Review

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Review of instrumental texture measurements as phenotypic tool to assess textural diversity of root, tuber and banana food products

Oluwatoyin Ayetigbo,[a,b*] Santiago Arufe,[a,b] Antonin Kouassi,[a,c] Laurent Adinsi,[d] Michael Adesokan,[e] Andres Escobar,[f] Luis Fernando Delgado,[f] Abiola Tanimola,[g] Oluyinka Oroniran,[g] Cédric Kendine Vepowo,[h,i] Mariam Nakitto,[j] Elizabeth Khakasa,[k] Ugo Chijioke,[l] Kephas Nowakunda,[k] Gérard Ngoh Newilah,[h,m] Bolanle Otegbayo,[g] Noel Akissoe,[d] Mathieu Lechaudel,[b,n] Thierry Tran,[a,b,f] Emmanuel Oladeji Alamu,[e,o] Busie Maziya-Dixon,[e] Christian Mestres[a,b] and Dominique Dufour[a,b]

Abstract

Roots, tubers and bananas (RTBs) contribute immensely to food security and livelihoods in sub-Saharan Africa, Asia and Latin America. The adoption of RTB genotypes in these regions relies on the interplay among agronomic traits, ease of processing and consumer preference. In breeding RTBs, until recently little attention was accorded key textural traits preferred by consumers. Moreover, a lack of standard, discriminant, repeatable protocols that can be used to measure the textural traits deter linkages between breeding better RTB genotypes and end user/consumer preferences. RTB products texture – that is, behaviour of RTB food products under unique deformations, such as disintegration and the flow of a food under force – is a critical component of these preferences. The preferences consumers have for certain product texture can be evaluated from expert sensory panel and consumer surveys, which are useful tools in setting thresholds for textural traits, and inform breeders on what to improve in the quality of RTBs. Textural characterization of RTBs under standard operating procedures (SOPs) is important in ensuring the standardization of texture measurement conditions, predictability of textural quality of RTBs, and ultimately definition of RTB food product profiles. This paper reviews current SOPs for the textural characterization of RTBs, including their various associated methods, parameters, challenges and merits. Case studies of texture characterized during development of SOPs and evaluation of texture of RTB populations are discussed, together with insights into key textural attributes and correlations between instrumental, sensory and consumer assessment of texture unique to various RTB food

* Correspondence to: O Ayetigbo, French Agricultural Research Centre for International Development (CIRAD), UMR QualiSud, Rue Jean François-Breton, 34398 Montpellier, France E-mail: oluwatoyin.ayetigbo@cirad.fr

a French Agricultural Research Centre for International Development (CIRAD), UMR QualiSud, Rue Jean François-Breton, Montpellier, France

b QualiSud, Univ. Montpellier, Avignon Université, CIRAD, Institut Agro, IRD, Université de La Réunion, Montpellier, France

c Université Nangui Abrogoua (UNA), Abidjan, Ivory Coast

d Laboratoire de Sciences des Aliments, Faculte des Sciences Agronomiques, Universite d'Abomey-Calavi (UAC-FSA), Calavi, Benin

e Food and Nutrition Laboratory, International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria

f The Alliance of Bioversity and the International Center for Tropical Agriculture (CIAT), Cali, Colombia

g Department of Food Science and Technology, Bowen University, Iwo, Nigeria

h African Centre for Banana and Plantain Research (CARBAP), Douala, Cameroon

i University of Douala, Douala, Cameroon

j International Potato Center (CIP), Kampala, Uganda

k National Agricultural Research Laboratories (NARL), Kawanda, Uganda

l National Root Crops Research Institute, Umudike (NRCRI), Umuahia, Nigeria

m University of Dschang, Dschang, Cameroon

n UMR Qualisud, CIRAD, F-97130 Capesterre-Belle-Eau, Guadeloupe, France

o Food and Nutrition Sciences Laboratory, International Institute of Tropical Agriculture (IITA), Lusaka, Zambia

products. Hardness was considered a universal key textural attribute to discriminate RTBs. The review should provide adequate insight into texture of RTB food products and critical factors in their measurement. It aims to promote inclusion of texture in breeding pipelines by investigating which textural traits are prioritized by consumers, particularly since the inclusion of textural traits has recently gained prominence by breeders in improving RTBs.

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

Keywords: texture profile analysis; standard operating protocols; textural attributes; food product profiles; RTB

INTRODUCTION

The most consumed root, tuber, and banana crops (RTBs) in sub-Sahara Africa, Asia and Latin America are yam, cassava, sweet potato, potato, plantain and cooking banana. From these main crops, a wide array of different products can be obtained, and these food products may be classified as pasty/doughy (e.g., pounded yam, *eba*, *fufu* and *matooke*), steamed/boiled (e.g., boiled sweet potato, cassava, yam, potato and plantain), fried (e.g., fried plantain (*aloco*), potato and sweet potato) and granular (*attiéké*). The pasty products are generally made from steaming or cooking the raw fleshy parts of RTBs, or the meal or mash that has been fermented or unfermented, and pounding or vigorously stirring or mashing into a homogeneous or partly homogeneous paste consistency. The boiled products are made by steaming or boiling the cut fleshy or pulpy parts of raw RTBs until considered tender enough for consumption, and these boiled products are generally consumed almost globally. The fried products are produced by frying in oil for brief periods after cutting or slicing into sizeable portions until sufficiently done. Due to large variations in preparation methods of the RTB products, especially pasty products, efforts have been made to produce standard procedures for preparation of these products.[1-6]

Conventional RTB breeding programmes often focused on agronomic (yield, disease and pest resilience, early maturity, ease of harvest) and nutritional traits as criteria for developing new genotypes. Inadequate consideration of consumer preferences often result in poor adoption of new genotypes after release. Texture has been identified as a key qualitative trait for focus in successful development of advanced clones,[7] and is therefore the main focus of this review.

Food texture encompasses the behaviour of foods when subjected to various types of deformation that may occur during preparation, processing, transport, storage and use. Foods are viscoelastic in nature, comprising elastic and viscous components. Deformations in RTB food products result from strain due to stress applied as tension, compression, penetration or oscillation forces, and less often rotation or shear forces. A number of physicochemical factors (under genetic control) have been found to influence the texture of RTBs, such as starch composition and behaviour, granule size, cell wall structure, pectic composition, water absorption and swelling.[8]

Ultimately, the consumer's sensory perception will determine textural acceptability. However, from a practical breeding perspective, it is highly advantageous to have faster methods to apply to medium- and high-throughput screening to select the most preferred clones for release and adoption. It is therefore important to determine the texture of RTBs by instrumental protocols that can simulate sensory texture as much as possible, and to establish mathematical relationships between instrument and sensory perception. Sensory traits can thus be quantitatively predicted based on instrumental measurements.[9-12] In addition, thresholds of texture attributes of RTB foods can be provided to breeders when textural data are juxtaposed with consumer surveys, thereby linking texture from raw product to controlled processing and to consumer preferences.

We review the main protocols for determining instrumental texture of RTB food products already published in the literature, with a focus on their discriminant power to differentiate between RTB genotypes. Each procedure has certain advantages and challenges associated with their use with each food product type. Most of the raw data assessed in this review were collected from open-access studies from various research institutions in different locations such as CIRAD, UAC-FSA, IITA, CIAT, NRCRI, BOWEN University, CARBAP, CIP, NARL and UNA. The original data were reprocessed to evaluate the robustness, discriminance and repeatability of the instrumental methods. The assessed products are boiled cassava, yam, plantain, potato and sweet potato, *eba*, *fufu*, pounded yam and *matooke*. Finally, data on hardness, as an exemplary attribute of RTB texture, were analysed by discriminant and partition analyses.

STANDARD OPERATING PROCEDURES FOR RTB TEXTURE

Food texture is a quality attribute specific to the controlled conditions under which it is determined. It can be influenced by several factors such as quality of raw material determined by genetics, age of harvested material, ripening stage, preparation methods, temperature, time, geometry of test samples, instrument and testing methods. Traditional RTB foods in Africa are produced under varying customary practices that have not been harmonized/standardized, making it difficult to regulate their influence on textural quality. Consequently, there is the need to develop standard operating procedures (SOPs) for the evaluation of texture of RTB products. An acceptable SOP facilitates textural measurements that are accurate, repeatable and capable of discriminating contrasting genotypes.

Accuracy and statistical methods

Accuracy is evaluated by statistical tools such as coefficient of variation (CV) of mean, standard deviation (SD) or standard error of mean (SEM). Texture values with low CV of mean (< 20%), relative SD and SEM are considered accurate.[13] Repeatability can be evaluated by the statistical significance of differences between the means of two or more replicate groups consisting of at least six measurements of a texture attribute of a genotype. The statistical tools used could be a difference test (two-tailed *t*-test for two groups of variables) or one-way analysis of variance (ANOVA) for more groups.[14] Probability value of difference between replicate means at or greater than 5% ($P \geq 0.05$) suggests insignificant differences between replicate measurements of an instrumental texture parameter and therefore good repeatability. Probability value below 5% ($P < 0.05$) for differences among mean instrumental texture parameter of genotypes suggests significant differences between the genotypes. Post hoc separation of means of texture parameter among the genotypes reveal discriminance among the genotypes. Furthermore, a discriminant (canonical) analysis may be conducted to estimate and visualize discriminant profiles considering all the texture attributes or key texture attributes as dependent covariates, while the genotypes (or other independent variables) are the categorical variable. It may also give information on the most discriminant textural parameter.

Other multivariate statistical tools used in discriminating RTB genotypes are regression, multivariate regression, multiple correlations and principal component analysis (PCA) and hierarchical clustering.[14] Software such as JMP Pro, SPSS, R statistics, XLStats and SAS is used in the statistical analysis.

The SOP should produce instrumental textural values that can be correlated with key sensory textural attributes, to provide significant ($P < 0.05$) relationships between instrumental and sensory texture or consumer perception, with the long-term objective being the accurate estimation of sensory textural quality of RTBs using rapid instrumental methods. To achieve valid correlations between instrumental and sensory texture, SOPs have been developed to assess sensory texture for various RTBs[15-22] following detailed guidelines,[23-25] particularly since different methods are used to assess sensory texture in various works.

Instrument, operating conditions and standardization of procedures for assessing texture

Other key considerations in the development of suitable SOPs are calibration of instrument, operating conditions and standardization of sample geometry. In the context of RTBs, different texture analysers can be used (i.e., TA.XT texture analyser, Stable Micro Systems, Godalming, UK; Perten Texture analyser TVT6700, Perten Instruments, Springfield, IL., USA) fitted with adjustable load cell system, motorized crosshead, probes/fixtures/attachments point and test rigs.

Operating conditions such as temperature and environmental conditions should be controlled during texture measurements. Large temperature variations may alter sample texture of RTB, which are known to be starchy. Products such as *eba*, pounded yam, *fufu* and *matooke* retrograde rapidly on exposure to ambient conditions. Boiled products such as cassava, yam or plantain harden and lose moisture rapidly after boiling. The texture parameter settings also play an important role in accuracy of measurements. Trigger force, which is the minimum resistance to deformation force that will initiate capture of measurements, is commonly set at 5 g for most textural measurements. It may also be set up to 0.5% of the load cell value deployed, depending on the hardness of food product and the size of the pieces used for the texture measurement: larger pieces allow using a higher trigger force, which may help buffer artefacts caused by uneven sample surface or shape.

In extrusion of boiled cassava, for instance, a trigger force of 1000 g has been used with success,[26] with a sample 6 cm long × 5.5 cm diameter, but a trigger force of 25 g was unusable for boiled plantain from samples of very soft texture by penetration.[5] For most TPA (texture profile analysis, which simulates deformation by double compression, similar to the chewing action of the jaws on food) measurements, strains can be set up to about 75% of the original length of the sample[27] or even up to 100% for the texture–extrusion test. However, for penetration tests, distance settings are preferred, typically, up to half the length of sample bulk or sufficient lengths until structural failure of dough sheets for extension tests.[28,29]

Pre-test, test and post-test speeds vary widely. Ordinarily, test speeds are preferably lower (0.5–3 mm s^{-1}) than pre-test (1–10 mm s^{-1}) and post-test speeds (5–20 mm s^{-1}) to increase sensitivity to the texture character within the food structure matrix. The time between the TPA compression cycles could vary between 5 and 20 s, particularly because exposure time needs to be limited during measurements. The sample geometry is also an essential factor to be considered as it affects texture values. Regularization of sample geometry has been achieved by cutting, halving, boring or moulding RTB samples using rigid materials. In banana and plantain, the hand, bunch and finger samples should be selected in a representative manner because there may be variations in physicochemical composition or texture in these physiological parts and at different maturity stages.[30,31] Similarly, the size and shape of roots and tubers should be standardized.

Sensitivity of textural protocols to RTB food product profiles

Depending on the intrinsic textural nature of the RTB, different textural measurement protocols may be applied to a specific product or category.

Products from raw materials having fibrous networks, hard crusts, stratified or layered matrices may have location-specific texture, often better captured by penetration or extrusion protocols. Large variation in texture exists in different parts of RTBs. The proximal, central and distal parts of cassava and yam often have a very wide variation in texture that may be linked to their biophysical composition, while potato and sweet potato texture may be little affected by this phenomenon. Cooking banana and plantain are often homogeneous in texture. The penetration test seems to be more discriminant for boiled products, but extrusion has also been found to discriminate.[32]

Exemplary situations are discussed for some product categories, and a comparison of the discriminating power of textural protocols is presented. For boiled products, penetration and extrusion textural protocols have proven to be better at discriminating between genotypes than TPA, although all the protocols are discriminating. Nevertheless, penetration is often less repeatable than TPA. Such results were found for boiled sweet potato texture measured by an SOP.[32,33] Penetration was more appropriate to measure the texture of boiled plantain and cooking banana than TPA because it could better discriminate between genotypes[5,32,34] (Fig. 1). For texture evaluation, some studies showed that penetration and extrusion protocols better discriminated between genotypes for boiled cassava[35] and boiled yam (Adesokan *et al*. 2023, unpublished data), as compared to TPA (Fig. 2). TPA and uniaxial compression were, however, equally discriminant for the texture parameters of boiled sweet potato.[11] Nonetheless, TPA protocol provides more detailed information on textural parameters that cannot be measured by penetration, such as adhesiveness, cohesiveness, resilience, springiness, chewiness and gumminess. A review on TPA parameters,[36] however, opined that mechanical assessment of texture considering parameters such as yield stress, failure strain, toughness and stiffness complemented by physical methods such as acoustic signature may better suit the true textural character of some food products, and

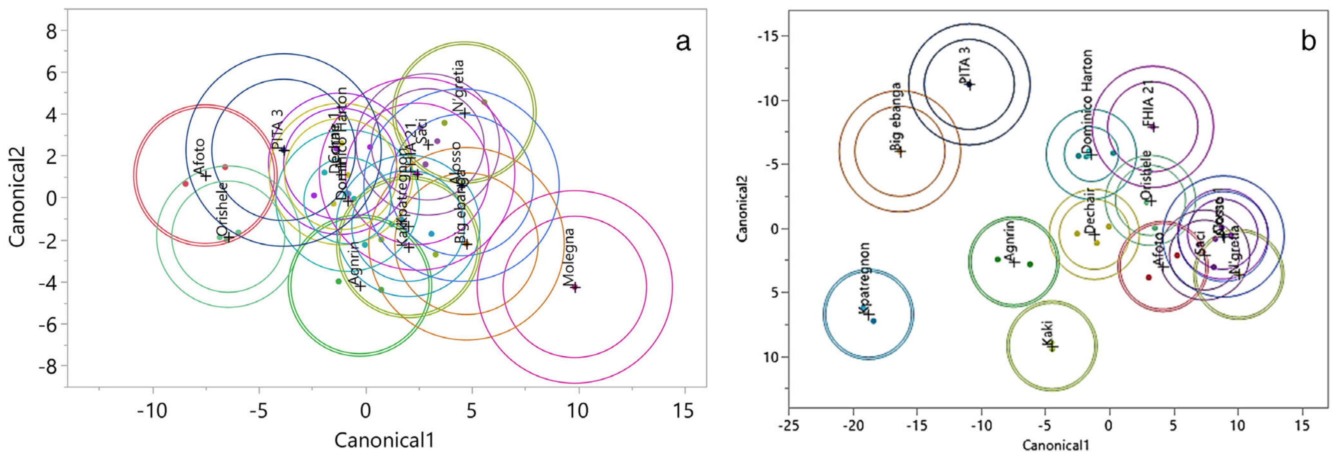

Figure 1. Example of canonical analysis showing discrimination between texture of cooked banana from 16 cooking and dessert banana genotypes by TPA (a) and penetration (b).

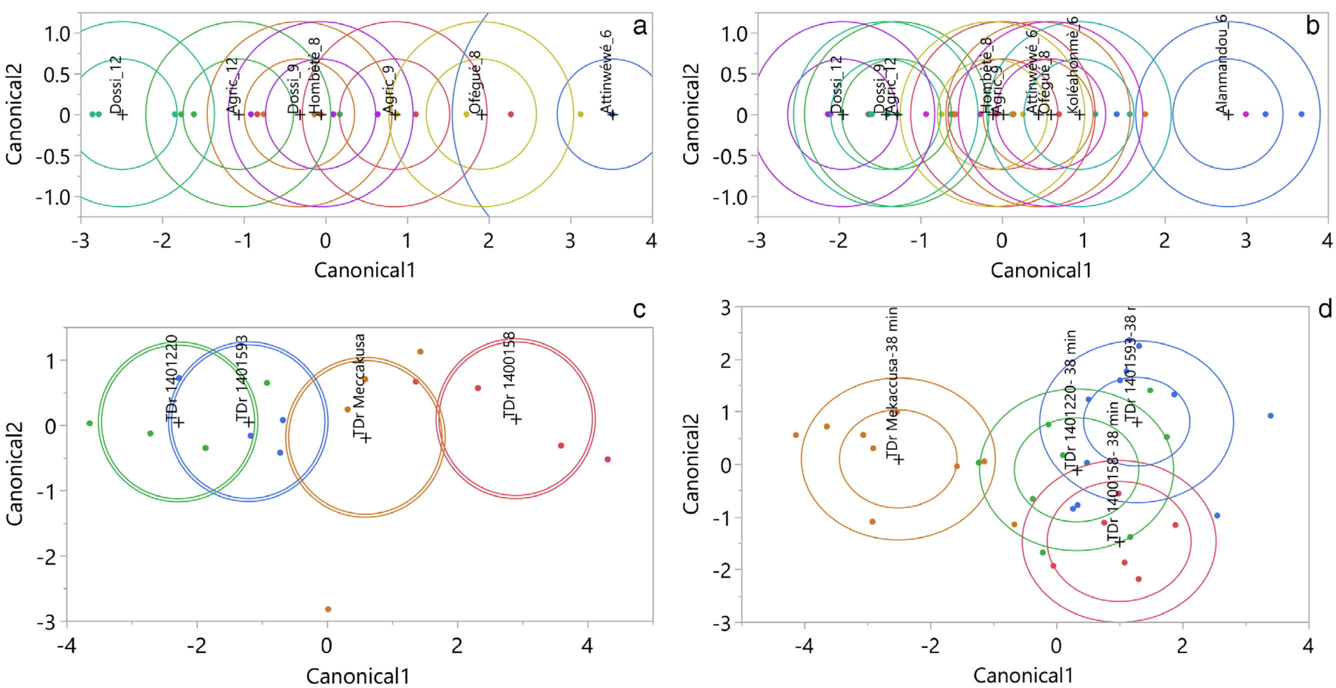

Figure 2. Example of canonical analysis showing discrimination between hardness texture of boiled cassava from nine yam genotypes by penetration and TPA (a,b, respectively), and between texture parameters of boiled yam from four yam genotypes by extrusion and TPA (c,d, respectively).

that TPA parameters should not be correlated simply with conventional sensory evaluations. This is arguable as other reservations on these opinions on TPA parameters have been raised.[37]

Products that have been produced from processes that involve reconstitution (pounding, stirring, milling) improve the homogeneity of the food matrix in such a way that texture is almost representative throughout the whole bulk of the food. Such pasty products (e.g., *eba*, *fufu*, pounded yam) are amenable to texture protocols such as TPA, extrusion, extensibility and lubricated squeezing flow (LSF).[2,3,28,29] TPA and extrusion protocols are repeatable and adequately discriminate between genotypes, including species-related textural differences, particularly in the case of pounded yam.

Penetration cannot be satisfactorily used for pasty products because they have a homogeneous matrix that is not local-specific, while penetration probes are designed for point-texture sensitivity. Some RTB products such as pounded yam, *fufu* and *eba* have unique traits – for example, extensibility – that cannot be measured either by TPA or penetration but by extension protocols such as uniaxial extensibility, biaxial extension or Kieffer dough gluten extension (KDGE).[27] Pounded yam texture measured by standard methods[28,29] revealed that biaxial extension and uniaxial extensibility protocols both discriminated yam genotypes well (Fig. 3(a, b)). Uniaxial extensibility protocol was only marginally more discriminant than the LSF protocol. On the other hand, uniaxial extensibility was a more discriminant protocol than LSF when *fufu* extension textural parameters were measured (Fig. 3(c,d)) by adapted standard methods.[28,29] In the literature,[38] wheat flour doughs were accurately discriminated into weak, intermediate and strong dough by uniaxial extension, where maximum resistance to extension was the most discriminant textural parameter.

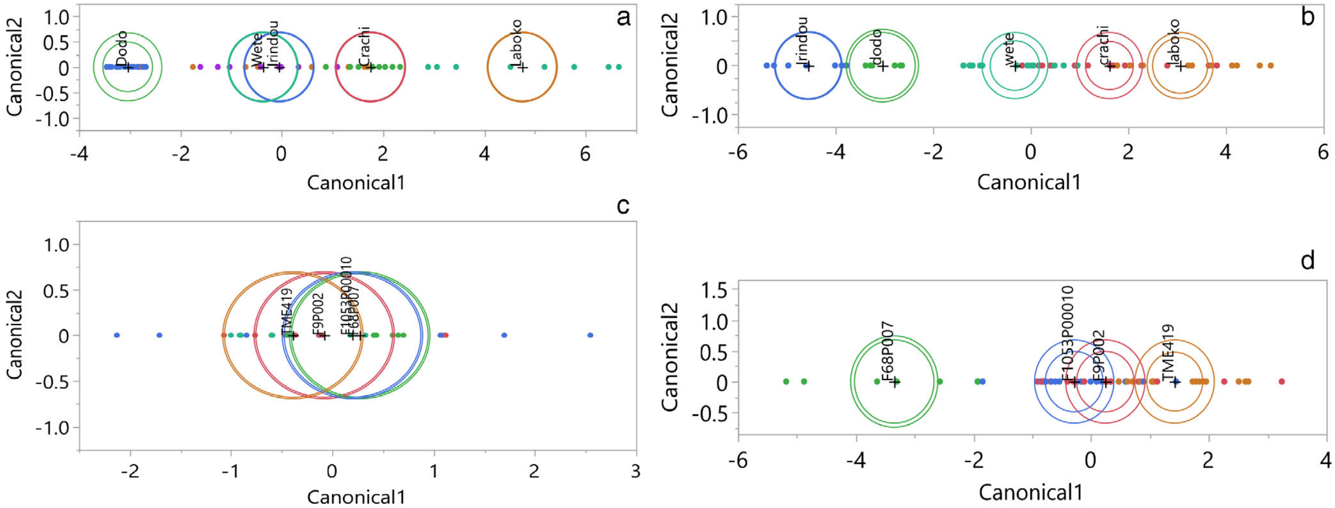

Figure 3. Example of canonical analysis showing discrimination between extensibility texture parameters for pounded yam made from five yam genotypes (a,b), and for *fufu* made from four cassava genotypes (c,d) measured by biaxial extension (LSF, a,c) and uniaxial extensibility (b,d).

Fried RTB food products have unique mealy/friable texture with chewable or crunchy/fracturing components to which extrusion and TPA are better suited. The geometry of samples is relevant in deciding appropriate texture protocols. For instance, the texture of fried plantains (*aloco*) of diminutive size (10 mm × 10 mm) may be measured by penetration using wide-angle conical probes that do not lift the sample from the test platform or by TPA. For other fried products such as French fries, research conducted on the texture of samples from various potato varieties, the puncture, Warner–Bratzler guillotine cut and compression tests were found to be more accurate, discriminant and more correlated with sensory texture than three-point bend and Volodkevich jaw bite tests.[13]

The texture of *attiéké*, a granular product from cassava, may not be accurately measured by the protocols hitherto mentioned due to the loose granular nature, but may be measured through the Kramer shear cell system.

CASE STUDIES ON INSTRUMENTAL AND SENSORY TEXTURE ATTRIBUTES OF RTB

Many instrumental textural attributes of RTBs were analysed in order to streamline the key textural parameters preferred by consumers relevant to each product profile that are essential to breeding programmes. As previously noted, these products may be classified as pasty/doughy, steamed/boiled, fried or granular. Some of these textural ramifications are discussed below and in Tables 1 and 2.

Steamed/boiled products

Boiled cassava

A study carried out on steamed cassava reported significant differences in texture among cassava genotypes for all the instrumental texture attributes measured by TPA, penetration and extrusion,[35] though genotypes were better discriminated by TPA and penetration. Similar discrimination was reported for boiled cassava texture from landraces and hybrids.[39] TPA and extrusion hardness were not significantly different, but both were different compared to penetration hardness. Correlations showed that penetration hardness was significantly related to TPA hardness and extrusion hardness. Penetration–area under the curve was also significantly related to extrusion–area under the curve.

Other studies evaluated texture of different cassava genotypes that were boiled using an SOP for extrusion texture.[26] The genotypes were discriminated by texture. Relating them to their cooking quality, the PCA clustered the genotypes according to fast, slow and intermediate cooking genotypes and also classified the extrusion texture into two groups: those associated with mealiness (Endforce:Maxforce, Distance at Maxforce) which were discriminant by maturity, and those associated with hardness (Endforce, Maxforce, Linear distance, Area under the curve, Gradient), which were discriminant by harvest period.

Instrumental and sensory texture of different varieties (landraces and improved clones) of sweet and bitter cassava harvested over three harvest regimes (10, 12 and 14 months after planting) were assessed for texture by puncture test (firmness) and sensory evaluation (friability) after boiling for 45 min. Results classified boiled roots into cohesive, very cohesive, friable and very friable clusters.[10] The landraces had better friable texture than the improved clones, explaining the better adoption/preference of the landraces for boiled cassava consumption. Firmness varied significantly across the different parts of the cassava root, was not influenced by maturity at harvest, was very discriminant between the varieties, correlated significantly with sensory friability and may be used to estimate the friability of boiled cassava.

Boiled yam

Boiled yam texture was measured by TPA compression and penetration following an SOP.[6] The TPA protocol was repeatable but the penetration method was not. The most discriminating TPA attributes, from highest to lowest, were hardness, adhesiveness, chewiness and cohesiveness. Both hardness and area under the curve (penetration attributes) were equally discriminant. The PCA of the first two components revealed differences in the way genotypes were clustered by the two protocols. Highly significant correlations were found between TPA hardness and penetration hardness and between TPA hardness and penetration–area under the curve. TPA chewiness was also significantly related to penetration hardness and area under the curve. However, using an extrusion protocol for boiled white yam texture characterization,[40] it

Table 1. Texture protocols, key textural attributes, discriminant attributes and significant relationships between texture attributes of RTB foods steamed/boiled and fried product profiles

RTB food product	Texture method	Repeatability	Discriminant	Discriminant instrumental texture attributes	Key sensory texture traits	Key significant correlations between textural attributes	References
Boiled cassava	TPA	ND	Yes	Ha, area under curve	Ease of chew, Mealiness	TPA hardness & Penetration hardness & Extrusion hardness	32,35
	Penetration	ND	Yes	Ha	Ease of chew, Mealiness	Penetration area under curve & Extrusion area under curve	32,35
	Extrusion	ND	Yes	Slope of curve/gradient	Ease of chew, Mealiness	Extrusion area under curve & Penetration area under curve	32,35
	Extrusion	ND	Yes	Gradient	Hardness, Mealiness, Stickiness	Endforce:Maxforce & Mealiness	26,32
	TPA and Penetration	ND	Yes		—	—	39
	Puncture (firmness)	ND	Yes	Firmness	Friability	Firmness & Friability	10
Boiled plantain and dessert banana	Craft knife 40° Cone Cylindrical borer	ND	Yes	Firmness	—	—	22
	TPA	Yes	Yes	Ha, Gu, Re, Che	Firmness, Che	Resilience & Firmness, Resilience & Wetness, Hardness & Wetness, Gumminess & Wetness, Springiness & Firmness	6,12
	Penetration	Yes	Yes	Ha, area under curve	Firmness, Che	No correlations	5,32
	TPA	ND	Yes	Sp, Co	ND	TPA (Hardness, Gumminess, Chewiness) & Penetration (Maxforce, Meanforce, Area under curve)	34
	Penetration	ND	Yes	Maxforce, Meanforce	ND	TPA (Hardness, Gumminess, Chewiness) & Penetration (Maxforce, Meanforce, Area under curve)	34
Boiled yam	TPA	ND	Yes	Ha, Gu and Ch	Friability, Che	TPA hardness & Penetration hardness	6,32
	Penetration	ND	Yes	Maxforce	Friability, Che	TPA chewiness & Penetration area under curve	6,32
	TPA	Yes	Yes	Ha, Ad, Che, Co	Friability, Che	TPA hardness, Chewiness & Penetration hardness, Area under curve	6,32
	Penetration	No	Yes	Ha, area under curve	Friability, Che	Penetration hardness, Area under curve & TPA hardness, Chewiness. Hard to break & Hardness & Area under curve	6,32
	Extrusion	Yes	Yes	Ha	Ha, Che	Hardness & Work done to extrude	32,40
Boiled potato	Penetration	No for 20 min Yes for 40 min	Yes (20 min)	Ha	Firmness, Mealiness	ND	32
	Uniaxial Compression TPA	ND	Yes	Deformation modulus Stress Strain	Mealiness	Deformation modulus, stress and strain & Mealiness	23

Table 1. Continued

RTB food product	Texture method	Repeatability	Discriminant	Discriminant instrumental texture attributes	Key sensory texture traits	Key significant correlations between textural attributes	References
Boiled sweet potato	TPA and penetration	Yes	Yes	Ha	Firmness, Mealiness	ND	10,11,25
Fried Sweet potato	Penetration	Yes	Yes	Ha, area under curve	Crispiness, Crunchiness, Mealiness	Peak force & Sensory hardness Area under curve & Sensory hardness, Crunchiness & Mealiness	55

Chewiness: Che – the mechanical textural attribute related to the amount of work required to masticate a solid product into a state ready for swallowing.
Springiness: Sp – the degree to which food can recover between the end of the first bite and the beginning of the second in the mouth.
Cohesiveness: Co – the work required to overcome the internal bonds of a material.
Resilience: Re –the mechanical textural attribute relating to the rapidity of recovery from a deforming force.
Hardness: Ha – the maximum force required to deform a sample.
Friability/Mealiness/Crunchiness/Crispiness: the sensory textural attribute related to cohesiveness, and to the force necessary to break or disintegrate a food product into crumbs or pieces.
Gumminess: Gu – the mechanical textural attribute related to the cohesiveness of a tender product.
Adhesiveness: Ad – the work required in overcoming the attractive force between a product and the contact surface.
Stickiness: the textural sensory attribute associated with the extent of attraction perceived between the food product and the fingers/palms of the hand.
Firmness: Fi –the textural sensory attribute representing how stiff, tough or hard a food product is before breaking.
Wetness –the textural sensory attribute representing how moist a food product is.
ND: not determined.

was found that extrusion protocol was more repeatable and discriminant compared to TPA. The extrusion hardness was a more discriminant attribute than work done by extrusion (area under the curve). PCA, discriminant and hierarchical analyses supported these outcomes and the superior performance of extrusion over TPA. Significant correlations were found between extrusion hardness and sensory hardness and sensory chewiness.

In another study using the SOP,[6] 48 different yam genotypes were boiled and the texture was determined by TPA and penetration. The genotype, yam section (proximal, central, distal) and cube selected for measurements significantly influenced the penetration texture attributes (Maxforce and Total area under the curve), but there were no differences among tubers from the same genotype. Similarly, the genotype contributed significantly to differences in TPA texture attributes, but tuber and cube selected generally had no significant effect. TPA had a higher significant difference (*P*-value) in hardness between the genotypes than the penetration Maxforce. The most discriminating TPA attributes were hardness, gumminess and chewiness, while Maxforce was discriminating for penetration. TPA *versus* penetration hardness and Total area under the curve *versus* chewiness were significantly correlated.

Boiled plantain

Fifteen edible plantain varieties (categorized to include dessert bananas, banana hybrids, plantain landraces, cooking banana hybrids and cooking banana landraces) were analysed for boiled textural characteristics (firmness, compression work, linear distance) by three textural methods/probes (craft knife, 40° edge plastic conical, cylindrical borer). The 40° conical test was the more accurate and discriminant protocol among the varieties.[41] Firmness was judged to be the easiest criterion to discriminate among varieties, as plantain landraces seem to be more firm than other genotypes, while cooking bananas were softer.

The texture of boiled plantains from hybrids and landraces collected from three different locations was measured by TPA and penetration using an SOP.[5] The TPA and penetration tests produced accurate, repeatable measurements. The genotypes were significantly different from one another. Both methods discriminated genotypes, especially the penetration protocol. For TPA, hardness, gumminess, resilience and chewiness were the more discriminatory attributes, while for penetration, hardness and area under the curve were the most useful. The only significantly correlated attributes between both methods were penetration hardness *versus* TPA chewiness. Only TPA attributes (resilience, hardness, springiness, gumminess, chewiness) correlated significantly with sensory wetness and firmness but no correlations for penetration attributes and sensory wetness and firmness were found.

Another work[34] measured texture by TPA and penetration for boiled plantain and dessert banana made from 16 genotypes harvested and ripened to mature green, half-ripe and fully ripe stages. It was deduced that TPA springiness and cohesiveness were the most discriminant TPA attributes. Ripening stage had the most significant influence on the TPA and penetration attributes, while the measurement temperatures (50 and 60 °C) had no significant influence on TPA attributes but influenced penetration. PCA and discriminant analysis showed that the ripening stages clustered separately in different components. It was also found that penetration discriminated the genotypes by texture better than TPA, but TPA was better at discerning among ripening stages than penetration. There were significant correlations

Table 2. Texture protocols, key textural attributes, discriminant attributes and significant relationships between texture attributes of RTB foods pasty/doughy product profiles

RTB food product	Method	Repeatability	Discriminant	Discriminant instrumental texture attributes	Key sensory texture traits	Significant correlations between textural attributes	References
Eba	TPA	Yes	Yes	Che, Sp, Co, Ha	Ha, St, Mo, Sm	ND	3,32
	TPA	ND	Yes	Ha, Ad, Mo, Gu	—	—	46
	TPA	Yes	Yes	Re, Ha, Gu, Co	Ha, St, Mo, Sm	TPA Ha & Sensory Ha TPA Co & Sensory Mo	3,32
Fufu	Fruit pressure tester	ND	Yes	Firmness	—	—	47
	TPA	ND	Yes	Ha, Gu, Co	—	—	48
	TPA	Yes	Yes	Ha, Gu, Co	St, Mo, Sm, Ha	ND	2,32
	TPA	Yes	Yes	Re, Ha, Gu, Co	St, Mo, Sm, Ha	TPA Co & Sensory Sm TPA Co & Sensory Mo TPA Co & Sensory St	2,32
Pounded yam	Compression adhesion	ND	Yes	Firmness, adhesion	—	—	49
	TPA	ND	Yes	Ha, Sp, Co, Gu, Ad	—	—	50
	Extrusion	ND	Yes	Extrusion force and Area under curve	—	—	51
	TPA	ND	Yes	Ha, Co, Sp, Mo	—	—	54
	Back extrusion	ND	Yes	Co, Fi, Ad	—	—	53
	TPA	Yes	Yes	Ha, Sp, Co, Gu, Ad	St, Mo, Sm, Ha	ND	32,54
	TPA	Yes	Yes	Gu, Ha, Ad	St, Mo, Sm, Ha	Ch, Gu, Co *vs.* Mo & St	32,54
	Extensibility	Yes	Yes	Ex, Area under curve	St	Ha & Ex, Ha & Consumer likeability	28
	Extensional viscosity	Yes	Yes	BEV	St	BEV & Consumer likeability BEC & Area under curve	29
Matooke	TPA	ND	Yes	Ha	Fi, Sm	TPA Ha & Sensory Ha, St, TPA Ad & S Sm, Mo	1,32
	TPA	Yes	Yes	Ha, Ad	Fi, Sm	ND	1,32
	Penetration	Yes	Yes	Ha	Fi, Sm	ND	32

Chewiness: Che – the mechanical textural attribute related to the amount of work required to masticate a solid product into a state ready for swallowing.
Springiness: Sp – the degree to which food can recover between the end of the first bite and the beginning of the second in the mouth.
Cohesiveness: Co – the work required to overcome the internal bonds of a material.
Hardness: Ha – the maximum force required to deform a sample.
Adhesiveness: Ad – the work required in overcoming the attractive force between a product and the contact surface.
Gumminess: Gu – the mechanical textural attribute related to the cohesiveness of a tender product.
Resilience: Re –the mechanical textural attribute relating to the rapidity of recovery from a deforming force.
Firmness: Fi –the textural sensory attribute representing how stiff, tough or hard a food product is before breaking.
Extensibility: Ex – represents the extent of displacement the test food product can sustain before structural failure.
Bi-extensional viscosity: BEV– the viscosity of the food product derived from calculation of force–displacement extension curves into stress–strain data, taking cognizance of geometry of the sample.
Mouldability: Mo – the sensory attribute representing the ability for a food product to be rolled into a compact ball mass between the finger or palm of the hands.
Stretchability: St – the sensory attribute representing the extent of displacement when tension is applied to a food product before it breaks when pulled apart between the fingers.
Smoothness: Sm – the sensory attribute evaluating the perception of the ability of a food product not to stick and to form a homogeneous mass between the finger or palm of the hands.
ND: not determined.

between TPA hardness, gumminess and chewiness and all the penetration texture attributes.

Boiled potato

Research was conducted on the texture of potato cylinders (12 mm diameter, 10 mm height) obtained from seven varieties cooked for 20–25 min and analysed by uniaxial compression and TPA.[42] Uniaxial compression was more discriminant among genotypes and harvest regimes than TPA and accurately described the sensory texture of boiled potato (especially by discriminant textural parameters such as deformation modulus, stress and strain at fracture, with good assessment of boiled potato mealiness).

Eighteen potato genotypes were steamed for 20 min or 40 min and analysed for texture by penetration (Nakitto *et al.* 2022, unpublished data). The genotypes were better discriminated at 20 min steaming than at 40 min steaming, but steaming at 40 min produced better repeatability of hardness and work done to penetrate. The most discriminant attribute at 20 min steaming was peak force (hardness). The PCA clustering was different for the two steaming times, suggesting that the longer steaming may have further altered the texture of potato. The tuber number and tuber piece from which analysed samples were obtained had no significant effects on textural attributes of genotypes. Significant correlations were found between instrumental parameters (peak force, area under curve) and sensory fracturability and hardness.

Four New Zealand potato cultivars whose texture was analysed by TPA in the raw and cooked form also had significantly discriminant disposition.[43] In the uncooked form, hardness was the most discerning textural attribute, while springiness was the least. Cooking reduced discriminability (e.g., larger differences were required to reach statistical significance).

Boiled sweet potato

Two sweet potato genotypes were boiled and the hardness was measured by TPA and penetration.[33] Two methods of preparation were explored. The *kitchen* method mimics the traditional method of boiling sweet potato in Uganda by halving 70 mm long pieces of roots and cooking for 50 min. The *strict* method involves preparing regular sizes of sweet potato and steaming for 25 min. The boiled sweet potatoes prepared by both methods were not significantly different in hardness (both protocols were equally discriminant), and the cooking replicates were repeatable. TPA hardness was significantly higher than penetration hardness. Discriminant analysis also showed that the genotypes and measurement methods were more important than the preparation method.

A revised SOP[4] using TPA was considered for instrumental texture of boiled sweet potato from 14 genotypes. Good repeatability between measurements and discrimination between the genotypes were observed, with the most discerning textural parameters being hardness and cohesiveness. The PCA grouped one genotype as associated with gumminess, chewiness and hardness; other genotypes as associated with springiness and cohesiveness; and a third group of genotypes as associated with adhesive and resilient nature.

In another work,[44] five sweet potato varieties were analysed by uniaxial compression and wedge fracture tests to determine their texture parameters such as hardness (peak positive force) and toughness (deformation work done). The wedge fracture test was considered valid at discriminating genotypes of the boiled sweet potato varieties, while the uniaxial compression test did not discriminate among the genotypes. Texture data from the wedge fracture test correlated with cooking time with significantly higher coefficients than uniaxial compression test. Another study showed significantly different TPA, penetration and uniaxial compression textural parameters of boiled sweet potato from different varieties.[11]

Pasty/doughy products

Eba

Although few studies assessing the texture of *eba* have been published,[45,46] TPA was used for determining its textural quality, showing that this technique was able to discriminate samples in terms of hardness, adhesiveness, mouldability and gumminess, but not for stretchability. Moreover, no correlation between sensory and instrumental texture was observed.

An SOP was first developed to characterize the instrumental texture of *eba* made from four genotypes of cassava by TPA.[3] The protocol had good accuracy, repeatability and discriminability. The most discerning attributes were chewiness, springiness, cohesiveness and hardness. The SOP was further used to analyse the instrumental texture of *eba* from different cassava genotypes, while sensory texture was evaluated by trained panellists. The most discriminating attributes are resilience, hardness, gumminess and cohesiveness, in that order. PCA of combined instrument and sensory texture revealed that instrumental hardness, sensory hardness and sensory mouldability were closely related in a component space. Instrumental adhesiveness, cohesiveness and resilience were also closely associated with sensory adhesiveness within another component space. Stretchability was poorly associated with any instrumental texture attribute and requires an alternative protocol, such as lubricated squeezing flow, to establish a relationship with extensional properties.

Fufu

Fufu texture was evaluated with a fruit pressure tester.[47] The tester was used to penetrate the *fufu* in the container and readings indicating softness or hardness were recorded to. Recently, *fufu* texture was analysed through TPA for six different *fufu* samples.[48] An SOP to characterize the instrumental texture of *fufu* made from four cassava genotypes was developed and proved to be accurate, repeatable and discriminant among the genotypes.[2] In particular, the attributes hardness, resilience, gumminess and cohesiveness were the most discriminating. PCA, hierarchical and discriminant analysis clearly clustered the genotypes in similar groups.

Pounded yam

Several techniques have been used in the literature to assess the textural behaviour of pounded yam. Firmness of pounded yam was determined by sample compression, while the adhesion was determined by compressing/decompressing cycles.[49] Otegbayo *et al.*[50] first assessed the textural properties of pounded yam using TPA. They were able to differentiate among samples of the same species (*Dioscorea rotundata* or *D. alata*) and relate them to sensory evaluation. Later, Akissoe *et al.*[51] determined firmness of pounded yam by extrusion, showing that extrusion force (N mm^{-2}) and area under the curve (N mm) were significantly different among samples, while maximum force (N) parameter failed to discriminate. Analysis of textural properties of *D. alata* samples by TPA demonstrated significant differences for hardness, cohesiveness, springiness and mouldability.[52] More recently, consistency, firmness, cohesiveness and adhesiveness of pounded yam were successfully demonstrated using the back extrusion technique.[53]

Other studies analysed pounded yam from four genotypes by TPA.[54] The TPA texture attributes showed good repeatability, and all the genotypes were significantly different from one another. The significance level was more significant for genotypes, followed by genotype × replicate, and replicates effect. The discriminant attributes were hardness, followed by springiness, gumminess, cohesiveness, adhesiveness, chewiness and stickiness. PCA clustered genotypes together in the same component as the attributes cohesiveness, springiness, chewiness and gumminess, while other genotypes were associated with adhesiveness and another one was associated with hardness.

Stretchability is a very key attribute among the sensory attributes preferred by consumers of pounded yam[8] and it cannot be directly measured by TPA, penetrometry or extrusion. Therefore, other instrumental texture protocols have been developed to describe stretchability by extensional texture attributes. Tubers from different genotypes were pounded, and two instrumental protocols (uniaxial extensibility and lubricated squeeze flow) were developed to measure extensibility of the pounded yam.[28,29] It was found that the protocols were accurate, repeatable and discriminant between the yam genotypes. Some genotypes were closely related to hardness, extensibility, extensional viscosity and consumer likeability. Significant relationships were found between extensibility texture attributes, extensional viscosity and consumer likeability. Sensory stretchability also correlated significantly with the area under the curve.[28]

Matooke

Several genotypes of the traditional East African highland banana, *matooke*, produced by steaming and pressing to a pulpy consistency, were analysed by TPA.[1] Although genotypes were significantly different for hardness, the traits' cohesiveness and adhesiveness were not significantly different among genotypes. Thus, the only discriminant attribute was hardness. Significant correlations were found between TPA hardness and sensory hardness, moistness and stickiness; and among TPA adhesiveness, sensory smoothness and mouldability. PCA associated some genotypes with hardness, while others were associated with cohesiveness. Furthermore, because *matooke* may be steamed with or without peeling, the texture of pulp+peel and peeled pulp were tested by penetration, and the texture of steamed pulp was determined by TPA. The penetration protocol was repeatable, and the pulp+peel penetration force was significantly higher than the peeled pulp penetration force. Both measurements were significantly influenced by the genotypes. The penetration forces were very discriminant, while hardness and adhesiveness were the most discriminant attributes from the TPA protocol.

Fried products

There are very few reports on fried RTB food products in the literature detailing a range of RTB genotypes, instrumental textural protocols, relationships with sensory texture and discriminant ability of the protocols.

Fried sweet potato

The texture of fried sweet potato from different genotypes was determined by penetration, and sensory texture was analysed (Nakitto *et al*., 2022, unpublished data). Significant genotype differences were found for the peak force (hardness) and area under the curve (work done to penetrate). Both textural attributes equally discriminated different genotypes. There was moderate repeatability among replicate samples. PCA showed some genotypes associated with instrumental and sensory hardness, while others were associated with sensory crunchiness and mealiness. There were significant correlations between peak force, area under the curve and sensory hardness of fried sweet potato. Crunchiness and mealiness were significantly related, in agreement with another report.[55] The hierarchy classes of the genotypes clustered into classes of good, intermediate and poor for fried sweet potato.

Fried potato

A study was conducted on instrumental and sensory texture of French fries from contrasting potato varieties using five measurement protocols[13]: puncture test, three-point bending test, Warner–Bratzler guillotine cut test, Volodkevich jaw bite test and double-compression tests. The puncture, Warner–Bratzler guillotine cut and double compression tests were found to be more accurate and discriminant and correlated better with sensory texture than the three-point bend and Volodkevich jaw bite tests. Chewiness was the most discriminant parameter for the double compression test. PCA of instrumental and sensory texture grouped the French fries samples into three clusters. The first cluster group was rough and fracturable; the second group was mealy and adhesive; and third cluster was tough, firm, chewy, crisp, resilient and springy.

In summary, the texture of the various products could be analysed by unique or a range of instrumental protocols that can provide information on the suitability of the protocol vis-à-vis reproducibility of measurements, discriminability and relatability with sensory assessment and consumer preferences.

GLOBAL OUTLOOK ON RTB FOOD PRODUCT TEXTURE: HARDNESS AS AN EXEMPLARY ATTRIBUTE

To categorize the global RTB food product instrumental texture data, discriminant and partitioning analyses were carried out considering the hardness attribute as *response*, while product profile, crop and texture protocol were regarded as *categories*. Hardness was selected because all the textural protocols measure hardness/Maxforce; it is a common key discriminant attribute for RTB food products and it correlates with most sensory attributes. Partitioning was conducted on 675 hardness values across the categories until the optimum number of splits that produced the highest explained variation (R^2) was reached.

Discriminant analysis showed that hardness of boiled cassava is discriminant from other food products. Hardness of boiled yam, boiled plantain and pounded yam are closely related, but are also slightly discriminant from boiled sweet potato (Fig. 4). On the other hand, the hardness of *fufu*, *eba*, *matooke*, fried sweet potato and boiled potato are not discriminant. With regard to the textural protocols, the extrusion protocol records very discriminant hardness values compared to hardness of other protocols (TPA, penetration and extensibility) (Fig. 5), probably due to the higher load resistance to deformation caused by the extruder blade. Based on the RTB crops considered, cassava seems quite discriminant in hardness from other crops (Fig. 6). Yam and plantain are closely related in hardness, just as potato, sweet potato and banana are also closely related in hardness.

The result of partitioning (Supporting Information Fig. 1) shows that the hardness recorded by extensibility, TPA and penetration

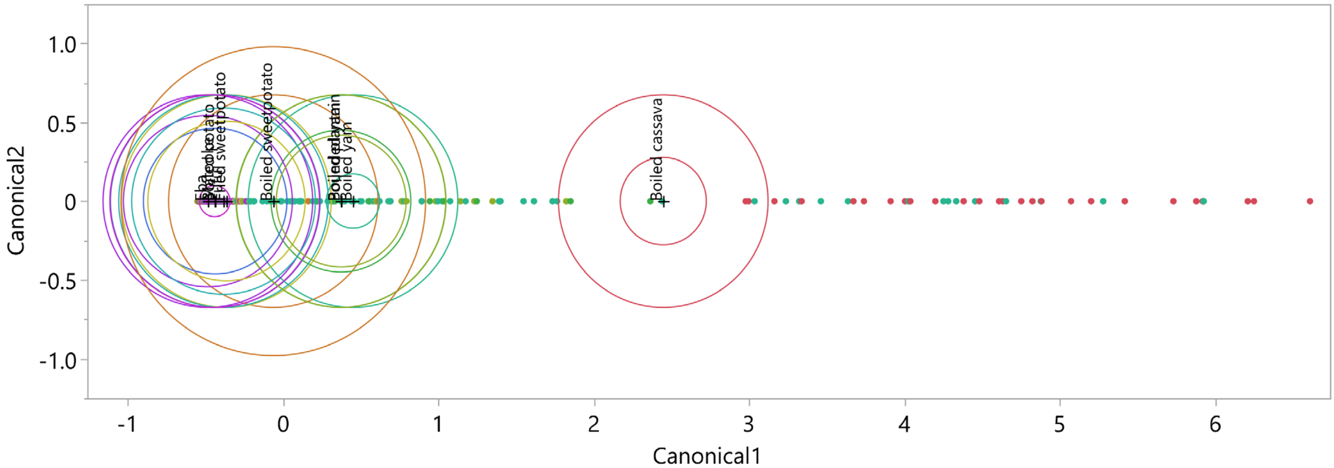

Figure 4. Discriminant analysis of hardness texture of RTBs by food product type.

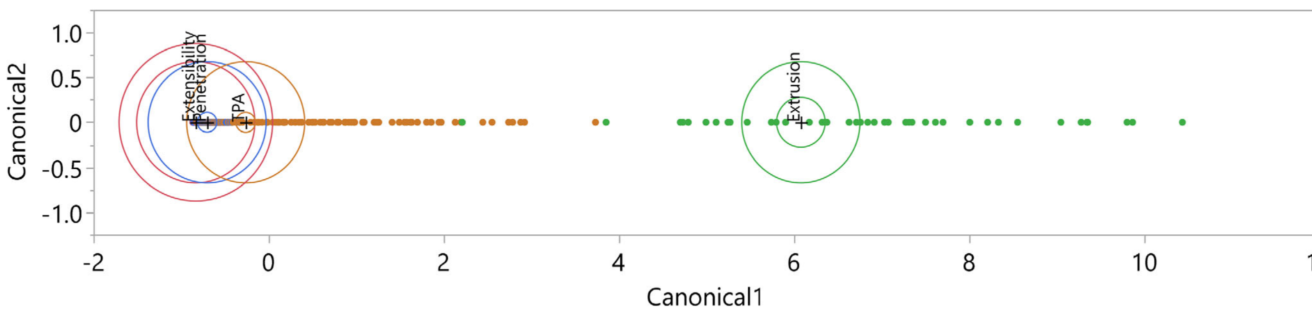

Figure 5. Discriminant analysis of hardness texture of RTBs by textural protocol.

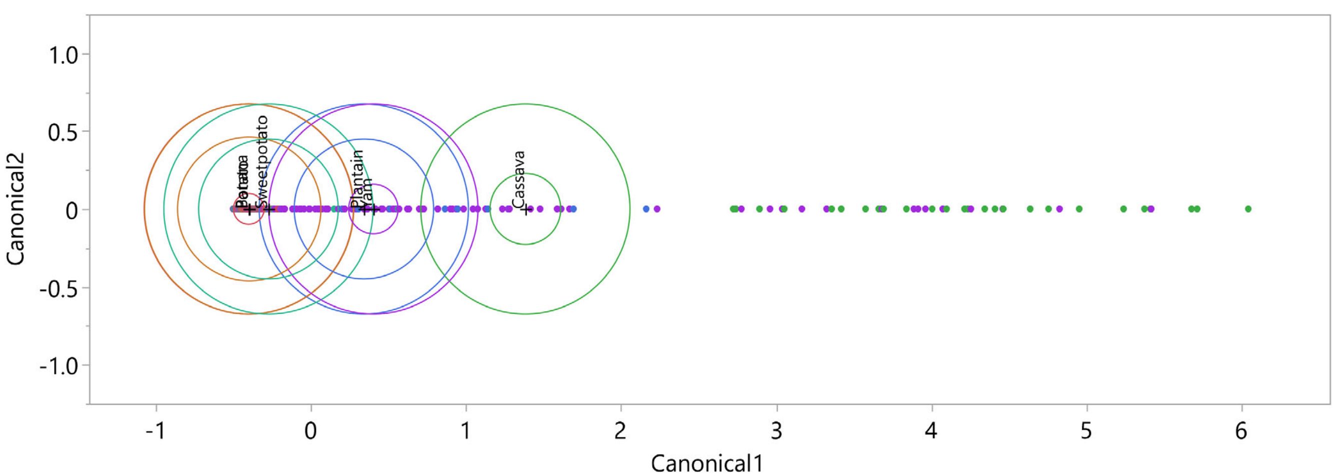

Figure 6. Discriminant analysis of hardness texture of RTBs by crop.

protocols is partitioned separately from that of the extrusion protocol due to the hardness of cassava product. Further split of the partition showed that the food products *eba*, *matooke, fufu*, boiled potato and fried sweet potato clustered together, similar to the discriminant pattern, and ascribed to the hardness measured by penetration protocol, while boiled sweet potato, boiled yam, boiled plantain and pounded yam were also clustered together. The explained variation ($R^2 = 0.80$) was optimal at three splits.

In conclusion, it is important to develop standardized protocols that can be used by breeders and food scientists as mid-throughput tools to study the diversity of texture of RTB genotypes. This should provide means of identifying which genotypes are associated with key discriminant textural attributes and which textural protocols will enhance rapid discrimination of the genotypes that will lead to development of breeds that are preferred by consumers.

There is no doubt that encouraging the inclusion of texture as inheritable traits into breeding pipelines for RTB programs will play a significant role in improving adoption of new breeds that will be appreciated by consumers.

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Conceptualization: AO, AS, MC, DD.

Data curation: AO, AS, MC, KA, AL, AM, EA, DLF, TA, OO, KVC, NM, KE, AEO.

Formal analysis: AO, AS, MC.

Investigation: AO, AS, KA, AL, AM, EA, DLF, TA, OO, KVC, NM, KE.

Methodology: AO, AS.

Supervision: CU, NK, NNG, OB, AN, LM, TT, AEO, MDB, MC, DD.

Validation: CU, NK, NNG, OB, AN, LM, TT, AEO, MDB, MC, DD.

Visualization: AO, AS.

Writing – original draft: AO, AS.

Writing reviewing and editing: MC, DD, TT.

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The authors declare no conflict of interests.

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The data that support the findings will be available in CIRAD Dataverse at https://dataverse.cirad.fr/dataverse/CIRAD?q=&types=datasets&sort=dateSort&order=desc&page=1 following an embargo from the date of publication to allow for commercialization of research findings.

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

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