^a	0.91 ^a	0.02 ^a	0.15 ^a	0.91 ^a
Standard error	559.65	289.80	137.21	0.04	0.01	0.01	0.04
<i>Dioscorea alata</i> [†]							
TDa1400301	5796 ^a	-731 ^a	-1042 ^b	0.91 ^a	0.03 ^a	0.08 ^{bc}	0.91 ^a
TDa1100224	3562 ^a	-733 ^a	-530 ^a	0.95 ^a	0.01 ^{ab}	0.06 ^c	0.95 ^a
TDa1215201	4694 ^{bc}	-1362 ^{bc}	-1102 ^b	0.97 ^a	0.014 ^{ab}	0.13 ^a	0.97 ^a
TDa1100432	4188 ^b	-974 ^{ab}	-1010 ^b	0.99 ^a	0.01 ^{ab}	0.09 ^b	0.99 ^a
TDa1100201	4986 ^b	-1693 ^c	-1340 ^c	0.99 ^a	-0.01 ^{bc}	0.08 ^{bc}	0.99 ^a
TDa1100316	4970 ^b	-2482 ^d	-1412 ^c	0.97 ^a	-0.02 ^c	0.13 ^a	0.97 ^a
Mean	4699 ^b	-1329 ^a	-1073 ^a	0.96 ^a	0.01 ^a	0.09 ^b	0.96 ^a
Standard error	311.6	277.1	127.3	0.01	0.01	0.01	0.01
Landraces [‡]							
Lasinrin (TDr)	9812 ^a	-2272 ^a	-1927 ^c	1.00 ^a	0.03 ^a	0.18 ^{bc}	0.04 ^c
Kamilu (TDr)	4463 ^d	-4815 ^b	-1366 ^b	1.00 ^a	0.02 ^a	0.41 ^a	0.08 ^a
Awanah (TDr)	9159 ^b	-5126 ^b	-2544 ^d	1.00 ^a	0.01 ^a	0.21 ^b	0.05 ^{ab}
Ewura (TDa)	5436 ^c	-1539 ^a	-988 ^a	0.98 ^b	0.01 ^a	0.08 ^c	0.05 ^{ab}
Mean	6933	-3730	-1716	1.00	0.00	0.24	1.00

[†] Means with the same superscript letter in the same column under yam genotypes (*D. rotundata* and *D. alata*) are not significantly different at $P < 0.05$.

[‡] Means with the same superscript letter in the same column under Landraces are not significantly different at $P < 0.05$.

Correlation between QDA and consumer testing

The QDA and the consumer testing results of the pounded yam samples from landraces from southwest Nigeria were correlated to validate the food quality attributes of pounded yam. There were correlations (Fig. 2) between the QDA and consumer testing in terms of smoothness ($R^2 = 0.99$), stretchability ($R^2 = 0.94$), moldability ($R^2 = 0.98$), stickiness ($R^2 = 0.64$), color ($R^2 = 0.85$) but there was no significant correlation ($P > 0.05$) between them in terms of the softness/hardness ($R^2 = 0.31$) of the pounded yam samples.

Instrumental texture profile analysis (TPA)

The results of TPA on the pounded yam samples showed that those from *D. rotundata* were harder, more cohesive and less adhesive than pounded yam samples made from *D. alata* genotypes (Table 4). This agrees with previous authors.^{6,22,23} The TPA could also discriminate between the textural quality of pounded yam samples made from *D. alata* and *D. rotundata* genotypes (Fig. 3). TDr IGN 21 and *D. rotundata* were highly discriminant and had the longest distance from all *D. alata* genotypes. Through the TPA, it was also possible to classify the pounded yam samples into three hierarchical classes, which clustered the genotypes into pounded yam of contrasting textural quality: not preferred quality (red color) the less preferred quality group (TDr1100180) and preferred quality group [TDr IGN 21 (Ilgangan) (a landrace that was used as check, TDr1401419, and TDr0900067)] (Fig. 3). Pounded yam samples from genotypes, similar in textural quality, can be observed and compared to genotypes of known quality (e.g., TDr IGN 21). Representative TPA profiles for

pounded yam (from both species) with preferred and non-preferred textural quality are presented in Fig. 4.

Correlation of instrumental TPA with QDA

The correlations between QDA and TPA for textural quality are presented in Table 5. Generally, there were good and positive correlations between instrumental cohesiveness with sensorial moldability and stretchability. In *D. alata*, there were correlations between TPA and QDA parameters in terms of hardness, stickiness, cohesiveness, TPA cohesiveness and QDA stretchability, while in *D. rotundata* there were correlations between TPA and QDA in terms of cohesiveness and hardness and also between TPA cohesiveness and QDA stretchability. The magnitude of correlations increased when both *D. alata* and *D. rotundata* genotypes were considered separately. Significant correlations were also found between sensory stretchability and instrumental stringiness but varied according to species combinations. However, this correlation was negative (combining the two species), significant for *D. alata*, but not significant for *D. rotundata*. There was significant positive correlation, between sensory moldability and instrumental stiffness (when both species were combined). The respective correlations for the individual species, however, were not significant. Instrumental stiffness was positively correlated with sensorial adhesiveness and hardness for both species individually, but not in the combined analysis. There were a few additional correlations that reached statistical significance but not in a consistent way for the two species (Table 5).

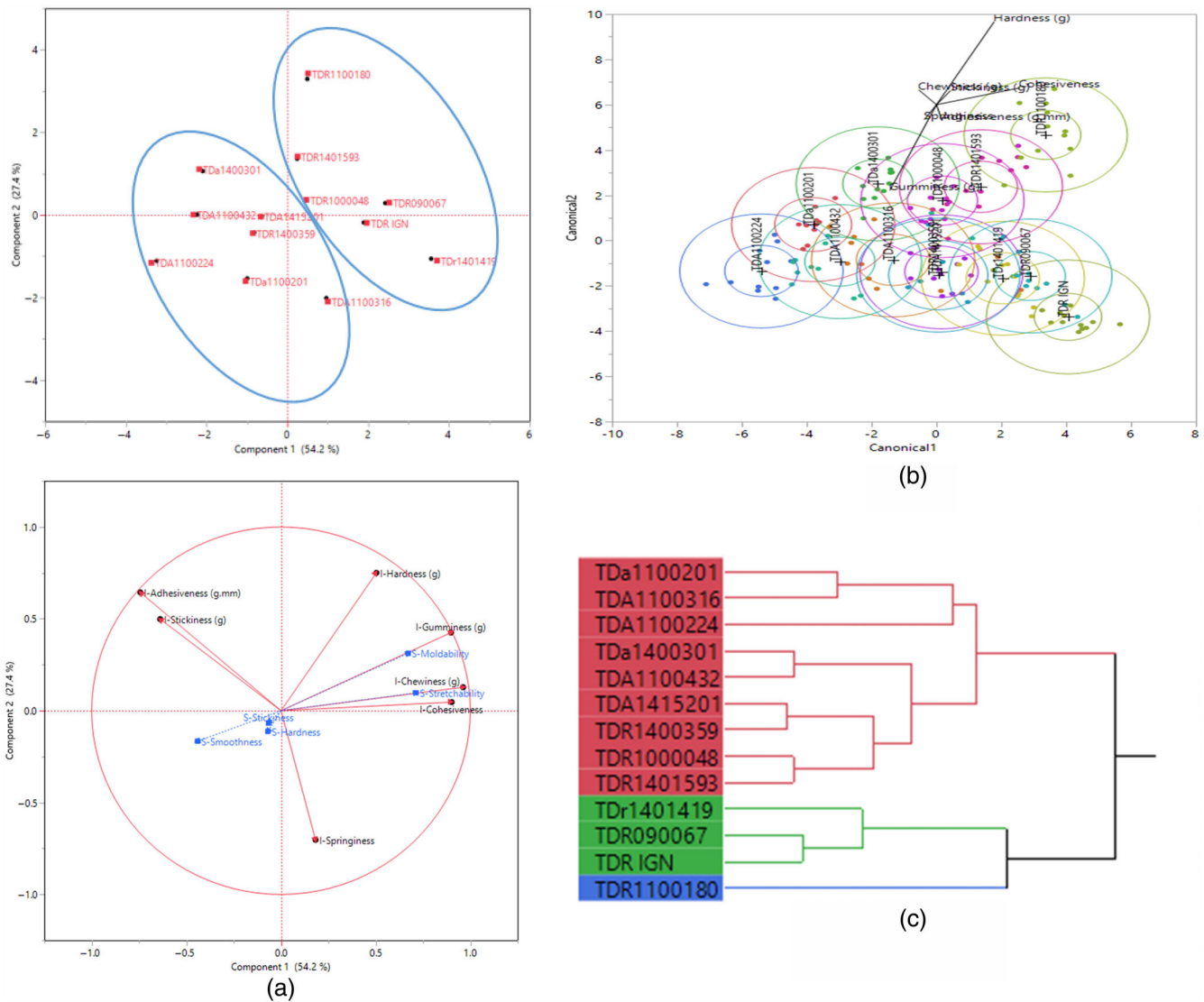


Figure 3. Texture profile analysis of pounded yam from 12 yam genotypes and one landrace (TDr IGN 21 (Ilgangan)). (a) Principal component analysis (PCA) of texture profile analysis of pounded yam from 12 yam genotypes and one landrace (TDr IGN 21 (Ilgangan)). (b) Discriminants of pounded yam texture made from 13 genotypes of yam. (c) Hierarchical clusters of textural quality of pounded yam made from 12 yam genotypes and one landrace (TDr IGN 21 (Ilgangan)).

Chemical composition

There was variability in chemical composition of the yam genotypes (Table 6), which confirmed previously reported intraspecies and interspecies variation in the chemical composition of yam.^{15,24} Generally, there was an insignificant difference ($P > 0.05$) in the mean value of starch (45.0% versus 44.9%), moisture (6.1% versus 5.6%) and fat (0.3% versus 0.3%) contents of *D. rotundata* and *D. alata* species, respectively. However, there were significant ($P < 0.05$) intraspecies differences for the sugar, moisture, ash, protein and crude fiber contents. Regarding the antinutritional contents, *D. alata* varieties had the highest mean tannin content (1.23%), while *D. rotundata* genotypes had the highest mean phytic acid (1.32%).

Color

The activity of PPO enzyme over 100 s in fresh roots (oxidative browning) (Fig. 5), for breeders' lines, in both species increased with time. *Dioscorea rotundata* genotypes had higher PPO activity

than those of *D. alata*. PPO activity was also higher for the *D. rotundata* landraces (except for Lasinrin), compared to the *D. alata* variety Ewura.

The result of the instrumental color measurement for the yam genotypes from breeders' lines is presented in Table 7. The color of yam genotypes from *D. alata* was lighter, as shown by the higher L^* (lightness) and lower a^* (red-green axis). In comparison, *D. rotundata* genotypes had a higher intense yellow color, shown by a higher value of b^* (yellow-blue axis). A similar trend in the color of the pounded yam samples was observed, though the values were lower than in the raw yam tubers.

Correlation between the chemical composition of yam varieties and QDA of pounded yam samples

Table 8 shows the result of Pearson correlation analysis between the chemical composition of the yam tubers and sensory attributes (QDA) of pounded yam samples made from them. In both the breeders' lines and the landraces, significant associations

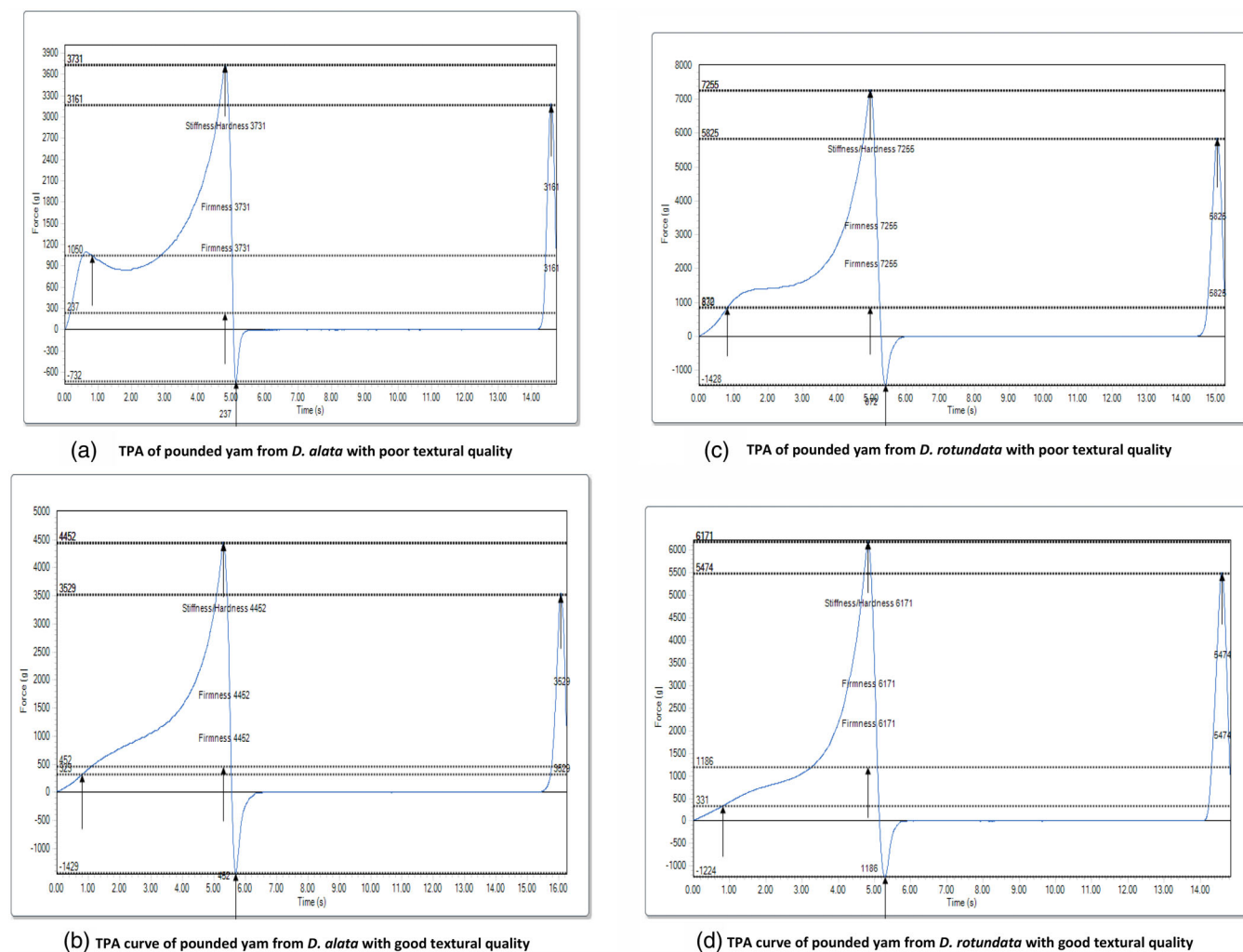


Figure 4. Representative texture profile analysis (TPA) of pounded yam from *Dioscorea alata* and *Dioscorea rotundata* varieties. (a) TPA of pounded yam from *D. alata* with poor textural quality. (b) TPA curve of pounded yam from *D. alata* with good textural quality. (c) TPA of pounded yam from *D. rotundata* with poor textural quality (d) TPA curve of pounded yam from *D. rotundata* with good textural quality.

were observed between chemical compositions of raw tubers (ash, protein, fat, starch, moisture, tannin and phytate) and the sensory attributes of pounded yam.

Prediction of sensory attributes of pounded yam through biophysical traits

Predictions were based on the quality attributes of the yam landraces used for consumer studies. Linear multiple regressions were applied to predict the sensory attributes from the biophysical parameters (Table 9). The best model was limited to two parameters based on a high coefficient of determination (R^2) already obtained (> 0.99). Based on this predictive model, the smoothness, adhesiveness/stickiness, moldability/cohesiveness, and stretchability (all with $R^2 = 1.00$), and hardness ($R^2 = 0.99$) of pounded yam samples can be predicted by varying pairs of parameters. In addition, the texture analyzer parameters of adhesiveness ($R^2 = 1.00$), cohesiveness ($R^2 = 1.00$) and hardness ($R^2 = 1.00$) can be used to predict the stickiness and moldability of pounded yam. In contrast, the color of the pounded yam samples can be efficiently predicted by CIE indices (L^* , a^* , b^*) of the Hunter colorimeter ($R^2 = 1.00$).

DISCUSSION

Consumer acceptability test

The most liked pounded yam samples were from Lasinrin, Awana and Gbongi-Kamilu (Table 1) with sensory characteristics such as 'smooth', 'moldable', 'good aroma', 'stretchable', 'sweet taste', 'soft'. Figure 1 describes the cluster groups of consumers and shows that more than half of the consumers interviewed disliked the sample prepared from Ewura. Pounded yam from this variety had been described from participatory processing diagnosis as a non-preferred variety because it produces very poor quality (not moldable, not stretchable, lumpy) pounded yam.²¹

Generally, in the consumer test, good quality pounded yam samples were described as 'stretchable', 'soft', 'smooth', 'moldable', 'not sticky', 'white/creamy/yellow' depending on the yam flesh color, 'sweet taste' and 'good aroma'. This agreed with the food quality profile described by Otegbayo *et al.*¹² The samples from Lasinrin, Gbongi-Kamilu and Awana fit into this group. However, it should be noted that previously in the participatory processing diagnosis,²¹ Gbongi-Kamilu was described as less preferred (when in the fresh state) in comparison with the other varieties as a result of changes in flesh color during processing

Table 5. Correlation between instrumental texture parameters and descriptive sensory evaluation parameters for pounded yam made from *Dioscorea rotundata* and *Dioscorea alata* varieties

Sensory parameters ^a	Instrumental parameters			Stringiness (mm)	Resilience (no unit)
	Adhesiveness (g.mm)	Cohesiveness (no unit)	Stiffness/hardness (g)		
<i>Dioscorea alata</i>					
Adhesiveness	0.76	-0.11	-0.68	-0.14	0.27
Moldability/cohesiveness	0.00	0.60	0.01	0.12	-0.13
Hardness/softness	0.78	0.09	0.63	0.25	0.30
Stretchability	-0.03	0.70	0.09	0.51	0.70
<i>Dioscorea rotundata</i>					
Adhesiveness	-0.11	0.29	-0.54	-0.67	-0.36
Moldability/cohesiveness	-0.25	0.81	0.12	-0.06	-0.29
Hardness/softness	0.11	-0.45	0.64	0.58	0.44
Stretchability	-0.42	0.92	-0.35	-0.35	-0.36
<i>Dioscorea alata</i> and <i>Dioscorea rotundata</i> combined					
Adhesiveness	0.34	0.01	-0.50	-0.32	-0.09
Moldability/cohesiveness	-0.19	0.84	0.51	-0.39	0.21
Hardness/softness	-0.32	-0.32	0.17	0.42	-0.14
Stretchability	-0.30	0.91	0.26	-0.52	-0.02

Note: Values in bold typeface are significantly correlated.

and the 'not too good' quality of its pounded yam. But on storage (which was the state during which the consumer test was done), the quality of the pounded yam sample improved (as described by the consumers), this implied that storage must have led to some changes in its biochemical composition which was reflected in its food quality attributes; this agrees with Otegbayo et al.²⁵ on pounded yam made from stored yam tubers.

In summary, the results of the consumer test in both countries Nigeria (southwest and southeast) and the Republic of Benin point to the fact that the key quality traits in pounded yam are color and textural quality (stretchability, smoothness, moderate hardness, moldability and moderate stickiness). It should be noted that although the consumers rated sweetness and aroma as attributes of pounded yam, they unanimously reiterated that this was because the pounded yam was served to them without stew. About 91% of the respondents (Fig. S2) stated that they usually eat the pounded yam with stew; hence the stew would have masked off the taste and aroma. Therefore, taste and aroma were not considered key quality attributes in pounded yam.

Correlation between QDA and consumer testing

Correlation between the QDA and consumer testing validates the key quality traits – color and textural quality (smoothness, stretchability, moldability, stickiness) – identified in pounded yam and to be passed on to breeders.

Instrumental texture profile analysis (TPA)

There was no significant ($P > 0.05$) relationship between the instrumental texture and sensory hardness, smoothness or stickiness when all genotypes were analyzed together (confirming PCA description). However, as a follow-up analysis, the yam genotypes were treated on species basis [because these yam species (*D. rotundata* and *D. alata*) are uniquely different in their chemical compositions, starch properties and textural properties of their food products]. In *D. alata*, there were correlations between TPA

and QDA parameters in terms of hardness, stickiness, cohesiveness, TPA cohesiveness and QDA stretchability, while in *D. rotundata* there were correlations between TPA and QDA in terms of cohesiveness, hardness and also between TPA cohesiveness and QDA stretchability. Correlations between TPA and QDA have been reported previously.⁴ The correlation of cohesiveness and stretchability in pounded yam from both yam species implies that for pounded yam to be stretchable, it must be cohesive. This also points to the fact that the TPA can be used to measure cohesiveness in pounded yam distinctively in place of a sensory panel.

There were significant correlations ($P < 0.05$) between other secondary instrumental parameters, chewiness, gumminess, cohesiveness, and sensory moldability and stretchability (Supporting Information Table S1 and Figure S3). However, these are not taken as key parameters since pounded yam consumers do not chew it, and the stew taken with it does not allow it to be gummy. From the correlations between TPA and QDA it can be inferred that these correlation results, TPA can be a medium-throughput phenotyping method to characterize the textural quality of pounded yam in place of QDA.

Color

Results assessing color agree with the findings of Anosike and Ayaebene²⁶ that the PPO activity in *D. rotundata* is higher than that of *D. alata* but is in contrast to the findings of Otegbayo et al.,²⁷ which reported higher PPO activity in *D. alata* than that in *D. rotundata*. Variations in these authors' reports may result from differences in the botanical origin of the yam varieties used by the different authors. The QDA results in this study (Tables 2 and 3) also corroborated the results of PPO activity because pounded yam samples from the *D. alata* varieties were described as creamy by the trained panelists, while pounded yam from *D. rotundata* was described as yellow. According to Omidiji and Okpuzor,²⁰ only 40% of browning in *D. rotundata* is PPO activity related. Other

Table 6. Chemical composition of *Dioscorea rotundata* and *Dioscorea alata*

Species/variety [†]	Moisture (%)	Ash (%)	Protein (%)	Fat (%)	Starch (%)	Sugar (%)	Crude fiber (%)	Tannin (%)	Phytate (%)
<i>Dioscorea rotundata</i> [‡]									
TDr1401419	5.23 ± 0.06 ^d	2.31 ± 0.07 ^d	4.51 ± 0.06e	0.30 ± 0.00a	48.89 ± 0.40b	4.67 ± 0.02b	1.54 ± 0.02c	0.18 ± 0.08d	1.21 ± 0.01d
TDr1100180	6.67 ± 0.06 ^c	2.50 ± 0.04c	5.25 ± 0.04c	0.20 ± 0.00f	46.99 ± 0.59c	4.50 ± 0.02d	1.75 ± 0.03b	0.57 ± 0.10c	1.35 ± 0.01b
TDr1400359	4.41 ± 0.02 ^e	1.59 ± 0.04f	6.19 ± 0.04a	0.33 ± 0.01a	35.30 ± 0.69f	4.62 ± 0.01c	1.54 ± 0.01c	1.75 ± 0.04a	1.24 ± 0.01c
TDr0900067	9.37 ± 0.08 ^a	2.73 ± 0.01b	6.33 ± 0.06a	0.23 ± 0.01e	44.74 ± 0.62d	3.90 ± 0.01e	2.08 ± 0.06a	0.97 ± 0.11b	1.55 ± 0.01a
TDr100048	5.19 ± 0.11 ^d	2.37 ± 0.07d	5.59 ± 0.07b	0.27 ± 0.00c	49.57 ± 0.66b	4.87 ± 0.02a	2.06 ± 0.05a	0.49 ± 0.10c	1.18 ± 0.01e
TDr1401593	5.27 ± 0.06 ^d	2.85 ± 0.04a	6.18 ± 0.08a	0.32 ± 0.00b	52.42 ± 0.31a	4.69 ± 0.01b	1.61 ± 0.04c	0.47 ± 0.17c	1.21 ± 0.01d
TDr IG N 21	6.89 ± 0.11b	2.06 ± 0.04e	4.71 ± 0.09d	0.25 ± 0.00d	36.98 ± 0.60e	3.92 ± 0.02e	1.06 ± 0.05d	0.18 ± 0.09d	1.54 ± 0.01a
Mean	6.15b	2.34a	5.53a	0.27a	44.98a	4.45a	1.66a	0.66a	1.32b
Standard deviation	1.67	0.42	0.74	0.05	6.50	0.39	0.35	0.55	0.06
<i>Dioscorea alata</i> [§]									
TDa1400301	5.82 ± 0.01 ^c	2.70 ± 0.01 ^d	5.60 ± 0.04 ^c	0.32 ± 0.00 ^a	41.95 ± 0.83 ^c	4.58 ± 0.01 ^e	1.84 ± 0.00 ^e	1.53 ± 0.04 ^a	1.25 ± 0.01 ^a
TDa1100224	4.46 ± 0.05 ^e	4.04 ± 0.07 ^a	7.81 ± 0.04 ^a	0.35 ± 0.00 ^a	47.85 ± 0.37 ^d	5.01 ± 0.01 ^a	2.06 ± 0.00 ^e	0.94 ± 0.05 ^c	1.05 ± 0.00 ^d
TDa1215201	5.87 ± 0.06 ^c	3.01 ± 0.05 ^c	5.71 ± 0.07 ^c	0.3 ± 0.00 ^a	45.25 ± 0.36 ^b	4.59 ± 0.01 ^e	1.85 ± 0.03 ^e	1.27 ± 0.16 ^b	1.24 ± 0.01 ^a
TDa1100432	6.40 ± 0.02 ^a	3.17 ± 0.06 ^b	6.07 ± 0.04 ^b	0.31 ± 0.00 ^a	42.52 ± 0.81 ^c	4.66 ± 0.01 ^d	2.19 ± 0.02 ^b	1.15 ± 0.04 ^b	1.23 ± 0.01 ^a
TDa1100201	6.09 ± 0.04 ^b	3.12 ± 0.04 ^{cb}	6.06 ± 0.11 ^b	0.29 ± 0.00 ^a	49.18 ± 0.30 ^a	4.83 ± 0.01 ^b	2.25 ± 0.04 ^a	1.55 ± 0.13 ^a	1.15 ± 0.00 ^c
TDa1100316	4.92 ± 0.04 ^d	3.20 ± 0.06 ^b	6.02 ± 0.03 ^b	0.33 ± 0.00 ^a	42.61 ± 0.49 ^c	4.75 ± 0.01 ^c	1.99 ± 0.01 ^d	0.98 ± 0.03 ^c	1.18 ± 0.01 ^b
Mean	5.59a	3.20b	6.21b	0.32a	44.89a	4.74b	2.03b	1.23b	1.18a
Standard deviation	0.74	0.45	0.81	0.02	3.06	0.16	0.17	0.26	0.08
Landraces									
Lasirin (TDr)	6.02 ± 0.25 ^{ab}	1.73 ± 0.02 ^b	5.57 ± 0.16 ^{bc}	0.48 ± 0.05 ^b	54.43 ± 0.25 ^b	7.44 ± 0.12 ^b	1.27 ± 0.001 ^c	0.36 ± 0.00 ^d	1.63 ± 0.01 ^a
Kamilu (TDr)	5.04 ± 0.06 ^{bc}	1.46 ± 0.05 ^c	6.41 ± 0.15 ^b	0.23 ± 0.01 ^c	52.72 ± 0.11 ^c	7.17 ± 0.08 ^b	1.25 ± 0.01 ^c	0.53 ± 0.02 ^b	1.54 ± 0.04 ^a
Awanah (TDr)	4.96 ± 0.10 ^c	1.61 ± 0.04 ^{bc}	4.78 ± 0.23 ^c	0.41 ± 0.04 ^b	55.38 ± 0.48 ^a	7.28 ± 0.12 ^b	2.17 ± 0.01 ^b	0.40 ± 0.00 ^c	1.00 ± 0.04 ^b
Ewura (TDr)	6.28 ± 0.67 ^a	2.37 ± 0.09 ^a	7.50 ± 0.58 ^a	0.71 ± 0.05 ^a	53.11 ± 0.08 ^c	8.53 ± 0.09 ^a	2.29 ± 0.02 ^a	1.98 ± 0.01 ^a	0.80 ± 0.04 ^c
Mean	5.57	1.79	6.07	0.46	53.91	7.60	1.75	0.83	1.24
Standard deviation	0.67	0.40	1.16	0.20	1.22	0.62	0.56	0.78	0.41

[†] Analysis done on dry weight basis.
[‡] Means with the same letter in the same column in *D. rotundata* are not significant at 5%.
[§] Means with the same letter in the same column in *D. alata* are not significant at 5%.
^{||} Means with the same letter in the same column in landraces are not significant at 5%.

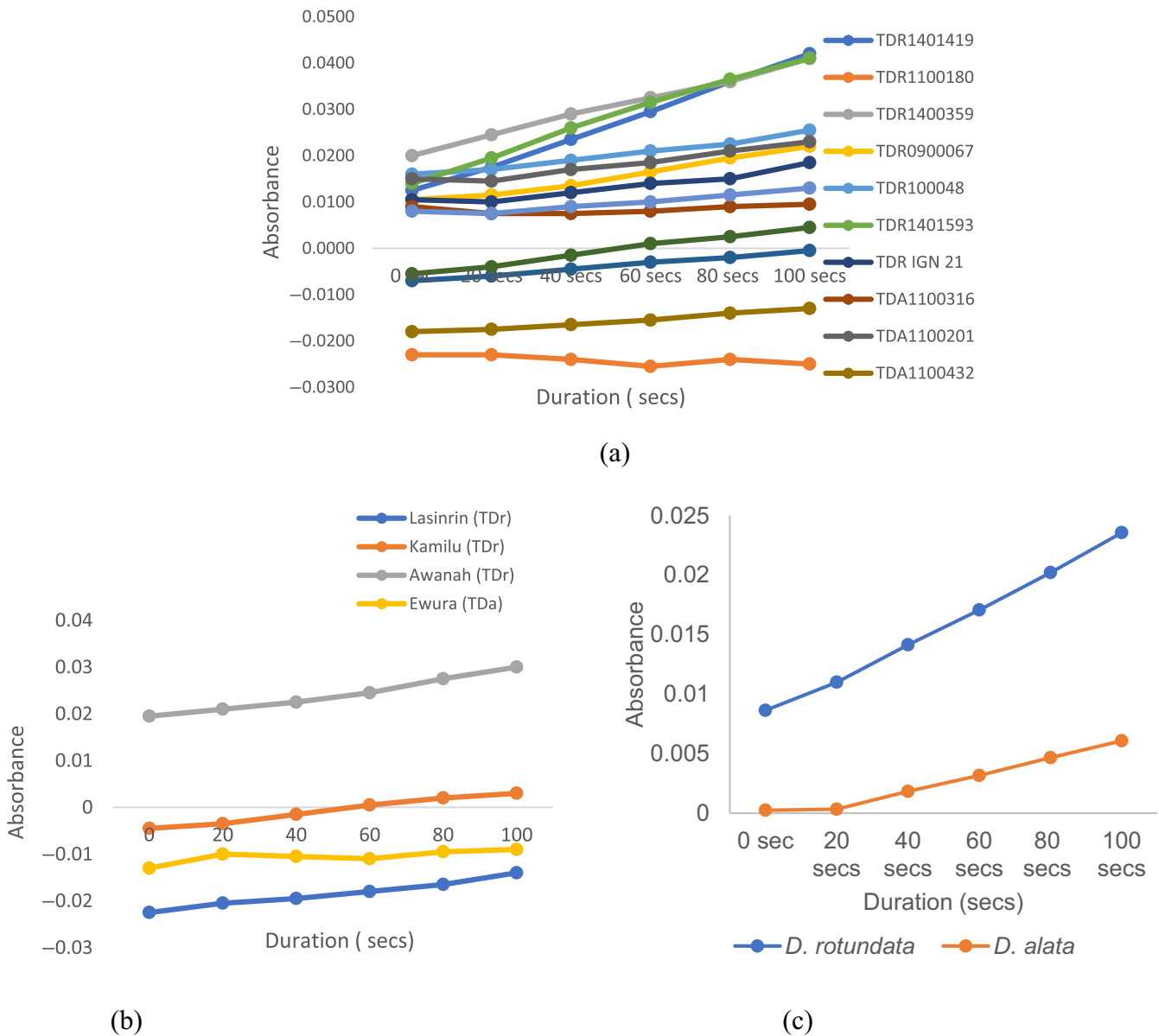


Figure 5. Polyphenol oxidase (PPO) activity in *Dioscorea* species. (a) PPO enzyme activity in raw *Dioscorea alata* and *Dioscorea rotundata*. (b) PPO enzyme activity in raw yam landraces. (c) Summary of PPO enzyme activity in raw *Dioscorea* species.

parietal components such as moisture, protein, tannin, and phenolic profile can influence the color of yam products.^{19,26} Hence the PPO activity of the yam tubers may be an index of browning rate and suggests a possible medium throughput phenotyping tool to assess the browning rate of yam products.

From chromameter measurement, the color of yam genotypes from *D. alata* was lighter, as shown by the higher L^* (lightness) and lower a^* (red-green axis). In comparison, *D. rotundata* genotypes had a higher intense yellow color, shown by a higher value of b^* (yellow-blue axis). A similar trend in the color of the pounded yam samples was observed, though the values were lower than in the raw yam tubers. This may be due to thermal degradation of originally colorless complex phenolics to colored phenols²⁸ or other reactions, such as Maillard reactions during the cooking of the yam. Chromameter measurement could be used as a high throughput method to evaluate the color of pounded yam, as a criterion of consumer acceptance.

An image analysis method has also been developed²⁹ to evaluate color in fresh yam tubers. Its advantage is the ability to capture color in heterogeneous (not smooth) surfaces; hence this will circumvent having to carry out many measurements at different points as done with the chromameter. The standard operating procedure for its potential use for high throughput color estimation in pounded yam is being worked on in the RTBfoods project.

Correlation between the chemical composition of yam varieties and QDA of pounded yam samples

Significant associations were observed between the sensory attributes of pounded yam and chemical composition as estimated by NIRS: ash, protein, fat, starch, dry matter, tannin and phytate. Other authors^{7,15,30,31} have also shown that root or tuber content of dry matter, protein and sugars can be determinants of quality in root and tuber crops. This observation implies that the yam

Table 7. Instrumental color measurement of *Dioscorea* species

	Raw tuber at 0 min [£]			Raw tuber after 10 min [*]			Pounded yam		
	L*	a*	b*	L*	a*	b*	L*	a*	b*
<i>Dioscorea rotundata</i> [†]									
TDr1401419	86.16 ± 3.21 ^a	-2.21 ± 0.35 ^{cb}	18.80 ± 0.17 ^c	83.23 ± 0.54 ^{ab}	-1.81 ± 0.30 ^b	18.59 ± 0.88 ^c	76.26 ± 0.69 ^a	-1.84 ± 0.32 ^c	16.09 ± 0.43 ^d
TDr1100180	83.49 ± 0.45 ^{ab}	-5.09 ± 0.20 ^e	29.57 ± 0.44 ^b	82.20 ± 0.38 ^b	-5.20 ± 0.06 ^{ed}	30.00 ± 0.33 ^b	67.73 ± 1.57 ^{fe}	-4.85 ± 0.15 ^e	25.98 ± 0.85 ^b
TDr1400359	81.51 ± 0.15 ^{bc}	-1.51 ± 0.32 ^b	15.82 ± 0.13 ^d	79.39 ± 0.11 ^{cd}	-0.96 ± 0.00 ^b	16.41 ± 0.01 ^c	73.73 ± 0.11 ^b	-0.80 ± 0.04 ^b	12.65 ± 0.02 ^e
TDr0900067	80.14 ± 0.48 ^c	0.93 ± 0.07 ^a	13.98 ± 1.08 ^d	77.80 ± 0.07 ^d	0.69 ± 0.69 ^a	17.36 ± 1.87 ^c	66.89 ± 0.35 ^f	1.04 ± 0.03 ^a	12.02 ± 0.04 ^e
TDr100048	84.61 ± 0.35 ^{ab}	-3.27 ± 0.06 ^d	19.57 ± 0.56 ^c	84.89 ± 0.59 ^a	-3.14 ± 0.17 ^c	18.98 ± 1.22 ^c	69.41 ± 0.04 ^d	-3.48 ± 0.22 ^d	18.37 ± 0.61 ^c
TDr1401593	79.66 ± 0.11 ^c	-2.83 ± 0.90 ^{dc}	31.68 ± 0.81 ^{ab}	81.10 ± 2.15 ^{bc}	-4.53 ± 0.67 ^d	33.29 ± 2.43 ^a	68.66 ± 0.06 ^{ed}	-3.48 ± 0.00 ^d	27.74 ± 0.27 ^a
TD IG N 21	83.70 ± 0.39 ^{ab}	-6.07 ± 0.06 ^f	32.25 ± 1.97 ^a	82.50 ± 0.00 ^b	-5.64 ± 0.00 ^e	33.46 ± 0.00 ^a	71.93 ± 0.01 ^c	-5.73 ± 0.26 ^f	28.06 ± 0.62 ^a
Mean	82.75	-2.86	23.09	81.59	-2.94	24.01	70.66	-2.73	20.13
Standard deviation	2.40	2.31	7.81	2.39	2.36	7.83	3.43	2.36	7.03
<i>Dioscorea alata</i> [‡]									
TDa1100316	86.50 ± 0.27 ^a	-2.03 ± 0.01 ^d	17.59 ± 0.82 ^{cb}	84.74 ± 0.06 ^a	-2.04 ± 0.03 ^c	17.43 ± 0.59 ^c	83.78 ± 1.77 ^a	-2.59 ± 0.04 ^e	17.76 ± 0.31 ^a
TDa1100201	84.13 ± 0.04 ^c	-1.76 ± 0.00 ^c	17.51 ± 0.08 ^{cb}	84.64 ± 0.09 ^a	-1.89 ± 0.01 ^{cb}	18.24 ± 0.03 ^b	71.69 ± 0.93 ^c	-2.54 ± 0.06 ^e	15.18 ± 0.18 ^c
TDa1100432	83.1 ± 0.05 ^d	-1.27 ± 0.09 ^b	18.06 ± 0.04 ^b	83.99 ± 0.10 ^b	-1.57 ± 0.01 ^{cb}	17.82 ± 0.01 ^b	85.70 ± 0.00 ^a	-1.72 ± 0.01 ^d	16.08 ± 0.02 ^b
TDa1100224	81.375 ± 0.02 ^c	-0.78 ± 0.06 ^a	19.59 ± 0.21 ^a	81.14 ± 0.16 ^c	-0.16 ± 0.86 ^a	20.22 ± 0.04 ^a	70.09 ± 0.11 ^c	-1.19 ± 0.02 ^c	14.95 ± 0.33 ^c
TDa1415201	84.93 ± 0.01 ^b	-1.22 ± 0.06 ^b	19.33 ± 0.23 ^a	84.22 ± 0.23 ^b	-0.98 ± 0.20 ^{ba}	18.48 ± 0.23 ^b	65.18 ± 0.08 ^d	-0.86 ± 0.01 ^b	14.76 ± 0.14 ^c
TDa1400301	85.395 ± 0.46 ^b	-1.29 ± 0.04 ^b	16.6 ± 0.69 ^c	84.83 ± 0.01 ^a	-1.14 ± 0.12 ^{cb}	15.47 ± 0.18 ^d	75.85 ± 0.09 ^b	1.27 ± 0.06 ^a	11.27 ± 0.04 ^d
Mean	84.29	-1.39	18.11	83.92	-1.3	17.94	75.38	-1.27	15.00
Standard deviation	1.81	0.44	1.15	1.40	0.69	1.55	8.04	1.43	2.13
Landraces [§]									
Lasirin (TDr)	82.43 ± 0.56 ^c	-5.05 ± 0.12 ^d	28.93 ± 0.39 ^a	79.52 ± 0.14 ^c	-4.86 ± 0.02 ^c	27.14 ± 0.12 ^b	66.17 ± 1.14 ^{ba}	-5.43 ± 0.13 ^d	26.55 ± 0.43 ^a
Kamilu (TDr)	81.60 ± 0.20 ^d	-4.72 ± 0.15 ^c	29.06 ± 0.86 ^a	79.98 ± 0.99 ^c	-5.15 ± 0.06 ^d	28.24 ± 0.22 ^a	62.47 ± 1.85 ^c	-0.49 ± 0.07 ^b	10.51 ± 0.10 ^c
Awanah (TDr)	83.21 ± 0.31 ^b	-2.54 ± 0.05 ^b	17.84 ± 0.22 ^b	82.39 ± 0.32 ^b	-2.27 ± 0.15 ^b	17.82 ± 0.02 ^c	67.61 ± 0.34 ^a	-1.68 ± 0.06 ^c	14.29 ± 0.10 ^b
Ewura (TDa)	84.06 ± 0.48 ^a	-0.34 ± 0.17 ^a	14.65 ± 0.51 ^c	83.89 ± 0.40 ^a	-0.27 ± 0.17 ^a	14.32 ± 0.62 ^d	65.34 ± 0.49 ^b	2.43 ± 0.12 ^a	10.68 ± 0.09 ^c
Mean	82.82	-3.16	22.62	81.45	-3.14	21.88	65.40	-1.29	15.51
Standard deviation	1.06	2.18	7.48	2.06	2.31	6.87	2.16	3.25	7.57

[†] Means with the same letter in the same column in *D. rotundata* are not significant at 0.05 level.

[‡] Means with the same letter in the same column in *D. alata* are not significant at 0.05.

[§] Means with the same letter in the same column in landraces are not significant at 0.05.

Table 8. Correlation between chemical composition of yam varieties and quantitative descriptive analysis (QDA) of pounded yam samples

	Smoothness	Adhesiveness	Moldability	Stretchability	Hardness	Color
<i>Breeders' lines</i>						
Moisture	-0.34	0.12	0.48*	0.48*	-0.54**	0.21
Ash	0.74**	-0.13	-0.69**	-0.76**	0.42*	-0.46*
Fat	0.48*	-0.03	-0.68**	-0.59*	0.54**	-0.46*
Protein	0.62**	-0.15	-0.61**	-0.64**	0.37	-0.28
Sugar	0.55**	-0.22	-0.55**	-0.67**	0.45*	-0.36
Starch	0.18	-0.22	-0.14	-0.29	0.01	-0.05
Amylose	-0.19	-0.08	0.36	0.21	-0.11	0.25
Crude fiber	0.62**	-0.20	-0.47*	-0.64**	0.10	-0.51**
Tannin	0.54**	0.10	-0.57**	-0.67**	0.08	-0.57**
Phytate	-0.58**	0.18	0.60**	0.69**	-0.48*	0.44*
<i>Landraces</i>						
Moisture	-0.60	-0.48	-0.46	-0.30	-0.36	0.76*
Ash	-0.94**	-0.34	-0.85**	-0.53	-0.42	0.50
Fat	-0.82*	-0.14	-0.67	-0.25	-0.63	0.38
Protein	-0.78*	-0.78*	-0.90**	-0.94**	0.30	0.74*
Sugar	-0.95**	-0.38	-0.88**	-0.61	-0.37	0.53
Starch	0.44	0.80*	0.63	0.86**	-0.55	-0.69
Amylose	0.53	-0.39	0.46	0.18	0.49	0.44
Dry matter raw tuber	-0.95**	-0.61	-0.98**	-0.89**	-0.01	0.63
Crude fiber	-0.68	0.34	-0.53	-0.12	-0.70	-0.27
Tannin	-0.99**	-0.47	-0.97**	-0.76*	-0.23	0.54
Phytate	0.76*	-0.23	0.64	0.26	0.64	0.18

*Correlation is significant at the 0.05 level (two-tailed).

** Correlation is significant at the 0.01 level (two-tailed).

tuber's parietal composition can influence the pounded yam's textural quality. The correlation of the dry matter content of the yam tubers with all the sensory attributes of the pounded yam except the adhesiveness further reinforces previous reports^{7,30,32} that dry matter and starch are essential determinants of textural quality in pounded yam.

Correlations between the protein content of the tubers and the smoothness, adhesiveness, moldability and stretchability of pounded yam may be a result of starch granule-associated proteins (SGAPs), which occur on the surface of starch granules and have been reported to influence starch functionality by affecting its pasting properties through the reduction in its viscosity, mechanical fragmentation and also conferring rigidity to the swollen granules, thus affecting the textural quality of the food product.^{33,34} In addition, proteins in starch

matrices have been reported^{35,36} to influence the textural quality of foods by interacting C-2 and C-3 hydroxyl groups of glucose units through hydrogen-bonding and act as a barrier preventing chain formation between amylose and amylopectin helices, thus affecting its starch retrogradation and its final viscosity; which affects the textural quality of the food product.

Fat may influence the textural quality of pounded yam due to the formation of amylose-lipid complexes, which alters the functionality of starches and hence its cooking properties.^{37,38}

A novel correlation observed in this study is that between the ash content of the tubers and the moldability of the derived pounded yam. It was observed that the more ash content, the less the moldability of the pounded yam [$R^2 = 0.53$ (Fig. S3c)]. Thus, ash can potentially be an interesting rapid test for

Table 9. Predictive models of sensory attributes from chemical and biophysical parameters based on data from landraces

Sensory attributes	Explicative variables	Regression equation/predictive models	R^2	P-Value
Smoothness	Starch (lab) and tannin (lab)	$24.62 - 0.24 \times \text{Starch} - 4.31 \times \text{Tannin}$	1.0	0.007
Adhesiveness/stickiness	Stickiness (TVT) and amylose	$4.45 - 1.85E-03 \times \text{Stickiness} - 0.14 \times \text{Amylose}$	1.0	0.020
Modability/cohesiveness	Stiffness/hardness (TVT) and cohesiveness (TVT)	$-4.05 + 1.05E-03 \times \text{Stiffness/Hardness} + 16.73 \times \text{Cohesiveness}$	1.0	0.006
Stretchability	Adhesiveness (TVT) and protein	$20.10 + 4.60E-04 \times \text{Adhesiveness} - 2.54 \times \text{Protein}$	1.0	0.011
Hardness	Starch (lab) and tannin (lab)	$54.47 - 0.88 \times \text{Starch} - 1.01 \times \text{Tannin}$	1.0	0.029
Color	a010_raw and L_py	$139.67 - 12.90 \times \text{a010_raw} - 2.08 \times \text{L_py}$	1.0	0.066

Abbreviation: TVT, texture analyzer parameter; a010_raw, red-green index (CIE) of raw tuber 10 min after cutting; L_py, lightness index (CIE) of pounded yam.

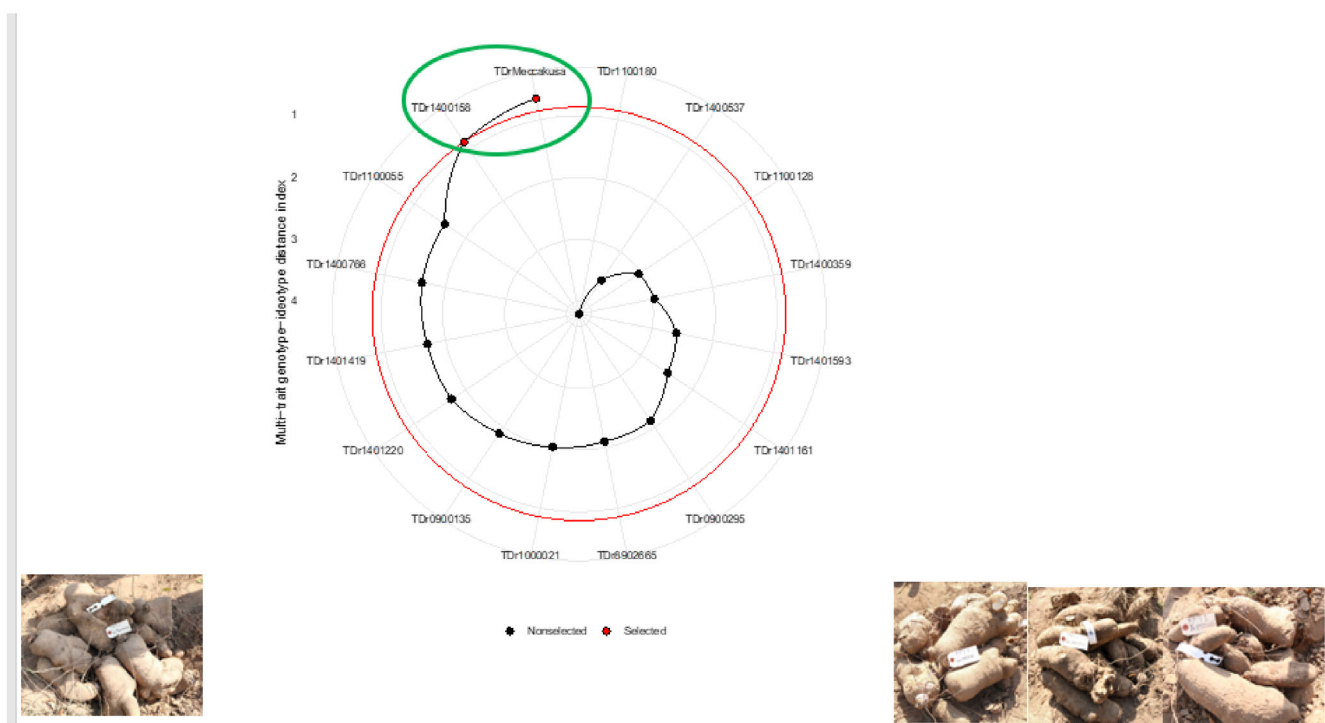
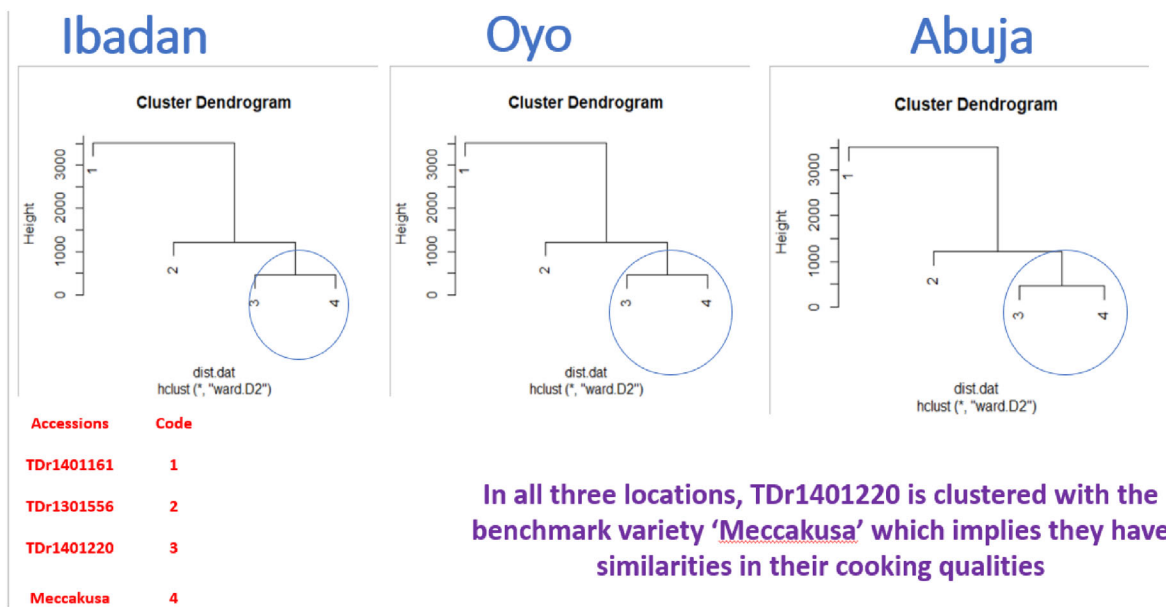


Figure 6. Sensory food product quality (FPQ) assay for pounded yam: Clustering of food quality traits of TDr1401220 with Meccakusa (landrace).

breeding. In addition, this observation of correlation of ash and moldability can be linked to the role of pectin in binding with divalent cations (from ash) to form a gel-like structure, which influences the texture of food by increasing its firmness and rigidity,^{22,39} therefore, the more divalent cations, the more the pectin is complexed.

The significant correlation of crude fiber with the smoothness of the pounded yam was expected, as this can be as a result of soluble and insoluble fiber in the yam tubers, which can affect the fibrousness of the pounded yam.²⁵

The correlation between tannin and phytate may result from forming soluble and insoluble complexes with divalent cations and proteins. These complexes may influence the textural attributes of the food product.³⁶ Phosphorous accounts for about 20–21% of phytic acid in root and tuber crops; it occurs in the form of phosphorous.⁴⁰ Phosphorous in the form of phosphomono esters has been implicated in influencing the textural quality of pounded yam through its effect on starch functionality, such as increasing starch swelling and viscosity, which in turn influence its textural quality.⁴¹

The main objective of this study was to identify the key biochemical traits in yam tubers that can predict the key food quality attributes of pounded yam and determine those that can be used in medium and high throughput methods by breeders. The biochemical traits being recommended in this study that can fulfill these objectives are dry matter, starch, amylose, and ash.

Breeders' perspective

This study demonstrates some key tools to predict the consumer-demanded quality attributes of pounded yam from instrumental TPA including stickiness/adhesiveness from the starch and amylose content of the tubers. Color can be objectively measured by means of a colorimeter and textural attributes such as adhesiveness and moldability of the pounded yam can be measured by texturometer, the added advantage of these methods being throughput will also reduce the screening and selection time for breeding lines. These throughput methods are now adopted in breeding programs using mostly preferred landraces in breeders' trials as benchmarks and selection index or selection decisions (Fig. 6). The yam breeders have applied these methods (TPA, QDA, PPO, instrumental color evaluation, and biochemical composition analysis by NIRS) as throughput methods in the selection of yam genotype TDr1401220 (from the raw yam, during processing and to the final product) which is being nominated as a candidate for national variety release using Meccakusa as the preferred landrace for pounded yam as a benchmark. This candidate was found to be clustered (have similar food quality attributes) with Meccakusa, one of the highly prized landraces for preferred pounded yam by consumers when planted in different locations.

AUTHOR CONTRIBUTIONS

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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.

REFERENCES

- Poudyal N, Hgaza VK, Kiba DI, Bomisso L, Aighewi B, Aké S *et al.*, Water yam (*Dioscorea alata* L.) growth and tuber yield as affected by rotation and fertilization regimes across an environmental gradient in West Africa. *Agronomy* **12**:792 (2022).
- Akissoe N, Hounhouigan J, Mestres C and Nago M, Effect of tuber storage and pre- and post-blanching treatments on the physicochemical and pasting properties of dry yam flour. *Food Chem* **85**:141–149 (2004).
- Arnau G, Abraham K, Sheela MN, Sartie A and Asiedu R, Yams, in *Root and Tuber Crops*. Springer, New York, NY, pp. 127–148 (2010).
- Otegbayo BO, Samuel FO, Kehinde AL, Sangoyomi TE and Okonkwo CC, Perception of food quality in yams among some Nigerian farmers. *Afr J Food Sci* **4**:541–549 (2010).
- Madu T, Chijioko U and Okoye B, Synthesis report for Yam in Nigeria, Umudike, Nigeria RTBfoods Project Report, 22p (2018).
- Otegbayo BO, Aina JO, Sakyi-Dawson EO, Bokanga M and Asiedu R, Sensory texture profiling and development of standard rating scales for pounded yam. *J Texture Stud* **36**:478–488 (2005).
- Akissoe N, Mestres C, Hounhouigan J and Nago M, Sensory and physicochemical quality of pounded yam: varietal and storage effects. *J Food Process Preserv* **33**:75–90 (2009).
- Ojokoh AO and Adeleke BS, Processing of yam paste (Amala): a product of fermented yam (*Dioscorea rotundata*) flour. *Int Ann Sci* **8**:87–95 (2020).
- Otegbayo BO, Oroniran O, Fawehinmi O and Ayandiji A, A state of knowledge review on yam. It's quality and sensory attributes. *RTBfoods Project Report* **13**:1–13 (2018). <https://doi.org/10.13140/RG.2.2.29758.00320>.
- Hahn SK, Osiru DSO, Akoroda MO and Otoo JA, Yam production and its prospects. *Outlook Agric* **16**:105–110 (1987).
- Nindjin C, Otokoré D, Hauser S, Tschannen A, Farah Z and Girardin O, Determination of relevant sensory properties of pounded yams (*Dioscorea spp.*) using a locally based descriptive analysis methodology. *Food Qual Prefer* **18**:450–459 (2007).
- Otegbayo B, Madu T, Oroniran O, Chijioko U, Fawehinmi O, Okoye B *et al.*, End-user preferences for pounded yam and implications for food product profile development. *Int J Food Sci Technol* **56**:1458–1472 (2021).
- Jeannette F, Faouziath S, Estelle LYL, Célestin T, Cartney IC, Innocent BY *et al.*, Sensory evaluation and consumers acceptability of some yam (*Dioscorea rotundata*) cultivars used as parents in a yam varietal development program in Benin. *Int J Curr Microbiol App Sci* **9**: 2083–2100 (2020).
- Otegbayo B, Oroniran O and Tanimola AR, Laboratory standard operation procedure for sensory characterization of pounded yam *RTBfoods_E_6_6_SOP_Sensory_Characterization* (2020a). https://mel.cgiar.org/reporting/download/report_file_id/25514.
- Otegbayo BO, Oguniyan DJ, Olunlade BA, Oroniran OO and Atobatele OE, Characterizing genotypic variation in biochemical composition, antinutritional and mineral bioavailability of some Nigerian yam (*Dioscorea spp.*) landraces. *J Food Sci Technol* **55**:205–216 (2018).
- Forsythe L, Tufan H, Bouniol A, Kleih U and Fliedel G, An interdisciplinary and participatory methodology to improve user acceptability of root, tuber and banana varieties. *Int J Food Sci Technol* **56**:1115–1123 (2021).

- 17 Otegbayo B, Oroniran O, Tanimola AR, Bolaji OA and Alamu A, Standard Operating Procedure for Instrumental texture evaluation of Pounded yam (2022). https://collaborative.cirad.fr/share/page/site/RTBfoods/documents22_03_10_SOP.
- 18 Madu T, Okoye B, Ukeje B, Onyemauwa N, Ofioe M, Flidel G *et al.*, Consumer testing of pounded yam in rural and urban areas in Nigeria, in *Understanding the Drivers of Trait Preferences and the Development of Multi-User RTB Product Profiles, WP1, Step 4*. RTBfoods Field Scientific Report, Umudike, p. 18 (2021). <https://doi.org/10.18167/agritrop/00638>.
- 19 Alamu OE, Adesokan M and Maziya-Dixon B, Calibration development for nutritional evaluation of yam (*Dioscorea* sp.) using near-infrared reflectance spectrophotometry (NIRS). *Cogent Chem* **5**:1565623 (2019).
- 20 Omidiji O and Okpuzor J, Time course of PPO-related browning of yams. *J Sci Food Agric* **70**:190–196 (1996).
- 21 Otegbayo B, Oroniran O, Fawehinmi O, Tanimola A and Bouniol A, Participatory processing diagnosis of pounded yam in Nigeria, in *Understanding the Drivers of Trait Preferences and the Development of Multi-User RTB Product Profiles, WP1, Step 3*. RTBfoods Project Report, Iwo, p. 22 (2021). <https://doi.org/10.18167/agritrop/00616>.
- 22 Effah-Manu L, Maziya-Dixon B, Wireko-Manu FD, Agbenorhevi JK and Oduro I, Yam pectin and textural characteristics: a preliminary study. *Int J Food Prop* **25**:1591–1603 (2022).
- 23 Otegbayo BO, Aina JO, Lawrence A, Sakyi-Dawson EO, Bokanga M and Asiedu R, Texture profile analysis applied to pounded yam. *J Texture Stud* **38**:355–372 (2007).
- 24 Omohimi CI, Piccirillo C, Roriz M, Ferraro V, Vasconcelos MW, Sanni LO *et al.*, Study of the proximate and mineral composition of different Nigerian yam chips, flakes and flours. *J Food Sci Technol* **55**:42–51 (2018).
- 25 Otegbayo BO, Asiedu R and Bokanga M, Effect of storage on chemical composition and food quality of yam. *J Food Process Preserv* **36**:438–445 (2012).
- 26 Anosike EO and Ayaebene AO, Purification and some properties of polyphenol oxidase from the yam tubers, *Dioscorea bulbifera*. *Phytochemistry* **20**:2625–2628 (1981).
- 27 Otegbayo BO, Developing indicators for phenotyping food quality traits in yam (*Dioscorea* spp), in *Technical Report on PEARLS GRANT Submitted to Bill & Melinda Gates Foundation*. Seattle, USA, pp. 1–203 (2020).
- 28 Akissoé N, Hounhouigan J, Mestres C and Nago M, How blanching and drying affect the colour and functional characteristics of yam (*Dioscorea cayenensis-rotundata*) flour. *Food Chem* **82**:257–264 (2003).
- 29 Cornet D, *SOP for Calibrated Color Measurements of RTB Foods Using Image Analysis*. RTBfoods Project Report, Montpellier, p. 17 (2020).
- 30 Lebot V and Malapa R, Application of near infrared reflectance spectroscopy for the evaluation of yam (*Dioscorea alata*) germplasm and breeding lines. *J Sci Food Agric* **93**:1788–1797 (2013).
- 31 Ikeogu UN, Davrieux F, Dufour D, Ceballos H, Egesi CN and Jannink JL, Rapid analyses of dry matter content and carotenoids in fresh cassava roots using a portable visible and near infrared spectrometer (Vis/NIRS). *PLoS One* **12**:e0188918 (2017).
- 32 Otegbayo BO, Ogunniyan D and Akinwumi B, Physicochemical and functional characterization of yam starch for potential industrial applications. *Starch/Stärke* **66**:235–250 (2014).
- 33 Baldwin PM, Starch granule-associated proteins and polypeptides: a review. *Starch - Stärke* **53**:475–503 (2001). [https://doi.org/10.1002/1521-379X\(200110\)53:103.0.CO;2-E](https://doi.org/10.1002/1521-379X(200110)53:103.0.CO;2-E).
- 34 Han XZ, Campanella OH, Guan H, Keeling PL and Hamaker BR, Influence of maize starch granule-associated protein on the rheological properties of starch pastes. Part I. large deformation measurements of paste properties. *Carbohydr Polym* **49**:315–321 (2002a). [https://doi.org/10.1016/S0144-8617\(01\)00347-2](https://doi.org/10.1016/S0144-8617(01)00347-2).
- 35 Preston KR, Protein-carbohydrate interactions, in *Interactions: The Keys to Cereal Quality*, ed. by Hamer RJ and Hosenev RC. AACC, St Paul, MN, p. 81e93 (1998).
- 36 Anyango JO, de Kock HL and Taylor JR, Evaluation of the functional quality of cowpea-fortified traditional African sorghum foods using instrumental and descriptive sensory analysis. *LWT-Food Sci Technol* **44**:2126–2133 (2011).
- 37 Verma DK and Srivastav PP, Isolation, modification, and characterization of rice starch with emphasis on functional properties and industrial application: a review. *Crit Rev Food Sci Nutr* **62**:6577–6604 (2022). <https://doi.org/10.1080/10408398.2021.1903383>.
- 38 Putseys JA, Lamberts L and Delcour JA, Amylose-inclusion complexes: formation, identity and physico-chemical properties. *J Cereal Sci* **51**:238–247 (2010). <https://doi.org/10.1016/j.jcs.2010.01.011>.
- 39 Gamonpilas C, Krongsin J and Methacanon P, Goh SM gelation of pomelo (*Citrus maxima*) pectin as induced by divalent ions or acidification. *J Food Eng* **152**:17–23 (2015).
- 40 Ravindran V, Ravindran G and Sivalogan S, Total and phytate phosphorus contents of various foods and feedstuffs of plant origin. *Food Chem* **50**:133–136 (1994). [https://doi.org/10.1016/0308-8146\(94\)90109-0](https://doi.org/10.1016/0308-8146(94)90109-0).
- 41 Otegbayo BO, Bokanga M and Asiedu R, Physico-chemical composition of yam starch: effect on textural quality of yam food product (Pounded yam). *J Food Agric Environ* **9**:145–150 (2011).