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Root, Tuber, and Banana Textural Traits
A Review of the Available Food Science and Consumer Preferences Literature

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Purpose

This document provides a review of the literature on textural attributes of root, tuber, and banana (RTB) crops with a focus on studies relevant for RTB crop research and development in Sub Saharan Africa (SSA). It includes texture-related consumer preferences studies for the RTB crops tropical yam, sweetpotato, banana/plantain, cassava, and potato, as well as the results of physicochemical and genetic studies (where available) detailing the current scientific understanding of drivers of textural traits. The document is organized by crop and is intended for use as a reference.

Introduction

Otoo & Asiedu (2009) argue that "sensory evaluation is not only the most important hurdle after all the necessary agronomic characteristics have been developed but also a major determinant of acceptability of the variety, as well as a major determinant in the subsequent adoption and use of the variety." Organoleptic (sensory) features of food include color, odor, flavor and texture. In addition to the importance of such attributes for consumer acceptance of new food

products, there is also substantial evidence that organoleptic attributes are associated with the secretion of gastric juices, which may increase the digestibility of foods, when the response to the food attributes is positive (Lisinska, 1989). Human perception of organoleptic attributes derives from a combination of food chemical properties and food structural properties (Bart, 2006).

Food scientists define texture as "the sensory and functional manifestation of the structural, mechanical and surface properties of foods detected through the senses of vision, hearing, touch and kinaesthetic" (Civille & Ofteda, 2012; Szczesniak, 2002). For fresh foods including fruit and vegetables, textural properties such as firmness are widely used as indices of readiness to harvest (maturity) to meet requirements for long term handling, storage and acceptability by the consumer. For processed foods, understanding textural properties allows for the control of operations such as heating, frying and drying to attain desired quality attributes of the end product (Chen & Opara 2013a).

In practice, relative to other common crop attributes such as yield, disease resistance, and food color and shape, food texture is difficult to measure and define (Chen & Opara, 2013b; Wilkinson, Dijksterhuis, & Minekus, 2001) and the links between consumer acceptability and crop characteristics are often complicated to establish. Though genetic make-up is thought to be the primary determinant of food texture, the relationship between a crop variety and its textural attributes can be very complex, depending not only on genetic factors and the passage of time (e.g., ripening), but also on environmental factors such as sun exposure, temperature, soil moisture, and climate trends during the growing season (Sams, 1999), and on postharvest handling and operating conditions such as storage temperature (Farag, Lyng, Morgan, et al., 2009; Konopacka & Plocharski, 2004; Lana, Tijskens, & van Kooten, 2005).

The texture of cooked root and tuber (RTB) crops is often cited as a primary determinant of consumer acceptability of new varieties, including those produced through traditional breeding and through genetic engineering. Yet to date, breeders have had limited information on the biochemistry and genetics of RTB crops needed to produce higher-yielding varieties that also have consumer-preferred textural characteristics. Breeding for well-defined traits such as yield, disease resistance, root/tuber shape, and nutrient content relies on more-or-less accepted quantitative metrics and (often) on well-understood genetic processes, and thus such breeding efforts can be practiced in a relatively cost-effective manner with results observed in early breeding generations. However, breeding for poorly-understood traits that require a subjective taste panel is expensive, subject to high variance, and requires a lengthier breeding process (to reduce numbers of selected lines for taste and sensory evaluation), greatly delaying the development and release of new varieties (Van Oirschot, Rees & Aked, 2003). If breeders had lab assays for texture-associated traits, whether biochemical, biophysical, or genetic, the expectation is that they could more quickly and effectively develop new varieties with desired characteristics including consistent or improved palatability for consumers.

Table 1 summarizes the availability of information on texture-related traits of RTB crops as determined by our review of the published literature to date supplemented by expert consultations. A small number of studies refer to consumer preferences for "texture" more generally – where possible these studies have been classified according to more specific textural attributes.

Table 1: Summary of Available Evidence on Textural Attributes of RTB Crops in Sub-Saharan Africa[1]

Trait	Yam	Sweetpotato	Banana/Plantain	Cassava	Potato
Hardness	✓	?	✓	?	-
Cohesiveness					
- ***Brittleness***	NA	NA	NA	NA	NA
- ***Chewiness***	NA	?	NA	NA	NA
- ***Mealiness***	✓	NA	NA	✓	✓
Viscosity	-	NA	-	✓	NA
Springiness	✓	NA	NA	NA	NA
Adhesiveness	✓	✓	NA	?	✓
Smoothness	NA	?	NA	?	✓
Particle Size	?	✓	NA	NA	✓
Particle Shape	NA	✓	NA	NA	-
Moisture Content	NA	✓	NA	NA	?
Fat Content	NA	NA	NA	NA	NA

Classification and Measurement of Textural Traits

[1] Symbols denote: At least one physicochemical or genetic driver known, important for consumer preference (✓); Drivers unknown but important for consumer preference (?); Drivers unknown, importance to consumer preference unknown (NA); and At least one driver known, importance to consumer preference unknown (-).

Food scientists consider the measurement of textural traits difficult due to the individual and complex nature of textural perception (Chen & Opara, 2013b; Wilkinson et al., 2001). The perception of texture is a dynamic process and composed of feedback from several senses (Wilkinson et al., 2001). There are also temporal elements to textural perception, from first bite to swallow. Noting this complexity, Szczesniak's (1963) pioneering work sought to make diverse but useful categorizations of textural traits and is largely accepted as the classification scheme for food texture. Table 2 summarizes this classification scheme.

Table 2: Classification of Textural Characteristics

Primary Parameters	Secondary Parameters	Popular Terms
Mechanical characteristics		
Hardness		Soft, firm, hard
Cohesiveness	Brittleness	Crumbly, crunchy, brittle
	Chewiness	Tender, chewy, tough
	Gumminess	Short, mealy, pasty, gummy
Viscosity		Thin, viscous
Springiness		Plastic, elastic, stretchable
Adhesiveness		Sticky, tacky, gooey
Geometrical characteristics		
Particle size and shape		Gritty, grainy, coarse, floury
Particle shape and orientation		Fibrous, cellular, crystalline
Other characteristics		
Moisture content		Dry, moist, wet, watery
Fat content	Oiliness	Oily
	Greasiness	Greasy

Source: Adapted from Szczesniak, 1963

To study food texture, researchers rely on both subjective and instrumental methods. "Subjective methods" of sensory evaluation (also referred to as "sensory perception") include assessments of food textural attributes using consumer surveys or panels. Consumers are asked to rate the textural attributes of different crop varieties, allowing the researcher to identify consumer-preferred textural attributes and to isolate different varieties with consumer-preferred characteristics (see for example Tomlins, Rwiza, Nyango et al., 2004). "Instrumental methods" refers to studies of textural attributes in a laboratory setting, relying upon standardized protocols and metrics to assess textural attributes and, ultimately, to identify the underlying genetic, biochemical, molecular, and micro- and macro-structural drivers of crop characteristics needed to enhance breeding efforts (Figure 1).

Figure 1: Overview of Food Product Textural Analysis Process[2]

A recent review by Chen & Opara (2013b) provided a comprehensive summary of past and present methods for analyzing and modeling food texture, beginning with subjective measurement of texture and proceeding to more modern instrumental food profile analysis methods including mechanical tests (using instruments to test foods' bending, puncturability, shearing force, and acoustic attributes) that are now applied routinely in many modern food processing industries. For example, texture profile analysis (TPA) uses equipment designed to imitate the mastication or chewing process, providing standardized data through which a wide range of food texture properties including hardness, springiness, adhesiveness, resiliency, fracturability, wateriness, gumminess, sliminess, and chewiness can be analyzed (Chen & Opara, 2013a).

Although subjective methods are still widely applied including in relatively recent literature on RTB crop characteristics (Tomlins et al., 2004), Chen & Opara (2013b) emphasize that instrumental methods are overwhelmingly preferred for informing breeding efforts, as the results of instrumental methods – if not always truly representative of consumers' textural perceptions – are both standardized and replicable. Moreover, relatively new technological applications offer non-destructive instrumental methods to study food texture (ways to study texture systematically without destroying the food sample under study), which can greatly expedite the testing process and also allow for repeat testing of the same sample over time. These methods include ultrasound techniques (used to identify firmness in fruits and vegetables) and optical techniques such as visible/near/mid-infrared spectroscopy (used to detect mealiness or firmness in fruits and vegetables,

[2] Green boxes represent the subjective consumer-side, and purple, the more objective breeder-side.

and tenderness in meat) (Chen & Opara, 2013b). Some of these techniques have already been applied to RTB crops (see e.g., Taylor, McDougall & Stewart, 2007).

Drivers of Food Product Textural Characteristics

Owing to the great diversity in textural attributes, there are many genetic, physicochemical, environmental, and processing-related drivers of food texture. Measurable food product characteristics with the potential to explain food product texture summarily include the attributes listed in Table 3.

Table 3: List of Measureable Food Product Characteristics

Measureable Food Product Characteristics
Biochemical characteristics such as lipid content, cell wall content and composition, particle size and shape, moisture content, amylose content, and mechanical factors
Cellular organelles
Chemical composition
Gelatinization properties
Granule morphology
Macro-structure of the food product (arrangement of starch granules in cells)
Microstructure
Organization of cells or the arrangement of tissue in the food product
Physicochemical properties, morphology and molecular structure of starch (amylose and amylopectin content)
Genetic drivers (e.g. polymorphism)
Starch digestibility
Swelling capacity

For RTB crops, starch structures are considered a primary characteristic that affects texture (Charoenkul, Uttapap, Pathipanawat et al., 2011). Approximately 80% of the dry matter in RTB crops is carbohydrates, which consist primarily of starch, mucilage, and sugars (Huang, Chiang, Chen et al., 2007; Kim, Wiesenborn, Orr et al., 1995). Starch itself has two major sub-components: amylose (a spiral polymer made up of D-glucose units) and amylopectin (a soluble polysaccharide and highly branched polymer of glucose found in plants). Amylose is a linear molecule while amylopectin is a larger branched polymer and the two are arranged in semi-crystalline granules (Burrell, 2003; Peroni-Okita, Simão, Cardoso et al., 2010). The ratio of amylose and amylopectin in starch may explain textural traits of food products. Of the key textural traits listed in Table 2, nearly all can be related to functions of amylose and amylopectin ratios, including viscosity, shear resistance, gelatinization, textures, solubility, tackiness, gel stability, cold swelling, and retrogradation (Satin, 1998).

A basic physical property of starch that breeders can utilize is starch granule size. Table 4 depicts the granule size distribution for various starch sources. A comparison of the degradation of starch in RTB crops including green banana, cassava and potato found that banana and potato starches had a higher heterogeneity of particle sizes while cassava starch had more homogenous granule size (Pineda-Gomez, Angel-Gil, Valencia-Munez et al., 2014).

Table 4: Variation in Starch Granule Size across Grain and RTB Crops

Starch Species	Granule Size Range (μm)	Average Granule Size (μm)
Waxy Rice	2-13	5.5
High Amylose Corn	4-22	9.8
Corn	5-25	14.3
Cassava	3-28	14
Sorghum	3-27	16
Wheat	3-34	6.5, 19.5
Sweetpotato	4-40	18.5
Arrowroot	9-40	23
Sago	15-50	33
Potato	10-70	36
Canna (Aust.Arrowroot)	22-85	53

Source: Adapted from Satin, 1998

While relatively little research has been conducted on the genetics of textural properties in RTB crops to date, some progress has been made in the study of other major food crops, including staple foods in SSA and South Asia. Interest in manipulating the texture and other properties of processed fruits and vegetables has spurred research regarding the cell wall, and in particular the role of pectin and its degradation (reviewed in Van Buggenhout, Sila, Duvetter et al., 2009). In a complementary publication, Sila et al. (2009) reviewed evidence on pectin structure-function relationships and methodological approaches toward understanding them, including such applications to texture as the role of pectin in gel formation in plant-based foods. Most studies of textural properties of grains and tubers focus primarily on starch structure. Starch, a biodegradable polymer, represents a major energy reserve in plants and a highly important source of energy for

humans. Phosphorylation, a key process for glycogen synthesis, is an important focus of genetic research as discussed with respect to potato tubers below.

As an initial example, we note that textural traits for sorghum are framed in terms of grain quality, which can be characterized by amylose content, protein content, lipid content, hardness, endosperm texture and peak gelatinization temperature. Starch content plays a role in determining these qualities, as do grain filling and thousand grain weight (TGW) (De Alencar Figueiredo, Sine, Chantereau et al., 2010). In an early paper on texture in a grain crop (sorghum), Rami et al. (1998) found close correlations among several quality traits including amylose content, dehulling yield, kernel friability, kernel hardness and kernel flouriness. These correlations pointed to high amylose content grains being more brittle, harder, and less apt to abrade. Amylose content was negatively correlated with protein content but positively correlated with yield factors, providing evidence of amylose content tracking variations in starch content.

Through mapping, quantitative trait loci (QTL) were found on seven linkage groups (l.g. A, D, K, C, F, G and H), while a chromosomal segment on linkage group F was identified as playing a key role in grain quality (Table 5). For population RIL379, 4 QTLs (flouriness, dehulling yield, amylose content and mold during germination) were determined to comprise an important part of the phenotypic variance. On the same linkage group, a set of four key QTLs were detected on population RIL249 for flouriness, kernel friability, kernel hardness and amylose content, consistent with other findings regarding amylose content and kernel physical properties (Rami, Dufour, Trouche et al., 1998). Grain quality, as defined by a vitreous hard endosperm and abrasion resistance with a high amylose content, was not negatively correlated with high productivity, which has potential to increase breeding productivity. In fact, no genetic obstacles to recombination - with the goal of both productivity and grain quality in guinea x caudatum crosses - were found. Although no causal relation between amylose content, kernel texture and tannin content was found, one extremity of l.g. F was found to be involved in all three traits. Further, co-localizations of QTLs involved in protein content and grain hardness or vitreousness implied that storage grain proteins are involved in kernel physical properties (Rami et al., 1998).

Table 5: Statistical Analysis and QTL Detection of Traits Measured in RIL379 and RIL249 Populations

		Parents				Progenies				SIM detection			CIM detection		
		Caud-atum	Guinéa	Mean	SD	Min	Max	W	P>W	H^2	*n*	R^2	Co-factor set	*n*	R^2
Thousand-kernel weight (g)	RIL379	20.30	12.60	17.49	2.78	10.20	24.40	.98	.4010	76.00	1	35.2	UMC23	3	30.8
	RIL249	22.30	21.80	20.05	2.91	12.20	33.40	.99	.8382	85.0	0	-		-	46.3
Kernel flouriness (1-5)	RIL379	4.50	3.50	4.40	0.64	3.00	5.00	.87***	.0001	63.70	2	57.1	B2/b2; UMC55	2	59.1
	RIL249	5.00	3.17	4.04	0.72	2.50	5.00	.94***	.0004	50.6	1	17.6	B2/b2	2	29.7
Kernel friability (PSI)	RIL379	-	-	-	-	-	-	-	-	-	-	-		-	-
	RIL249	16.65	10.14	15.08	2.28	9.62	22.60	.97	.2474	81.8	1	13.7	UMC58	2	24.5
Kernel hardness (AACC)	RIL379	-	-	-	-	-	-	-	-	-	-	-		-	-
	RIL249	297.49	353.46	317.98	17.76	286.84	361.15	.96			4	44.8	UMC58; BNL8.01; BML15.40	2	37
Amylose content (%)	RIL379	23.82	24.65	23.69	1.48	17.62	26.59	.95**	.0025	71.90	2	38.9	B2/b2	2	48.4
	RIL249	22.36	24.60	22.60	1.27	19.19	26.27	.97	.1996	72.1	2	23.2	BNL15.40	1	22
Protein content (%)	RIL379	11.81	12.18	12.35	1.15	9.42	16.78	.97	.0699	68.10	2	26	UMC84	1	19.1
	RIL249	11.44	14.21	12.98	1.35	9.56	16.44	.97	.1118	70.4	1	16.5	BNL7.25	3	40.2
Lipid content (%)	RIL379	-	-	-	-	-	-	-	-	-	-	-		-	-
	RIL249	3.00	3.96	3.40	0.38	2.39	4.46	.99	.8712	64.2	1	14.7	UMC115	1	14.7

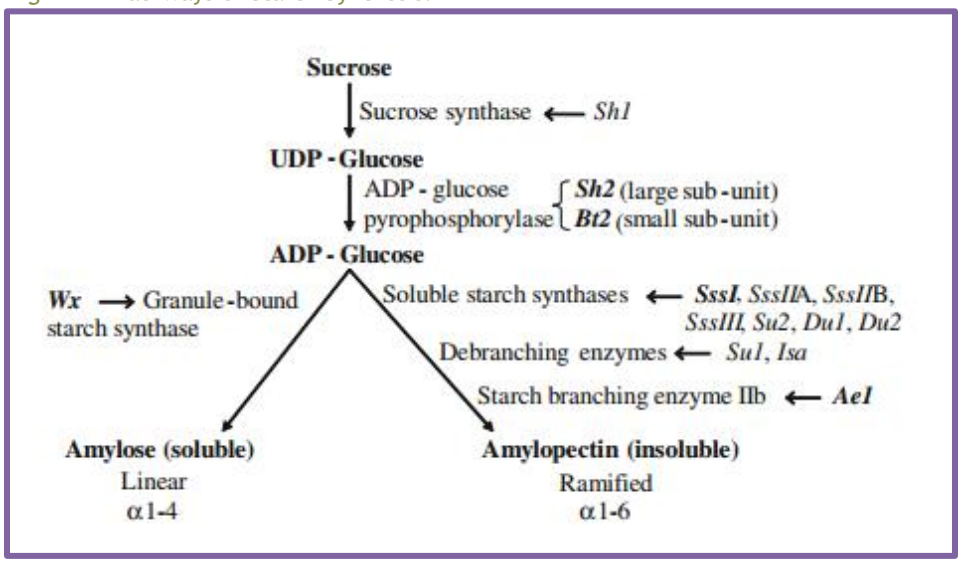
Source: Adapted from Rami et al., 1998

Chapman and colleagues (2012) carried out related research on tomatoes in which a quantitative trait locus (QTL) for fruit firmness was mapped to tomato chromosome 2. Ethylene response factor analysis showed increased expression associated with soft fruit texture in the mapping population. In contrast, pectin methylesterase expression was tightly linked with firm fruit texture.

In more recent work on sorghum, De Alencar Figueiredo et al. (2010) explored whether the polymorphism detected in six genes involved in starch synthesis (Sh2, Bt2, SssI, Ae1, and Wx) or grain storage proteins (O2) explained the phenotypic variability in traits of grain quality and yield components. An analysis of the associations between gene polymorphism and phenotypic traits found that Sh2, Bt2, Ae1, and Wx were associated with thousand grain weight while SssI and Ae1 were

associated with peak gelatinization temperature. Sh2 was associated with amylose content. O2 and Wx were associated with hardness and endosperm texture. No association was found between O2 and protein content. A summary of these relationships is shown in Figure 2. These results were consistent with QTL data for sorghum and for maize.

Figure 2: Pathways of Starch Synthesis.



Source: De Alencar Figueiredo et al., 2010

Finally, the research of Ross and colleagues suggests that multiple genes determine texture in potato tubers, with pectin methyl esterase activity along with several other genetic and physicochemical pathways linked to textural attributes of both raw and cooked potato (Ross et al., 2011a; 2011b), as reviewed in greater detail in the pages below.

RTB Crop-Specific Literature on Physicochemical or Genetic Determinants of Consumer-Desired Textural Qualities

Each of the following sections begins with a brief overview of the primary regions where each crop is grown and how it is prepared, and then continues with an overview of known consumer textural preferences based on sensory evaluation studies. Throughout the review, two distinct types of sensory evaluation of crops are referenced. "Descriptive Sensory Evaluation" refers to the identification and description of various sensory attributes using a panel of eight to twelve individuals trained to identify and describe a complete profile of sensory parameters such as appearance and flavor (Einstein, 1991). The other common methodology is consumer evaluation by non-trained individuals. Most consumer panels consist of fewer than 100 individuals, although some studies throughout this section included many hundreds of individuals. The studies reviewed typically include a wide range of sensory characteristics, and although the terms attributed to textural traits can vary, we have tried to link them to the categories used by Szczesniak (1963) whenever practical.

The evidence available on the physicochemical and genetic processes underlying these consumer-desirable texture traits is then summarized, including abundant research on general physicochemical properties of crops and crop varieties following from the basic physicochemical properties of starch granules (Satin, 1998). Where available, specific crop genotypes (varieties) and specific genetic markers associated with textural qualities are presented, although often specific genetic details are lacking (or perhaps proprietary and hence unpublished to date).

Geneticists, Plant Breeders, and Scholars Contacted

The review of physicochemical and genetic characteristics also included direct correspondence via telephone and email with crop breeders and researchers at both US and international research institutions. In most cases these experts confirmed our finding that the literature on genetic determinants of textural attributes in RTB crops remains thin, while some experts also noted that such traits are being actively explored in both the public sector (as in the recent cassavabase.org project) and in the private sector (where, as more than one expert observed, research findings are unlikely to be released publicly for some time).

The EPAR team contacted the following individuals and groups between August and October 2014 with specific queries about research and methodology for establishing genetic drivers of food texture carried out in their organizations or by their colleagues.

Name and Title	Institution
Ahlgoy, Patricia PhD	Syngenta, CHBS
Andersson, Meike S. PhD	HarvestPlus, Crop Development Specialist
Bakry, Fredric PhD	CIRAD
Baxter, Charles	Syngenta, GBJH
Bonierbale, Meredith PhD	CIP
Ceballos, Hernan PhD	CIAT
Cichy, Karen PhD	USDA ARS
De Jong, Walter PhD	Cornell University, Plant Breeding and Genetics
DeRose, Richard PhD	USRE, Syngenta
Dixon, Alfred PhD	IITA
Dorrity, Michael Graduate Student	University of Washington, Department of Biology
Dufour, Dominique PhD	CIAT, Food Science Specialist
Faustman, Elaine Professor	University of Washington, School of Public Health
Fields, Stanley Professor	University of Washington, Genome Sciences and Medicine
Fraser, Paul Professor	Royal Holloway University of London, Department of Biochemistry, CGIAR partner
Jansky, Shelley PhD	University of Wisconsin, USDA
Kim, Soo-Hyung Professor	University of Washington, School of Environmental and Forest Sciences, College of the Environment
Kulakow, Peter PhD	IITA (Cassava Specialist)
Lawler, Josh PhD	University of Washington, School of Forest Resources
López-Lavalle, Luis Augusto Becerra PhD	CIAT, Cassava Molecular Geneticist
Lopez-Montes, Antonio PhD	IITA
Lorez, Christine PhD	Syngenta, CHBS
Maziya-Dixon, Bussie PhD	IITA, Crop Utilization Specialist
Neff, Michael Professor	Washington State University, Molecular Plant Sciences Graduate Program
Okita, Tom PhD	Washington State University, Institute of Biological Chemistry
Osorno, Juan Professor	North Dakota State University, Plant Sciences
Peace, Cameron Professor	Washington State University, Department of Horticulture
Port, Jesse PhD	Stanford University, Center for Ocean Solutions, Fellow
Poutanen, Kaisa PhD	Academy of Finland, Food Technology and Nutrition Sciences
Ross, Heather PhD	Scottish Crop Research Institute, Plant Products and Food Quality Programme
Setter, Timothy PhD	Cornell University, Plant Breeding and Genetics
Swennen, Dr. Rony	IITA
Taylor, Mark PhD	Hutton Institute (Dundee, Scotland), Cell and Molecular Sciences
Thiele, Graham PhD	CPI (formerly), Director CGIAR Research Program on Roots, Tubers and Bananas
Tomlins, Keith Professor	University of Greenwich (UK), International Society for Tropical Root Crops President
Van Volkenburgh, E. Professor	University of Washington, Department of Biology
Zum Felde, Thomas PhD	CGIAR

Tropical Yam: Highlights

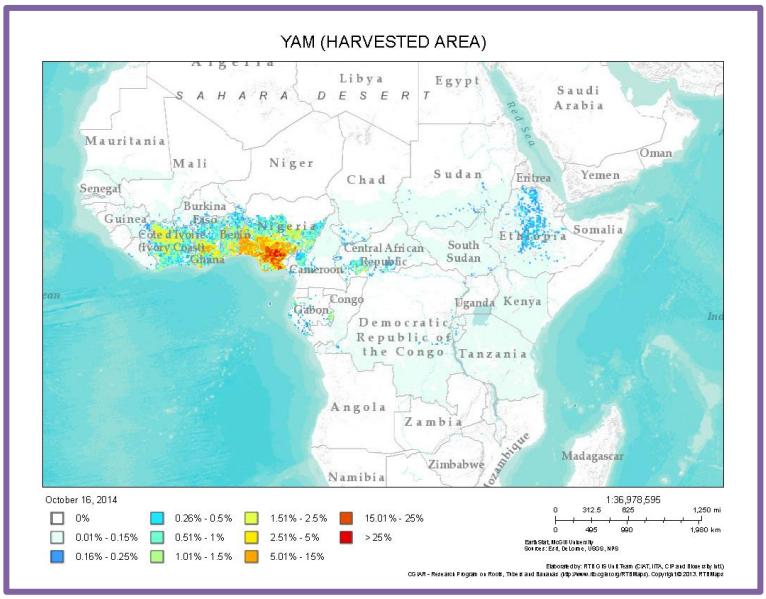
- Elasticity and non-stickiness are important textural qualities for *amala*, a pounded yam product.
- Starch particle size can also affect consumer preference for pounded yam products (the ideal range for flour particle size has been identified as 150-300 microns).
- Several textural characteristics have received attention in yam physicochemical and genetic studies, including starch particle size, shape and orientation; softness; elasticity; stickiness; and pasting characteristics.
- Published work relating physicochemical properties and textural qualities of yam emphasizes the impacts of storage and food preparation techniques on texture.
- Amylose content is reported as a key indicator of texture.

Tropical Yam (*Dioscorea spp.*): Food Texture Preferences in Sub-Saharan Africa

Yam (*Dioscorea spp.*) is an economically important staple food for more than 300 million people in West Africa, Asia, and the Caribbean. Africa produces 96% of the world's yam, and the top five producers are Nigeria, Côte d'Ivoire, Ghana, Bénin, and Togo. In 2013, Nigeria produced 40 million tonnes of yam, or more than the rest of the world combined (FAOSTAT, 2013). Production is shown in Map 1. Yam is nutritionally superior to other RTB crops, and is a better source of protein (Otoo & Asiedu, 2009). The species most commonly cultivated in West Africa are *D. rotundata* ("white yam") and *D. alata* ("water yam") (IITA, 2009), though *Dioscorea spp.* includes a wide array of vegetatively propagated tuber species, both diploid and polyploid. *D. cayensis* ("yellow yam") is regarded by most taxonomists to be in the same species as *D. rotundata*, and in Africa, *D. cayensis* is used to make pounded yam products much like *D. alata* (Kay, 1987). *D. dumentorum* ("bitter yam"), *D. opposita* ("Chinese yam"), *D. bulbifera* ("air potato"), and *D. trifida* ("Cush-Cush yam") are all cultivated less commonly than the aforementioned varieties (Kafilat, 2010).

Common Preparation of Yam in SSA

Map 1: Yam Area Harvested



In much of West Africa, yam is typically consumed as a paste called *amala* (Kordylas, 1990; Kafilat, 2010; Ayodele, Bolade, & Usman, 2013), created by pounding the pulp of boiled yam or reconstituting dried yam flour. To make *fufu*, another typical preparation, yam is boiled and pounded into a dough-like consistency, and then eaten alone or with a soup or sauce (Obadina, Oyewole, & Odubanjo, 2007). In Ghana, *fufu* is occasionally referred to as *sakora* or *sakoro*, and in some French-speaking portions of West Africa, it can be referred to as *couscous* (not to be confused with the North African dish *couscous*) (Obadina et al., 2007). In Nigeria, Bénin, and Ghana, yam is also consumed as dry-slices and as flour. However, dry-slices are not consumed widely (Kafilat, 2010). Yam flour can be referred to as *kokonte* (Bricas, Vernier, Ategbo et al., 1997) or *elubo* (Kafilat, 2010). Consumers often consider yam flour an inferior substitute for freshly pounded yam because flour is typically made from damaged yam tubers, though early studies by FAO reported no difference in nutritional value (FAO, 1993).

Consumer Preference Studies of Yam: Preferred Characteristics

Several textural characteristics have received attention in yam studies, including starch particle size, shape and orientation; softness; elasticity; stickiness; and pasting characteristics.

Amala, the primary use of yam in West Africa, is produced either from freshly pounded tuber or reconstituted yam flour. Yam flour, the most common processed yam product (Ayodele et al., 2013), is traditionally processed by peeling, parboiling, steeping for 13-24 hours, sun drying, and then milling (Kafilat, 2010). Whether fresh or reconstituted,

preference studies for *amala* (the end product) highlight important sensory factors including an elastic and non-sticky texture, a light brownish color, and a slightly sweet taste (Akissoe, Hounhouigan, Bricas et al., 2001; Mestres, Dorthe, Akissoe et al., 2004). In studies of *amala* produced using *D. rotundata* varieties, Akissoe et al. (2006) and Hounhouigan et al. (2003) found that elasticity and non-stickiness were among the primary factors consumers reported using to determine *amala* quality. In another *D. rotundata* study, Ayodele et al. (2013) examined yam flour softness, color, pasting characteristics, and physicochemical properties, and found that flour particle size was the most important sensory attribute to *amala* consumers, with the flour rated highest by Descriptive Sensory Evaluation (n=30 consumers) exhibiting particle sizes in the range of 150-300μm.

In an unpublished student thesis paper from the University of Agriculture in Ogun State, Nigeria, Kafilat (2010) found that various samples of *amala* made from *D. rotundata* yam were significantly different ($p < 0.05$) in terms of physical, functional, and sensory properties. The author notes that this may be due to the fact that yam flour is often adulterated with other flour-like substances when sold in local markets in Nigeria.

Literature regarding the preferred sensory characteristics of *fufu* is limited for yam, and instead primarily addresses *fufu* made of other starches, such as cassava.

Consumer Preference Studies of Yam: Variety Preference

D. rotundata and *D. alata* are the two most commonly cultivated yam species across Africa, Asia, and Latin America. *D. rotundata* is preferred in West Africa for products such as *fufu*, boiled yam or fried yam, in part due to its firmer texture (Wireko-Manu, Ellis, Oduro et al., 2014; Otoo & Asiedu, 2009). *D. rotundata*, particularly from the kokoro group, is also generally used for making *amala*.

Ekwu, Ozo & Ikegqu (2005) conducted a Descriptive Sensory Evaluation including a physicochemical and sensory analysis of the properties of flours made from three African varieties of white yam (*D. rotundata*) locally referred to as Ozibo, Okpebe, and Nwopoke. The sensory qualities assessed were texture, stickiness, appearance, and general acceptability. The results indicated that color, texture, and general acceptability of Okepebe and Nwopoke were statistically similar, while they differed significantly from Ozibo. Nwopoke was preferred by the consumer panel to make flour (*fufu*), followed by Okpebe. The authors concluded by stating that "whereas Okpebe has good *fufu* making qualities, traditional yam *fufu* producers generally use Nwopoke because of the difficulty in pounding Okpebe which has high stretchability potentials (Ekwu, Ozo & Ikegqu, 2005)."

Recent scientific studies have shown that *D. alata* has higher yield, better storage capacities, and higher nutritional value in comparison with *D. rotundata* (Baah, Maziya-Dixon, Asiedu et al., 2009; Wireko-Manu et al., 2014), which has led some crop scientists to argue that there is a great need to diversify the food uses of *D. alata* in SSA. Wireko-Manu et al. (2014) state that the need "to enhance the food security [of *D. alata*] cannot be overemphasized, especially processing it into forms that can enhance longer storage for use during the hunger or off seasons of most tropical crops." Ajibola et al. (1988) found that *D. alata* is frequently preferred for food uses such as porridge.

Recent work by Wireko-Manu et al. (2014) systematically compared *D. alata* and *D. rotundata* using a multiple comparison sensory test adapted from Meligaard et al. (1999) for pasty yam products. A multiple comparison test requires that the trained sensory evaluators compare each variety to a reference sample using a categorical scale. The authors found that *D. alata* varieties were either better than or not significantly different from *D. rotundata* in terms of color and texture on a 9-point categorical scale that included color, smoothness, consistency, elasticity, stickiness and hardness. *D. alata* demonstrated greater suitability for *amala*, which "could be attributed to the high gel strength of its flour, the parboiling of tubers before drying, which increases pasting properties, and the more browning observed during cooking." The authors concluded, "to increase production, market value and diversity of the food uses of water yam (*D. alata*), specific varieties of the species should be promoted for products such as *amala*, where they have comparative advantage over *D. rotundata* (Wireko-Manu et al., 2014)."

Babajide & Olowe (2013) conducted a consumer sensory evaluation of mixed water yam (*D. alata*) and cassava (*M. esculenta*) flour, which is often substituted for 100% yam (*D. rotundata*) flour *elubo* to make *amala* paste in the off-season of yam. Samples mixing the water yam and cassava flours in varying proportions were evaluated by 20 male and female panelists. The preferred sample for color was the sample made from 70% water yam flour and 30% cassava flour, which was rated as "like very much" and preferred to the control of 100% yam flour. Moldability, a preferred trait, increased as the proportion of cassava flour increased. The most preferred sample for aroma and for overall acceptability was also the 70-30 mix, with a similar score to that of 100% *D. rotundata* flour (Babajide & Olowe, 2013).

Nindjin et al. (2007) found that a panel of adult villagers in Côte d'Ivoire preferred *fufu* ("foutou") made from *D. cayenensis-rotundata* for textural attributes, whereas they disliked "foutou" made from *D. alata*. The authors reported that "easiness to mould" and springiness were among the most desirable characteristics for pounded yam products, and that

lumpiness contributed to the dislike of a particular yam cultivar. Otoo & Asiedu (2009) conducted a consumer sensory evaluation of 36 yam genotypes over a three-year period through the International Institute of Tropical Agriculture (IITA). The authors disaggregated their results by gender, occupation, and agroecology, and observed that agroecology had no significant effect on yam preferences for farmers ($p>0.1$), while there were gender differences in preferences for texture and taste. Farmers in this study considered taste, texture, color attractiveness, aroma, and aftertaste to be important determinants of overall acceptability. KUP__2000/001 was the most preferred genotype due to its superior taste, texture, aroma, and aftertaste. After the study, genotypes KUP__2000/001, 2002/001, and TDr/89/02665 were released in Ghana as new varieties called CRI_Pona, CRI_Kukrupa, and Mankrong_Pona, respectively (Otoo & Asiedu, 2009).

Finally, in one of the most comprehensive consumer preference studies for yam to date, Egesi et al. (2003) conducted an experiment in which trained panelists rated randomized samples from 40 accessions of *D. alata* cultivated in Nigeria in the form of boiled yam pieces (for mealiness, color, wetness, softness and taste) and pounded yam (for consistency, color, sheen, smoothness, stickiness, elasticity and hardness). This work was intended to identify potential parents for use in genetic improvement. Numeric ratings based on hedonic scales were collected for input into cluster analysis. Mealiness, color and taste were found to predict general preference for the boiled yam pieces, while consistency, color and stickiness tracked general preference for pounded yam.

Table 6: Mean (± standard deviation) Quality Attributes* of Pounded Yam from 40 Accessions of *D. alata*

Accession	Color	Consistency	Elasticity	Hardness	Sheen	Smoothness	Stickiness
TDa 289	5.40±1.24	1.07±0.26	1.40±0.51	2.73±0.46	1.87±0.99	1.40±0.83	1.60±0.12
TDa 291	5.28±1.36	1.17±0.38	1.44±0.51	2.44±0.70	1.39±0.50	1.50±0.51	1.94±0.04
TDa 294	5.94±0.97	1.71±0.39	1.76±0.22	3.76±0.20	1.88±0.78	1.76±0.66	1.47±0.41
TDa 297	5.27±1.31	1.53±0.44	1.80±0.11	3.60±0.33	2.53±0.42	1.33±0.62	1.60±0.35
TDa 316	4.76±1.09	1.12±0.33	1.71±0.17	2.88±0.49	1.41±0.62	1.06±0.24	1.94±0.04
TDa 85/00250	6.29±0.18	1.21±0.43	1.43±0.15	2.93±0.27	2.07±0.73	1.86±0.53	1.71±0.27
TDa 87/01091	4.93±2.40	1.29±0.47	1.57±0.12	3.07±0.47	1.86±0.66	1.50±0.52	1.60±0.40
TDa 89-2	3.06±1.84	1.75±0.20	1.94±0.05	3.88±0.04	2.44±0.53	2.19±0.54	1.25±0.45
TDa 89-3	4.36±2.76	1.21±0.43	1.57±0.35	3.14±0.36	1.71±0.61	1.57±0.51	1.64±0.30
TDa 92-2	4.14±2.08	1.50±0.85	1.67±0.22	3.73±0.12	2.33±0.42	2.00±0.85	1.53±0.08
TDa 92-3	5.40±1.03	1.27±0.46	1.53±0.42	3.40±0.15	1.87±0.74	1.60±0.63	1.53±0.08
TDa 93-36	5.35±1.11	1.76±0.21	1.88±0.03	3.88±0.10	2.00±0.71	1.18±0.39	1.29±0.47
TDa 94-126	1.19±0.47	1.12±0.33	1.53±0.41	2.41±0.51	1.53±0.62	1.59±0.62	1.82±0.10
TDa 94-56	5.33±1.14	1.67±0.29	1.78±0.20	3.33±0.49	1.72±0.67	1.39±0.61	1.39±0.50
TDa 94-72	5.00±1.58	1.23±0.60	1.69±0.28	2.77±0.60	1.54±0.66	1.54±0.66	1.69±0.28
TDa 94-73	5.08±1.86	1.92±0.04	1.85±0.12	3.92±0.06	2.69±0.18	1.85±0.55	1.38±0.51
TDa 94-94	5.40±1.30	1.20±0.56	1.47±0.52	2.73±0.46	1.87±1.06	1.27±0.46	1.53±0.32
TDa 95-101	4.77±2.32	1.15±0.38	1.62±0.51	3.00±0.41	2.23±0.73	1.46±0.66	1.62±0.35
TDa 95-102	5.12±1.05	2.00±0.79	1.88±0.04	3.71±0.17	1.94±0.56	1.35±0.61	1.35±0.49
TDa 95-14	4.86±1.35	1.07±0.27	1.57±0.15	2.79±0.43	1.64±0.74	1.14±0.36	1.79±0.15
TDa 95-163	5.22±1.55	1.17±0.38	1.83±0.10	2.78±0.43	1.72±0.46	1.39±0.50	1.67±0.29
TDa 95-23	4.71±0.69	1.18±0.53	1.65±0.33	2.53±0.51	1.47±0.51	1.12±0.33	1.88±0.11
TDa 95-25	6.47±0.32	1.00±0.00	1.60±0.35	2.33±0.49	1.53±0.52	1.33±0.49	1.87±0.13
TDa 95-27	4.65±0.86	1.24±0.56	1.65±0.27	2.59±0.62	1.65±0.61	1.29±0.47	1.82±0.11
TDa 95-290	5.55±1.13	1.18±0.40	1.55±0.42	2.82±0.40	1.82±0.60	1.55±0.52	1.55±0.42
TDa 95-303	5.08±0.76	1.08±0.28	1.54±0.44	2.85±0.38	1.54±0.52	1.15±0.38	1.69±0.30
TDa 95-307	4.80±1.08	1.00±0.00	1.47±0.52	2.40±0.74	1.33±0.62	1.33±0.49	1.67±0.25
TDa 95-321	4.75±1.24	1.13±0.34	1.53±0.42	2.81±0.54	1.56±0.51	1.31±0.48	1.75±0.25
TDa 95-322	5.61±1.09	1.17±0.38	1.61±0.31	2.78±0.43	2.00±0.77	1.22±0.55	1.72±0.25
TDa 95-323	6.50±0.68	1.88±0.86	1.94±0.26	3.47±0.16	2.00±0.61	1.59±0.62	1.53±0.41
TDa 95-324	4.31±1.89	1.06±0.24	1.76±0.24	2.88±0.33	1.82±0.73	1.41±0.51	1.53±0.41
TDa 95-326	4.86±1.23	1.07±0.27	1.50±0.45	2.57±0.51	1.36±0.50	1.50±0.52	1.71±0.27
TDa 95-75	5.06±1.06	1.61±0.78	1.67±0.19	3.17±0.71	1.83±0.62	1.67±0.59	1.61±0.35
TDa 95-84	5.24±1.20	1.59±0.71	1.53±0.35	3.29±0.59	1.65±0.70	1.59±0.71	1.41±0.38
TDa 95-92	4.79±0.71	1.11±0.32	1.68±0.18	3.00±0.33	1.26±0.56	1.42±0.51	1.89±0.10
TDa 96-10	5.22±1.44	1.39±0.61	1.61±0.38	2.39±0.50	1.83±0.62	1.50±0.71	1.82±0.08
TDa 96-3	6.48±0.21	1.22±0.55	1.67±0.29	2.50±0.51	1.61±0.70	1.39±0.61	1.89±0.10
TDa 96-4	6.57±0.11	1.24±0.56	1.65±0.21	2.47±0.62	1.94±0.83	1.59±0.71	1.65±0.29
TDa 96-8	4.60±1.35	1.13±0.35	1.73±0.22	3.00±0.53	1.67±0.72	1.33±0.62	1.73±0.26
TDa 96-9	5.44±1.46	1.33±0.97	1.61±0.31	2.94±0.42	1.50±0.52	1.39±0.61	1.82±0.11
Mean	4.87±1.54	1.32±0.48	1.65±0.28	2.99±0.48	1.79±0.65	1.47±0.56	1.65±0.26
Pr<F	***	***	***	***	***	***	***

*Hedonic scale: color (1-7); consistency (1-4); elasticity (1-2); hardness (1-4); sheen (1-3); smoothness (1-4); stickiness (1-2)
*** Significant at $P<0.001$
Source: Adapted from Egesi et al., 2003

Through subsequent analyses, Egesi et al. found that two thirds of their study accessions were rated as moderately or extremely well suited to boiling for consumption, while just over half were suitable for pounding. Of the total variation in preference for boiled yam, 83% was explained by the traits of mealiness, color and taste (explaining variance of 65%, 16% and 2% respectively). Mealiness and color were positively associated with general preference, while taste was not. For pounded yam, consistency, color and stickiness explained 96% of the total variation in general preference with contributions of 91%, 4% and 1% respectively for the three traits. Consistency, color and stickiness had a strong positive association with preference (Egesi, Asiedu, Egunjobi et al., 2003).

Tropical Yam *(Dioscorea spp.)*: Determinants of Food Texture

Despite its economic and socio-cultural importance, very little is known about the genetics and genomics of yam due to a combination of research neglect and biological constraints including: (i) vegetative propagation in most farm systems; and (ii) a long crop growth cycle of 8 months or more which hampers traditional breeding efforts (Mignouna & Abang, 2008). Nevertheless there is an emerging body of literature describing the physicochemical properties underlying textural attributes in yam, and some highly preliminary studies of yam genotypes exhibiting desirable characteristics.

Physicochemical Properties Related to Texture in Yam

Much of the published work relating physicochemical properties and textural qualities of yam emphasizes the impacts of storage and food preparation techniques on texture (Otegbayo, Asiedu & Bokanga, 2012; Asiedu-Larbi, 2010). A smaller literature covers physiochemical properties related to texture in yam, and one study has assessed the comparability of instrumental and sensory analysis.

Otegbayo et al. (2007) assessed whether instrumental texture profile analysis (ITPA) could serve as a measure of textural quality for pounded yam in the same manner as a trained sensory panel. The authors find that ITPA applied to *D. rotundata* Poir and *D. alata* L. achieved significant correlations with the sensory texture profile analysis performed by a trained panel. The authors concluded that "because texture profile analysis (TPA) has been successfully used to study the textural quality of pounded yam…it can be used in the food industry to study the texture attributes of pounded yam. It can also be used to screen yam varieties for textural quality for subsequent utilization." Cui and colleagues built on this work in a study that sought to validate instrumental and sensory textural evaluation in an herbal gel (Cui et al., 2011), but no studies were found that replicated the results found in Otegbayo et al. (2007).

Otegbayo et al. (2006) found that relative changes in the microstructure of yam when boiled served as indicators of textural quality: histological studies of tissue samples from raw *D. alata* and *D. rotundata* yam showed parenchyma cells in both species were three-dimensional and polyhedral in shape, with starch granules comprising a loose arrangement in *D. rotundata* and a dense arrangement in *D. alata*. The authors further observed a separation and "rounding off" of cells in cooked *D. rotundata* that contrasted with partial cell separation with no rounding in *D. alata*. Boiled yam characterized as "mealy" demonstrated complete cell separation and "rounding off" (*D. rotundata*) whereas yam rated as "waxy" showed partial retention of extracellular integrity (*D. alata*).

Baah et al. (2009) showed that *D. alata* had a lower starch content and lower peak, final and setback viscosities than *D. rotundata*, which may contribute to the poorer performance of *D. alata* for pounded yam products. The low pasting viscosities of yam flour created from *D. alata* may contribute to less favorable ratings by consumer preference panels. Studies have demonstrated that high pasting viscosities are preferred by customers for pounded yam products such as *fufu* (Oduro, Ellis, Aryeetey et al., 2000; Adebowale, Sanni, & Awonorin, 2005; Otegbayo, Aina, Asiedu et al., 2006).

Otegbayo et al. (2011) further evaluated physicochemical properties of yam starch in *D. alata* and *D. rotundata* including stretchability, cohesiveness, adhesiveness, and hardness of pounded yam, and textural changes over a four-month storage period. Results of sensory textural profiling showed that *D. rotundata* varieties exhibited a higher swelling power and lower amylose and water binding capacity, and were described as "cohesive, moderately soft, and less sticky compared to *D. alata*." Canonical analysis found significant ($p<0.5$) associations between these physicochemical properties and the observed textural qualities of the *D. alata* and *D. rotundata* pounded yam. The physicochemical results from D. *rotundata* were further validated using 18 other yam varieties from the same species.

In their Descriptive Sensory Evaluation, Ekwu, Ozo & Ikegqu (2005) assessed physicochemical properties of several local yam cultivars in Nigeria. They found that the swelling capacity at 30 C and 50 C of Nwopoke was significantly higher ($p < 0.5$) than Okpege and Ozibo. Okpebe and Nwopoke had the same water absorption capacity, but did differ significantly in comparison with Ozibo ($p <0.5$). Cooling time was found to have a significant effect ($p <0.5$) on the extensibility of all three *Dioscorea* varieties.

Riley and colleagues (2008) studied four varieties of *Dioscorea spp.* (*D. cayenensis* cultivar (cv.) yellow yam, *D. rotundata* cv. Lucea white yam, *D. alata* cv. white yam, and *D. esculenta* cv. Chinese yam), finding that yellow yam had the highest

relative amylose content (265.30 g/kg starch) and Chinese yam the lowest (111.44 g/kg starch). Relatedly, Chinese yam had the highest in vitro digestibility and glycemic index. Yellow, Lucea white, and *alata* white yam displayed a Type B crystalline structure, while Chinese yam displayed Type C crystallite. Amylose content (and in particular the amylose and amylopectin ratio) is a physicochemical trait closely linked with sensory textural characteristics (see Table 1).

Babajide, Henshaw & Oyewole (2008) studied pasting properties and sensory attributes of traditional dry preparations of four yam varieties in Nigeria. Varieties studied included *D. esculenta* ("Ijedo"), *D. alata* ("Ewura"), *D. rotundata* ("Abuja"), and "Mumuye" (a fourth local variety which the authors also labeled *D. rotundata*). The authors found that "dry-yam slices commonly processed from "Ijedo" variety can also be made from other white yam varieties such as "Ise-Osi,""Efuru" and "Abuja"." These varieties yielded products with comparable sensory and pasting properties to those from "Ijedo" variety. "Ise-Osi," "Efuru" and "Abuja" varieties were found to be suitable for dry-yam processing (i.e. for flour) in terms of sensory properties and pasting properties. These varieties were not found to be significantly different in terms of the aforementioned sensory traits than those of the "Ijedo" variety, used commonly in Nigeria. White yam varieties with high peak and final paste viscosities were also found to be suitable for dry yam products. Babajide et al. (2008) concluded that further studies to elucidate the physicochemical basis of varietal differences in the pasting viscosities of yam flour are required.

Brunnschweiler and colleagues (2006) found that the firmness of yam pastes from *D. cayenensis-rotundata* was rated higher than *D. alata*, and that firmness was related to the "more pronounced" cell disintegration of *D. alata* when assessed by light microscopy. The authors concluded that the overall texture of yam paste products in West Africa is largely determined by extracellular integrity and properties of the continuous starch phase as measured by the amylose fraction.

Akissoe and colleagues (2006) found that soluble matter and soluble amylose were indicators of sensory stickiness in *amala*. However, no clear relationship was observed between firmness and physicochemical characteristics or functional properties. In a later paper, Akissoe and colleagues (2011) found no significant correlation linking thermo-mechanical properties with textural qualities of pounded yam (adhesiveness, firmness). However, multiple regressions indicated that over 75% of the variation in yam firmness was explained by dry matter, soluble starch, and amylose content. The authors "hypothesize that pectin, the major component of cell wall middle lamella, plays a role in the textural quality of pounded yam."

Huang et al. (2010) found that yam starch exhibited a high pasting temperature, suggesting the presence of strong binding forces inside the granules. But S. Wang and colleagues (2006) found that starches separated from various *D. opposita* Thunb cultivars showed significant differences in physicochemical, morphological, thermal, and crystal properties. Furthermore, the amylose content of *D. opposita* Thunb starches resembled that of potato and corn starch, with an overall composition of 21.17-25.00%.

Isamah et al. (2000) tested levels of o-diphenolase, lipid peroxidation, superoxide dismutase, and catalase activity in the head, middle, and tail of variety *D. rotundata* Poir cv. Omi. They found elevated levels of tannins in the head area, which is the most bitter but the most productive for propagation. They noted the cultural practice of removing the head region before cooking as a response to bitterness, and cited other effects related to tannins including decreased digestibility, intestinal tract damage, and a possible carcinogenic effect. Lipid peroxidation was highest in the middle region, coinciding with low levels of antioxidant enzymes which defend cells against reactive oxygen species. Reactive oxygen molecules attack membranous structures, causing the characteristic tissue disintegration associated with rotting of tubers. Lipid peroxidation is initiated by free radicals and probably causes deterioration of cell membranes. Polyphenoloxidases are associated with enzymatic browning and off-flavor generation. These impair sensory properties and nutritive value (Isamah, Asagba, & Thomas, 2000).

Storage can significantly influence yam texture, with sugar, nonstarchy carbohydrate and dry matter content of the tubers increasing during storage while the starch, fat and protein content decreases (Otegbayo et al., 2012). Several researchers reported finding that pounded yam made from stored yam tubers was of better textural quality than that made from freshly harvested ones.

Genetic Drivers of Texture in Yam

Salda et al. (1998) evaluated yam flour from 15 genotypes shown in Table 7, exploring variation in starch-related traits including amylose content, swelling volume (SV), gelatinization temperature (GT), viscosity, stability ratio, hardness, stickiness, cohesiveness, adhesiveness and springiness. Low amylose flours (3.8-7.4%) were associated with relatively high SV, low GT, low paste viscosities, low stability, and soft, sticky, and cohesive gel textures. Higher apparent amylose flours were associated with moderately high and variable paste viscosity with firm, non-sticky gel textures. These results confirm earlier work highlighting the relative content of amylopectin and amylose as key drivers of texture (Whistler & Daniel, 1985). Low amylose starches are associated with lower GTs and higher enthalpies in combination with weak bonding, resulting in softer gels. For example, cooked tubers from *D. esculenta* and BSUA 1010 are relatively soft with good chewing

characteristics (Salda, Ramsden, Sun et al., 1998). Mealy and processing types (e.g. BSUA 093) with relatively high levels of amylose are reported to be grainy, floury, and dryer after cooking especially when freshly harvested.

Table 7: Genetic Variation in Starch-related Traits of Yam

	Apparent amylose content	Swelling volume (mL g^{-1})	Peak viscosity (PV)	Holding viscosity (HPV)	Final viscosity	Stability ratio HPV/PV	Hardness	Cohesiveness	Adhesiveness	Springiness
Dioscorea alata										
LA 077	21.4	75	508	480	704	0.95	72	0.6	124	2.12
BSUA09	15.6	79	403	304	383	0.75	127	0.6	117	10.2
BSUA10	14.8	82	345	346	430	1.00	216	0.8	35	22.1
BSUA10	14.9	51	398	328	401	0.82	66	0.6	110	15.4
IA 401	18.5	87	156	128	163	0.55	157	0.6	85	21.6
IA 227	20.1	95	77	83	54	1.09	45	0.6	55	16.4
Dioscorea esculenta										
IE 001	5.8	96	67	32	50	0.47	218	1.0	0.1	0.1
LE 007	3.8	143	108	63	90	0.58	241	0.8	0.1	0.1
LE 033	7.1	145	22	12	16	0.55	137	0.7	53	9.2
BSUE10	7.4	145	18	9	11	0.50	32	0.7	96	20.1
Dioscorea hispida										
BSUH11	11.2	131	745	456	658	0.61	113	0.8	80	20.1
Dioscorea pentaphylla										
BSUP	20.4	54	413	342	477	0.83	21	1.0	0.6	0.0
BSUP	19.2	48	86	139	188	1.63	20	1.0	0.1	0.0
Dioscorea rotundata										
IR 001	19.2	100d	410	197	516	0.48	77	0.6	106	21.3
HR 048	17.2	104c	482	198	198	0.41	52	0.6	109	21.3
LSD $_{0.05}$	0.6	3	74	35	60	49	49	0.3	64	8.1

LSD $_{0.05}$ indicates least significant difference between genotype means within a column
Source: Adapted from Salda et al. 1998.

A table summarizing textural characteristics, consumer preferred characteristics, physicochemical drivers of textural attributes, and genetic drivers of texture for yam is provided below:

Table 8: Summary of Determinants of Consumer-Preferred Textural Traits in Tropical Yam

Trait	Description	Consumer Preferred	Physicochemical Driver	Genetic Driver	Source
Hardness	See Tables 6 & 7	Soft +	Low amylose, soluble starch, dry matter, extracellular integrity	NA	Wireko-Manu et al. (2014); Otegbayo et al. (2006, 2011); Nindjin et al. (2007); Salda et al. (1998)
Cohesiveness	See Table 7	Mealiness + Moldable +	Low amylose, cell separation and "rounding off"	NA	Egesi et al. (2003); Salda et al. (1998); Otegbayo et al. (2006)
Viscosity	See Table 7	NA	Low amylose	NA	Salda et al. (1998)
Springiness	See Tables 6 & 7	Elastic +	Low amylose	NA	Wireko-Manu et al. (2014); Akissoe et al. (2001, 2006); Mestres et al. (2004); Hounhouigan et al. (2003); Otegbayo et al. (2011); Salda et al. (1998); Egesi et al. (2003)
Adhesiveness	See Tables 6 & 7	Sticky + Non-sticky + (depends on preparation)	Amylose content and solubility; soluble matter	NA	Wireko-Manu et al. (2014); Akissoe et al. (2001, 2006); Mestres et al. (2004); Hounhouigan et al. (2003); Egesi et al. (2003); Salda et al. (1998)
Particle Size (flour)	150-300 µm desired	150-300µm +	NA	NA	Wireko-Manu et al. (2014); Ayodele et al. (2013)
Particle Shape	Three-dimensional, polyhedral parenchyma cells	NA	NA	NA	Otegbayo et al. (2006)
Moisture Content	NA	NA	NA	NA	NA
Fat Content	NA	NA	NA	NA	NA
Texture	NA	Preference Rating +	NA	KUP__2000/001	Nindjin et al. (2007)

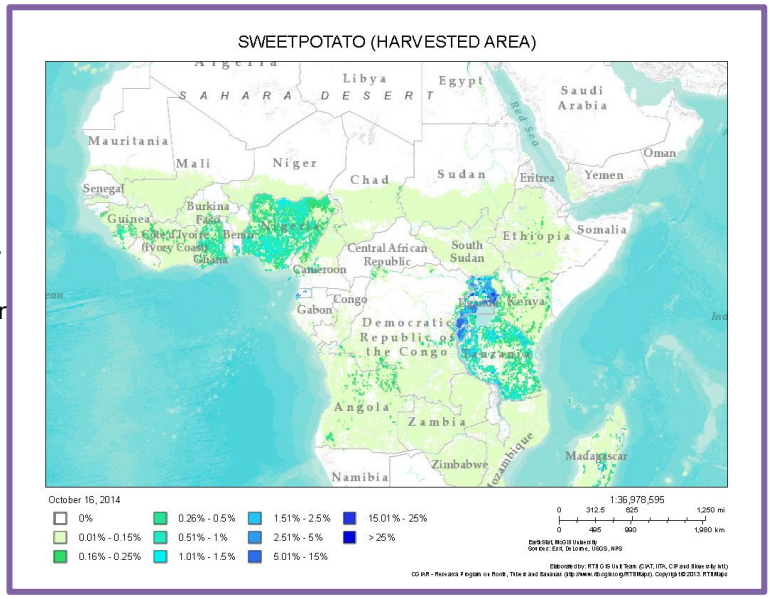
Sweetpotato: Highlights

- There is a paucity of literature concerning sensory evaluation of sweetpotato in SSA, but existing consumer studies reported that consumers prefer sweetpotato with high dry matter content (floury, starchy).
- Many sweetpotato textural traits appear to be environmentally determined (or to arise from gene-by-environment interactions).
- The pasting profiles of sweetpotato starch vary widely both across and within varieties.

Sweetpotato *(Ipomoea batatas)*: Food Texture Preferences in Sub-Saharan Africa

According to the International Potato Center (CIP) (2010), sweetpotato is the third most important food crop in Eastern and Central Africa. Sweetpotato is a critical crop for fighting Vitamin A deficiency, which affects an estimated 43 million children in Africa. Orange-fleshed sweet potato (OFSP) varieties have been developed to combat this disease. CIP (2010) stated that "the challenge is to breed OFSP varieties that meet consumer preferences and can compete with the traditional white and yellow-fleshed varieties." Sweetpotato is grown primarily on small plots by women, but production is expanding faster than any other major crop in SSA (CIP, 2010). Most consumer preference studies include women, and one study included in this review interviewed exclusively women and children. CIP attributes the recent growth in sweetpotato cultivation to changes in cropping patterns driven by major disease problems with Africa's cassava and banana crops. CIP maintains an extensive sweetpotato collection, with over 8,000 accessions from the Americas, Asia, and Africa (2010).

Map 2: Sweetpotato Area Harvested



Common Preparation of Sweetpotato in SSA

Sweetpotato is harvested throughout a considerable portion of Sub-Saharan Africa, though it is concentrated in areas of East and West Africa as shown in Map 2. Much of the published sweetpotato preparation literature is focused on South and Southeast Asia, whereas literature concerning common preparation practices in Africa remains sparse. In Kenya, sweetpotato roots are traditionally boiled or roasted (Kidmose, Agili & Thilsted, 2009). They are boiled in an aluminum or earthen pot under moderate heat. After the roots are covered with water, a layer of banana leaves or other cover is added. The sweetpotato is considered to be done when soft all the way through. The peel is usually removed before eating. There are three methods of roasting: raw and unpeeled roots are buried in hot ash, raw and unpeeled roots are roasted in a coal pot, or raw and unpeeled roots are roasted over netting (Kidmose et al., 2009).

Consumer Preference Studies of Sweetpotato: Preferred Characteristics

Primary sensory characteristics for sweetpotato (determined by quantitative descriptive analysis) include floury, smooth, soft, chestnutty, sweet, fibrous, grainy, moist and discolored.

Articles on consumer preferences for sweetpotato in Africa presented a relatively consistent picture that sweetpotato with higher dry matter (the starch content and "floury" quality of the crop) is generally preferred by both consumers and traders in East Africa (Kapinga, Ewell, Jeremiah et al., 1995; Kapinga, 1992). The authors indicate that taste was the most important criterion in evaluation, followed by cooking quality and color of the flesh and skin.

In a sweetpotato consumer preference study over a two-year period, Tomlins et al. (2004) found that starch, taste, and sweetness were the most dominant sensory attributes for consumers. No significant differences in mean consumer rating scores for fiber and texture were found among cultivars.

Tomlins et al. (2007) conducted a consumer preference study of orange-fleshed sweetpotato (OFSP) and pale-fleshed sweetpotato (PFSP) among children and mothers in the Lake Zone of Tanzania. They found that the majority of mothers and children gave high acceptability ratings to both OFSP and PFSP, that when ratings differed, it was due to fiber content, and that storage did not appear to affect acceptability. Tomlins et al. (2007) appears to be the only published consumer preference study conducted on this sub-population.

Figure 3: Sweetpotato Varieties

Source: Sajeev et al., 2012

Overall consumer preferences may pose a barrier to the widespread adoption of OFSP in Africa. Improved varieties with high Vitamin A content are orange to yellow. This coloration is perceived to be inferior to traditional white varieties, according to some consumer preference studies of men and women (De Groote & Kimenju, 2008). That said, some recent studies confirm that consumers also value nutritional benefits, and that recognition of a variety's potential to address a severe problem such as anemia may change the preferences of consumers (Birol, Asare-marfo, Karandikar, & Roy, 2011).

Consumer Preference Studies of Sweetpotato: Variety Preference

Sajeev et al. (2012) assessed several textural properties through both sensory and instrumental methods for white-fleshed, cream-fleshed, and orange-fleshed varieties of sweetpotato (see Figure 3). This study did not find textural similarity between raw tubers with the same flesh color; however when cooked, the flesh and flours of each color of tuber were found to have similar properties, as shown in Tables 9 and 10.

Sajeev and colleagues also conducted a sensory evaluation, finding that mealiness of cooked tubers decreased in the following order: "CO3-4 > SI 60 > SV 280 > 362-7 > Sree Varun > SV 98 > Sree Arun." The authors concluded that "similar trends could not be observed for the biochemical constituents of the sweet potato tubers, which showed that the textural characteristics of cooked tubers cannot be correlated to any specific component of the tubers but depends on a number of factors, such as quality of the starch, interaction between the components in the tubers, and the structural makeup of the tuber tissues." A Principal Component Analysis (PCA) revealed that clusters based on texture and pasting characteristics were similar to classifications which were associated with the color of the flesh of the tuber (Sajeev et al., 2012).

Table 9: Textural Properties of Sweetpotato Raw Tubers

	Puncture Test				Cutting/Shearing Test		
Varieties	Stiffness, N/s	Firmness, N	Toughness, Ns	Piercing force, N	Piercing energy, Ns	Cutting force, N	Cutting energy, Ns
White fleshed							
SI 60	22.99±1.17 b	90.19±6.46 b	1302±165.12 b	26.59±2.08 d	265.13±23.33 b	187.73±39.38 cd	2518±462.02 bc
SV 280	21.65±3.38 b	95.06±17.44 b	1334±255.37 bc	24.59±2.27 c	265.92±25.95 b	137.79±26.77 a	1809±354.97 a
CO3-4	17.23±4.8 a	106.01±15.5 c	1452±224.27 c	24.66±3.41 c	272.88±37.86 b	191.82±42.43 cd	2485±619.05 bc
Cream fleshed							
Sree Arun	18.13±3.32 a	88.47±9.15 b	1292±157.41 b	25.34±2.63 cd	255.23±26.25 b	211.51±44.75 d	2733±468.51 c
Sree Varun	22.05±4.25 b	89.76±6.67 b	1285±114.83 b	25.92±2.74 cd	267.07±24.14 b	167.84±57.75 bc	2166±739.48 ab
Orange fleshed							
362-7	22.93±6.20 b	75.88±8.85 a	1049±186.42 a	20.13±2.76 a	235.70±23.13 a	154.79±40.11 ab	1835±653.85 a
SV 98	22.35±4.09 b	93.49±7.61 b	1353±124.13 bc	22.23±1.96 b	265.67±20.60 b	169.78±38.88 bc	2229±571.47 b

Means with the same letters in a column are not significantly different ($p < 0.05$) by Duncan's multiple range test. ± denotes standard deviation. Varieties included: (a) 362-7; (b) CO3-4; (c) SI 60; (d) Sre Arun; (e) SV 280; (f) SV 98; (g) Sree Varun.
Source: Adapted from Sajeev et al., 2012

Table 10: Textural Profile Parameters of Cooked Sweetpotato Tubers

Varieties	Hardness, N	Adhesiveness, Ns	Springiness	Cohesiveness	Chewiness
White fleshed					
SI 60	19.62±5.54 b	−0.36±0.30 bc	0.943±0.273 a	0.270±0.091 ab	4.95±2.69 b
SV 280	17.23±4.91 b	−0.63±0.33 a	0.955±0.202 a	0.272±0.059 ab	4.56±1.91 b
CO3-4	26.84±11.14 c	−0.23±0.20 bc	0.0.964±0.21 a	0.218±0.036 a	5.89±3.56 b
Cream fleshed					
Sree Arun	9.36±5.74 a	−0.47±0.38 ab	1.020±0.468 a	0.234±0.046 ab	1.799±1.093 a
Sree Varun	16.06±8.41 b	−0.33±0.25 bc	0.919±0.182 a	0.276±0.085 ab	4.21±2.65 b
Orange fleshed					
362-7	16.12±4.03 a	−0.154±0.11 c	0.864±0.24 a	0.289±0.045 b	3.86±1.03 b
SV 98	14.76±3.18 ab	−0.35±0.15 bc	1.046±0.207 a	0.279±0.068 ab	4.18±1.14 b

Means with the same letters in a column are not significantly different ($p < 0.05$) by Duncan's multiple range test. ± denotes standard deviation. Varieties included: (a) 362-7; (b) CO3-4; (c) SI 60; (d) Sre Arun; (e) SV 280; (f) SV 98; (g) Sree Varun.
Source: Adapted from Sajeev et al., 2012

Laurie and colleagues (2013) compared 12 sweetpotato varieties (including Vitamin A-enhanced orange-fleshed varieties) in South Africa in one of the first studies to relate sensory attributes and consumer acceptance to chemical and instrumental measurements (Table 11). They found that high consumer acceptability was related to dry mass, sweetness and maltose content. However, the preferences found in this study may vary from larger sweetpotato-producing regions in SSA like East and West Africa, where the crop is a staple in some regions.

Table 11: Mean Acceptability Scores for 12 Sweetpotato Varieties

Variety	Acceptability for color	Variety	Acceptability for eating quality
Monate	3.56 ± 1.19	Monate	3.82 ± 1.19a
Excel	3.46 ± 1.32	Impilo	3.79 ± 1.38a
Beauregard	3.43 ± 1.35	2001_5_2	3.72 ± 1.25ab
Blesbok	3.43 ± 1.20	Serolane	3.71 ± 1.21ab
1999_1_7	3.39 ± 1.34	Excel	3.69 ± 1.36ab
Serolane	3.36 ± 1.32	Resisto	3.68 ± 1.31ab
2001_5_2	3.33 ± 1.35	W-119	3.67 ± 1.29ab
Impilo	3.31 ± 1.25	Ndo	3.65 ± 1.21ab
Resisto	3.26 ± 1.41	Blesbok	3.40 ± 1.30abc
Ndou	3.17 ± 1.42	1999_1_7	3.33 ± 1.34bc
W-119	3.04 ± 1.33	Khano	3.14 ± 1.44c
Khano	3.00 ± 1.38	Beauregard	3.11 ± 1.42c
Mean	3.31	Mean	3.56
F ratio probability	NS	*F* ratio probability	$P < 0.01$

Values are mean ± standard deviation. Means with a common letter do not differ significantly at the 5% significance level. NS = not significant. Varieties were rated on a hedonic scale: 1=very bad, 2=bad, 3=indifferent, 4=nice, 5=very nice
Source: Adapted from Laurie et al., 2013

Van Oirschot and colleagues (2003) used quantitative descriptive analysis to determine changes in sensory characteristics of sweetpotato after storage.[3] They studied five varieties in Kenya: SPK004 and Kemb10 (East African), Yan Shu 1 (Chinese), KSP 20 (bred by CIP in East Africa) and Zapallo (South American). Through Principal Component Analysis, the authors found that the differences between sweetpotato cultivars in the study were primarily determined by textural traits. Storage exhibited almost no effect on the sweet or chestnutty characteristics or on textural characteristics. In sum, the sensory changes that occurred during storage were less significant than the differences between cultivars.

Tomlins et al. (2004)[4] conducted a cluster analysis of consumer preference ratings for sweetpotato cultivars over a two-year period. This research was motivated by a desire to identify new cultivars that are both productive and appreciated by consumers. In survey and panel exercises, both consumers and traders expressed a general preference for sweetpotato with high dry matter content (starchy or floury) and good taste. The ratings underwent a cluster analysis to determine the factors driving preference. Three clusters emerged: the first scored low on sensory attributes, the second scored higher for stickiness, texture, chewiness, internal color, external color, appearance and odor, and the third scored highly for internal color, external color, appearance, odor, sweetness, taste and starch. Starch and stickiness were found to be the strongest drivers of preference. SPN/0 and Polista, part of the third cluster, were consistently rated as the most preferred, while Mzondwa and Serena were least preferred[5]. Relatedly, SPN/0 and Polista had the highest scores for taste, sweetness and starch, but the lowest scores for stickiness and texture. Women gave slightly higher ratings than men did to SPN/0, Ipembe, and Sinia B. The frequency of sweetpotato consumption was inversely related to the ratings for SPN/0 and Sinia B. Age had

[3] A similar approach in Côte d'Ivoire compared sensory properties of different yam varieties, *D. cayenensis-rotundata* and *D. alata* (Nindjin et al., 2007).
[4] Tomlins et al. (2004) conducted both a sensory analysis with trained assessors, and consumer testing (n=100). The sample was composed evenly of men and women, most aged 20-49.
[5] This study did not include the variety Tainug. Kidmose et al. (2009) report that Tainug has been found to retain the most Vitamin A in comparison with other varieties, such as SPK 004, Salyboro, Zapallo, 199062.1, Nyathi, and Odiewo. Sweetpotato is a significant source of Vitamin A for sub-Saharan Africa (Tomlins et al., 2004), and thus varieties that retain this water-soluble vitamin after cooking are important nutritionally.

no significant effect on preference. The highest-scoring cultivars may have been subject to factors not driven by genetics, including climatic and storage differences.

Furthermore, while there was limited locational variation in consumer preference ratings in this study (conducted in the Lakes Region of Tanzania), some of the cultivars studied varied from year to year and with location[6]. The authors indicated that more research is necessary to understand why some cultivars are not preferred consistently. Tomlins et al. (2004) also reported that their methods simplify screening assessment for optimum sensory characteristics. Screening programs "often consider a large number of cultivars, so any method that simplifies the assessment would be advantageous." Using stepwise discriminant analysis to determine the minimum number of sensory characteristics that could be considered while still distinguishing among other clusters[7] of cultivars, starch and stickiness were reported as key sensory attributes for distinguishing among clusters. The authors concluded that other factors such as yield, disease resistance, storability, cookability, and susceptibility to damage during transport could be incorporated into future consumer preference studies in East Africa.

In response to recent concerns that improved cultivars displace traditional varieties and lead to decreases in biodiversity, Zawedde et al. (2014) surveyed 102 farmer households across the top three sweet potato production zones in Uganda regarding their planting decisions. They found that very few varieties appeared across multiple regions. Most farmers expressed their preference for continued planting of existing varieties while also introducing new cultivars. Farmers further reported that drought-imposed losses tended to restrict diversity, along with limited land and suboptimal management access and opportunity. Factors which tended to lead to the introduction of new varieties included higher yield, taste and maturation timeframe, while existing varieties were appreciated and maintained for their robustness in the face of biotic and abiotic stress, good taste and yield stability – further reinforcing the importance of these parameters for breeders.

Sweetpotato *(Ipomoea batatas)*: Determinants of Food Texture

Recent studies have found significant variation in sweetpotato appearance and textural characteristics, even within the same country (see for example Ellong, Billard & Adenet, 2014).

Physicochemical Properties Related to Texture in Sweetpotato

Katayama and colleagues (2002) found that an improved sweetpotato line (Kanto 116) exhibited a low gelatinization temperature and changed starch fine structure as evidenced by abnormal starch granule morphology. However, starch content, amylose content, and tuberous root appearance of this sweetpotato were similar to other lines.

Tomlins et al. (2012) used principal component analysis to study how the sensory properties of 11 sweetpotato cultivars in Uganda varied with carotenoid and dry matter content (Varieties studied: orange-fleshed (Ejumula, Kakamega, SPK004/1, SPK004/6/6 and SPK004/ 1/1), yellow-fleshed (Tanzania and Naspot 1) and white-fleshed (Dimbuka, Nakakande, New Kawogo and Ndikirya N'omwami)). Biofortified varieties of OFSP had high carotenoid and low dry matter content, while traditional PFSP varieties had low carotenoid and high dry matter content and tended to be preferred by consumers. The study found that "orange cultivars were associated with pumpkin odour and taste, orange and uniform colour, soft and watery texture and smooth appearance, while the yellow varieties were associated with yellow colour and white fleshed varieties with sweet taste, crumbly texture, sweet potato odour and white colour." The association of OFSP varieties with watery texture suggests lower dry matter content (Tomlins, Owori, Bechoff et al., 2012). Correlations between the sensory scores for each attribute and dry matter and carotenoid contents are shown in Table 12.

***Table 12.* Correlations between Dry Matter Content, Carotenoid Content and Sensory Attributes of Sweetpotato**

	Dry matter content (%)	Log_{10} total carotenoid (µg/g fresh weight)
Sweetpotato odor	0.760**	-0.902**
Pumpkin odor	-0.721*	0.952**
Smooth appearance	-0.645*	0.673*
Yellow color	0.169	-0.075
Orange color	-0.780**	0.951**
White color	0.569	-0.865**
Uniform color (cut surface)	-0.070	0.090
Sweet taste	0.725*	-0.446
Pumpkin taste	-0.717*	0.917**
Crumbly texture (hand)	0.731*	-0.681*
Watery texture	-0.728*	0.667*

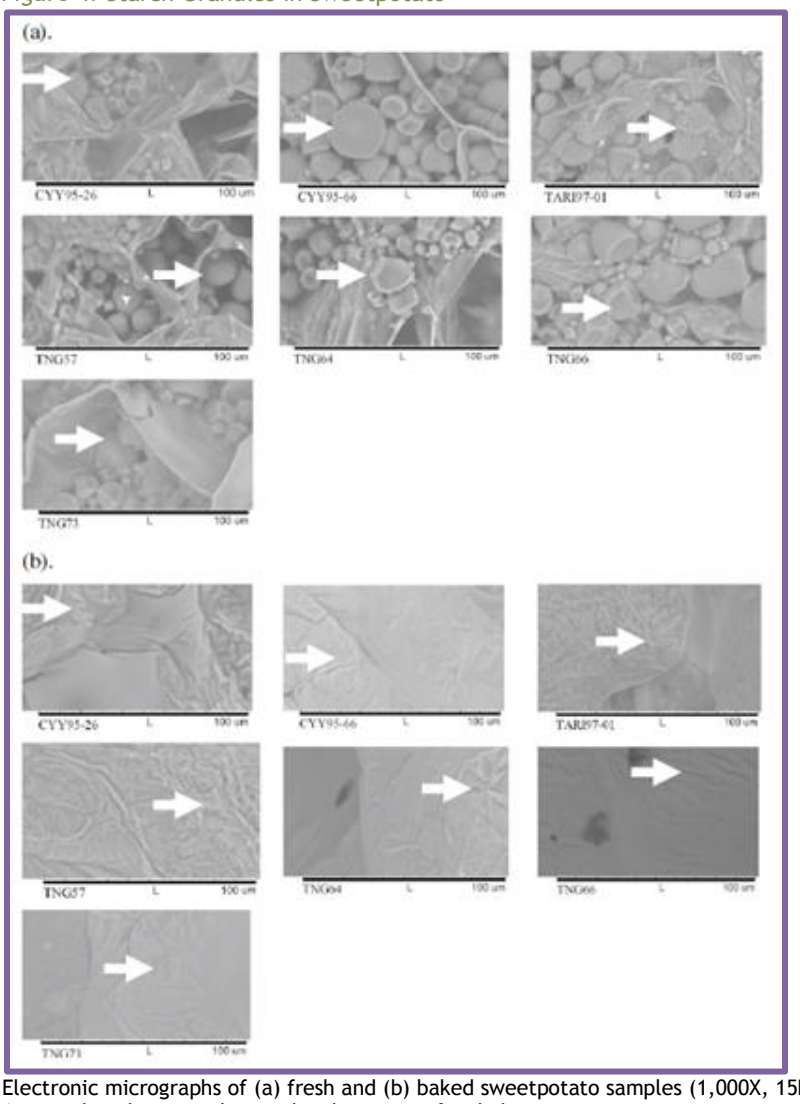
*** significant at P < 0.05**
**** significant at P < 0.001; n=11.**
***Source:* Adapted from Tomlins et al., 2012.**

Lai and colleagues (2013) used instrumental and chemical analysis to examine the effects of baking on sugar content and starch morphology in seven sweetpotato cultivars. Consistent with previous studies, they found that moisture content,

[6] This study was conducted within Tanzania, therefore all variation is within the country.
[7] Cluster analysis combined the sensory characteristics of all cultivars in the study and identified three clusters according to similarities in sensory properties.

which is correlated with physicochemical properties and sensory characteristics, decreased by 5-10% during baking. They found that while raw sweetpotato had very low maltose content, thermal processes induced maltose formation and increased the total sugar content by as much as 200% (including glucose, fructose, sucrose, and maltose). As the sweetpotato was heated, starch granules, which were oval-shaped and of varying size in raw sweet potato, gelatinized completely and were rendered invisible in electronic micrographs (see figure 4). The authors noted that as degradation of sweetpotato is a result of enzymatic reactions, starch granules also affect the shelf life of sweetpotato (Lai, Huang, Chan et al., 2013).

Figure 4. Starch Granules in Sweetpotato



Electronic micrographs of (a) fresh and (b) baked sweetpotato samples (1,000X, 15KV). Arrows show how starch granules disappear after baking treatment.
Source: Lai et al., 2013

Genetic Drivers of Texture in Sweetpotato

One breeder study estimated the genetic variance of starch digestibility of 25 sweetpotato genotypes (*Ipomoea batatas* (L.) Lam). Zhang, Collins, & Andrade (1996) found significant genotypic variation of starch, with some sweetpotato clones possessing starch digestibility equivalent to corn. The authors further found that genotypic variance was the dominant component in starch digestibility, concluding that "starch digestibility of sweetpotato could be improved to a level as that of corn through conventional breeding."

The pasting profiles of sweetpotato starch vary widely, as illustrated by Collado et al. (1999) through comparison of 11% and 7% starch concentrations and 44 genotypes as seen in Tables 13 and 14. At 11% starch, pasting was characterized by

high to moderate peak, major breakdown, and low viscosity in the cold paste (Type A in the classification of Schoch & Maywald (1968), developed for starch slurry in the range of 3 to 7%). At 7%, the pasting lacked a distinct peak with none to very slight breakdown and high viscosity in the cold paste, also called Type C. Negative correlation was found between peak viscosity (PV) and hot paste viscosity (HPV) for the 11% starch paste concentration with amylose content. Viscosity and setback ratio were correlated with adhesiveness of the starch gel. "Starch, amylose, hardness, and adhesiveness properties were assessed by genotype (all of these traits are defined in Szczeniak's paper on texture classification). However, differentiation among genotypes was better achieved from RVA pasting profiles at 11% starch concentration."

Table 13: Total Starch Content, Amylose Content, Swelling Volume, Solubility, and Starch Gel Texture of Sweetpotato

			Starch		Starch Gel Texture	
Genotype	Total starch (%)	Amylose (%)	Swelling Volume	Solubility	Hardness	Adhesiveness
CN94625	97.2	24.5	28.8	19.20	20.9	-13.6
CN94132	96.3	20.6	30.6	20.2	17.8	-13.4
CN148989	97.9	16.7	28.4	16.9	24.0	-21.2
CN1425170	98.1	17.6	31.9	20.1	34.3	-3.6
BPISP2	97.5	22.1	30.2	19.6	20.1	-11.7
Miracle	97.2	20.3	32.5	13.1	18.3	-33.6
26 Pariados	97.4	16.1	26.8	16.8	22.8	-35.6
13b Tres Colores	96.5	23.4	30.0	18.4	17.1	-38.8
Binicol	97.0	16.4	29.2	17.4	18.8	-25.3
30 Inubi	95.1	17.3	29.8	17.8	24.3	-35.5
Adams 3	93.7	15.2	28.5	17.0	26.5	-26.5
P5	96.1	20.6	31.6	21.0	20.5	-37.5
P16	98.6	19.4	29.5	18.1	21.5	-28.2
no. 46 CIP	97.1	15.2	30.0	18.8	20.7	-13.5
NTA1023	97.7	14.9	28.0	16.4	23.1	-5.3
12 Tres Colores	96.4	19.7	27.1	13.4	19.9	-18.5
Binoras 23	98.2	20.3	29.0	17.3	17.8	-21.1
Inubi Zam	97.0	20.6	31.8	21.4	21.2	-26.0
Catanduanes	97.2	16.7	28.1	16.5	23.5	-43.5
Taiwan	94.6	15.2	29.4	17.7	31.7	-52.0
Bureau	96.3	17.6	32.2	24.1	15.8	-16.5
no. 65 CIP	97.7	13.2	27.5	14.8	26.1	-5.6
L002	95.5	17.0	26.1	14.7	21.8	-18.6
NPSP	96.4	21.1	27.9	15.3	20.2	-39.9
PNG L6	97.9	18.0	27.6	15.4	23.9	-5.8
UPLSP2	97.8	22.4	24.7	12.5	16.0	-19.6
UPLSP5	97.0	14.0	27.3	14.2	21.9	0.0
46-12A	96.8	15.7	27.2	13.7	23.8	-11.0
89-2-10	98.9	29.7	32.5	14.6	18.4	-52.3
88ws623	98.2	18.8	27.5	14.4	21.1	3.0
G88	97.5	26.5	32.7	14.9	18.0	-13.5
25-11A	97.9	25.4	29.5	18.1	16.0	-19.6
G-139-21	97.2	15.7	25.2	12.4	22.5	-28.4
93-006	96.2	28.5	29.5	17.8	31.6	-31.1
VSP-6a	96.4	15.7	30.1	19.3	21.5	-19.4
VSP-6b	96.6	15.9	28.4	17.4	22.5	-28.4
V37-151	96.7	14.8	28.3	16.6	26.2	-16.1
OPS44	96.7	29.7	29.9	19.3	36.1	-37.8
VSP-7	95.9	12.9	30.1	19.6	19.9	-2.2
V30-595	97.2	28.3	24.5	13.2	25.6	-50.5
OP101-R89	96.5	18.0	30.9	20.6	20.6	-31.6
OPS101	96.0	15.7	29.5	18.1	22.0	-37.9
Inagahapon	97.0	16.9	26.4	12.1	37.1	-41.8
UPLSP4	98.0	17.6	27.6	15.3	24.1	-30.5
mean	96.9	19.1	29.0	16.9	22.7	-24.1
LSD (0.05)	0.6	0.3	0.6	1.5	2.5	3.8

Source: Adapted from Collado et al., 1999

Table 14: Correlations of Starch Gel Texture, Swelling Volume, Solubility, and Amylose Content with RVA Pasting Parameters at 11% Starch Concentration (*N*=44 Genotypes)

	Hardness	Adhesiveness	Swelling Volume	Solubility	Peak Viscosity	P_{time}^	Hot Paste Viscosity	Cold Paste Viscosity	Stability Ratio	Setback Ratio
Hardness	-									
Adhesiveness	-0.20	-								
Swelling Vol.	-0.18	-0.02	-							
Solubility	-0.09	0.07	0.66***	-						
Peak Viscosity	0.03	0.46***	-0.04	0.08	-					
P_{time}^	-0.29	0.19	0.08	-0.18	-0.10	-				
Hot Paste Visc.	-0.06	0.41**	-0.17	-0.26	0.75***	0.31*	-			
Cold Paste Visc.	-0.16	0.25	-0.13	-0.26	0.59***	0.32*	0.94***	-		
Stability Ratio	-0.18	0.03	-0.17	-0.48**	-0.18	0.63***	0.51***	0.64***	-	
Setback Ratio	-0.08	-0.58***	0.13	0.13	-0.80***	-0.26	-0.80***	-0.57***	-0.16	-
Amylose	0.06	-0.35*	-0.22	0.00	-0.89***	0.07	-0.72***	-0.60***	0.10	0.75***

*, **, and *** refer to significance at p < 0.05, 0.01, and 0.001, respectively.
^ P_{time} is the time from onset of increase in paste viscosity to the peak viscosity.
Source: Adapted from Collado et al., 1999

Many sweetpotato textural traits appear to be environmentally determined (or to arise from gene-by-environment interactions, not solely from genetic factors), which complicates breeding-based efforts to improve textural traits. Noda, Kobayashi & Suda (2001) found that soil temperatures during initial growing stages have a significant influence on starch properties of two sweetpotato cultivars, Ayamurasaki and Sunnyred, grown at 15, 21, 27, and 33 C: "When soil temperature increased from 15 to 33 C, the amylose content of the starch increased 5%, the average granule size increased 4 microns as the soil temperature increased from 15 to 27 C," and a "distinct reduction in short chains of amylopectin with DP 6 and 7" was observed. The researchers found "extensive" variations in starch gelatinization characteristics as soil temperature increased.

In an earlier paper, Noda and colleagues (1997) explored the effect of planting and harvesting dates on starch properties of sweetpotato, finding that amylose content was nearly independent of both planting and harvesting dates, that "the proportions of the short chains of amylopectin were lower at the earliest harvesting, while the planting date had little influence on the chain length distribution of amylopectin," that both the harvest and planting date had significant effects on pasting and gelatinization, that earlier planting and harvest dates were correlated with a lower peak viscosity, and finally, that both planting and harvesting affected the mean size of starch granules.

A table summarizing textural characteristics, consumer preferred characteristics, physicochemical drivers of textural attributes, and genetic drivers of texture for sweetpotato is provided below:

Table 15: Summary of Determinants of Consumer-Preferred Textural Traits in Sweetpotato

Trait	Description	Consumer Preferred	Physicochemical Driver	Genetic Driver	Source
Hardness	See Tables 10, 13 & 14	Soft +	NA	NA	Tomlins et al. (2004); Sajeev et al. (2012); Collado et al. (1999)
Cohesiveness	See Table 10	Chewy +	NA	NA	Tomlins et al. (2004); Sajeev et al. (2012)
Viscosity	See Table 14	NA	NA	NA	NA
Springiness	See Table 10	NA	NA	NA	Sajeev et al. (2012)
Adhesiveness	See Tables 10, 13 & 14	Sticky +	Viscosity and setback ratio	See Table 13	Tomlins et al. (2004); Collado et al. (1999); Sajeev et al. (2012)
Smoothness	See Table 12	Smooth +	NA	NA	Tomlins et al. (2012)
Particle Size	Varies	Grainy + Floury +	Soil temperature	NA	Kapinga et al. (1995); Kapinga (1992); Noda et al. (2001); Lai et al. (2013)
Particle Shape	Oval shape See Figure 4	Fibrous +	NA	Kanto 116 (this line exhibits abnormal starch granule morphology)	Kapinga et al. (1995); Katayama et al. (2002); Lai et al. (2013)
Moisture Content	NA	Moist + Starchy +	High starch content	SPN/0; Polista	Kapinga et al. (1995); Tomlins et al. (2004)
Fat Content	NA	NA	NA	NA	NA

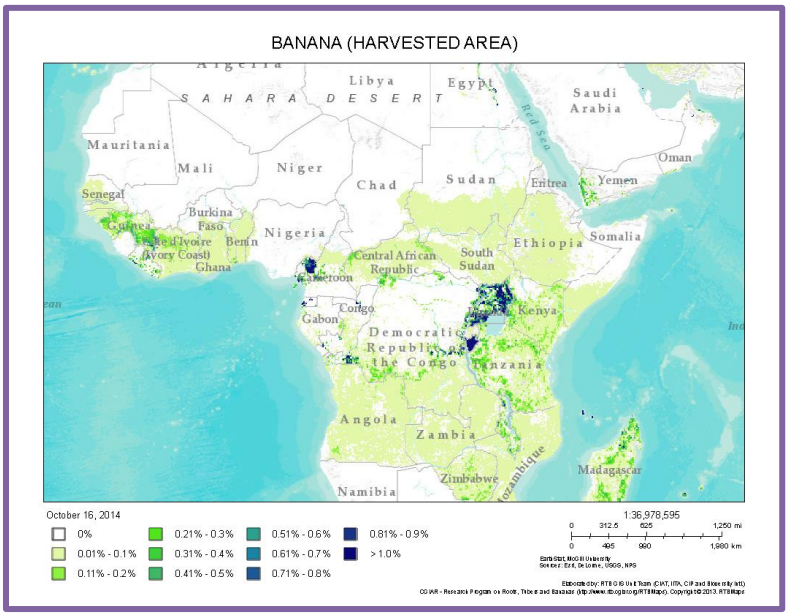
Banana/Plantain: Highlights

- Key sensory characteristics for banana include hardness (softness), taste (sweetness), and color (light yellow). Level of ripeness is also an important sensory component for consumers.
- New varieties may be rejected by some ethnic groups but accepted by others in SSA due to high variation in food preparation styles.
- Starch structures and other physicochemical properties of many *Musa* genotypes have been researched extensively.
- Banana fruit texture is especially dynamic due to the degradation of starch during fruit ripening. Multiple genes regulate ripening and softening.

Banana/Plantain *(Musa spp.)*: Food Texture Preferences

Plantain (*Musa spp.*, AAB group) and banana (*Musa spp.*) are important starch staples throughout West and Central Africa (Stover & Simmonds, 1987). Plantain is grown primary by smallholder farmers in Sub-Saharan Africa (Stover & Simmonds, 1987). Plantain's importance has been underpinned by its value for food security and job creation (Dzomeku, Darkey, Bam et al., 2007a). Both plantain and banana are important sources of rural income (Ortiz & Vuylsteke, 1996). Because of the growing pest and disease pressures on plantain and banana, there have been significant efforts to create pest and disease tolerant varieties. Most of the introduced hybrids are agronomically stable, high-yielding, and tolerant of disease and pests; however, studies on acceptability into local diets and consumer preference have been sparse.

Map 3: Banana Area Harvested



Common Preparation of Banana/Plantain in SSA

As seen in Map 3, banana/plantain is harvested throughout a large proportion of Africa, with particular concentration in East Africa. Africa produces 71% of the world's plantain, and 14% of the world's banana. Plantain is the most produced commodity in Uganda, the world's leading producer (FAOSTAT, 2013). There are many different ways to cook plantain (Dury, Bricas, Tchango-Tchango et al., 2002). In many parts of Africa, cooking banana is prepared by boiling or steaming, and then mashed, baked, dried, or pounded for *fufu*. In Cameroon, green banana is boiled and served as a sauce (FAO, 1993). Pounded banana products are also referred to as *ampesi* in various parts of Africa (FAO, 1993). *Kaakle* is another commonly prepared dish in West Africa, and it is created by blending overripe plantain or banana pulp with corn flour, salt, and spices to produce a paste.

Consumer Preference Studies of Banana/Plantain: Preferred Characteristics

Key sensory characteristics for banana include hardness (softness), taste (sweetness), and color (light yellow) (Dzomeku et al., 2007a). Depending on the preparation method, the amount of ripeness is also an important selection factor. Dzomeku et al. (2007a) stated, "Because of the varying methods of cooking and uses of plantains, the texture, particularly, the softness of the cooked plantain is very important in determining a good cooking plantain cultivar."

Another study conducted at an urban market in Kwara State of Nigeria finds similar sensory attributes among *Musa* varietals. The results of a consumer preference panel indicated that consumers generally prefer "fingers" (banana fruit) of medium or big size, hands containing 9-12 fingers, pulp with light yellow color, absence of black spots in the peel, firm texture, aroma and flavor of medium intensity, and medium-sweet fruits with a shelf-life of seven to nine days (Ayinde, Adiwume & Folorunsho, 2007).

Consumer Preference Studies of Banana/Plantain: Variety Preference

Dury et al. (2002) found that women in Cameroon have distinct varietal and ripeness preferences that correspond to the cooking method of plantain. In this study, the women surveyed indicated satisfaction with the quality of the cultivars of plantain available in local markets, but that income constrained their consumption.

Gold et al. (2002) found a high level of cultivar diversity among farmers in Uganda, with a mean cultivar count of 26 at each site used for the study. A range of 4 to 22 cultivars was found at each farm, with an average of 12.3. When interviewed, farmers cited reasons for diversity such as better food security, a variety of end uses, and the perception that each cultivar had unique strengths and weaknesses.

Leite and colleagues (2007) conducted a consumer preference analysis on two strains of dried banana (prata and d'agua) in Nigeria. Participants scored dried banana products obtained at lower temperatures (prepared with a tray dryer that reduces the drying time and creates a final product that is lighter in color) as "superior" to those of the commercial sample. The authors further found that in both strains, dehydration reduced carbohydrate, lipid, and protein content, more significantly at higher temperatures.

Nowakunda et al. (2000) found that, among 14 *Musa* cultivars introduced in Uganda, consumers rated new varieties as unacceptable for cooking purposes due to high tannin contents, hard texture, and poor taste compared with traditional cultivars. Cultivars FHIA-01, FHIA-17, and FHIA-23, however, received acceptable ratings for cooking purposes. Overall, cultivars FHIA-01, FHIA-03, Yangambi km5, and Saba received good ratings for juice characteristics, and could replace the traditional local juice-producing cultivars.

Dzomeku et al. (2008) assessed the consumer acceptability of three Musa hybrids (BITA-3, a cooking banana, and FHIA-21 and CRBP-39, plantain hybrids) for cooking uses such as *fufu*, *ampesi*, and fried ripe plantain with 500 farmers in central Ghana. A total of 360 male and female untrained taste panelists from four communities (Assin Foso, Adiembra, Bremang and Amoanin, in the two Assin districts of Ghana's Central region) participated in the study. At each location, panelists tried two samples of *fufu*, *ampesi*, and fried plantain made from local cultivars Apantu (for *fufu* and fried plantain) and Apem (for *ampesi*) and Musa hybrids (FHIA-21, BITA-3 and CRBP-39). Participants compared samples on the basis of texture, taste, color and overall acceptability using a categorical scale of 1-5. Dzomeku et al. (2008) reported no significant difference ($p<0.01$) between FHIA-21 and CRBP-39 and Apantu. They found that participants most preferred FHIA-21 and CRBP-39, which compared favorably with local triploids Apantu and Apem.

Dzomeku et al. (2007a) found that new varieties may be rejected by some ethnic groups but accepted by others in the Volta region of Ghana due to high variation in food preparation styles. The authors emphasized that the success of any new hybrid relies in part on acceptance of common dishes prepared with it. All four FHIA hybrids in this study were accepted when processed into *kaakle*. On a 5-point hedonic scale, the FHIA varieties demonstrated very little variability in sensory qualities, including texture (i.e. 1=Very soft to 5=Very firm) (Dzomeku et al., 2007a).

Dzomeku et al. (2007b) carried out a comparison of the farmer reported sensory qualities of IITA hybrids (BITA-3, BITA-2, PITA-4, PITA-1) with two local landraces and FHIA-21 from two locations in Ghana. The hybrids had good disease resistance and superior agronomic properties. FHIA 21 was rated highest by the farmers for yield, and taste and commercial potential. In addition a majority of farmers reported that the PITA hybrids had good taste properties and were suitable for fufu. BITA-2 was considered suboptimal due to its short and small fingers (Dzomeku, Quain, Lamptey et al., 2007b).

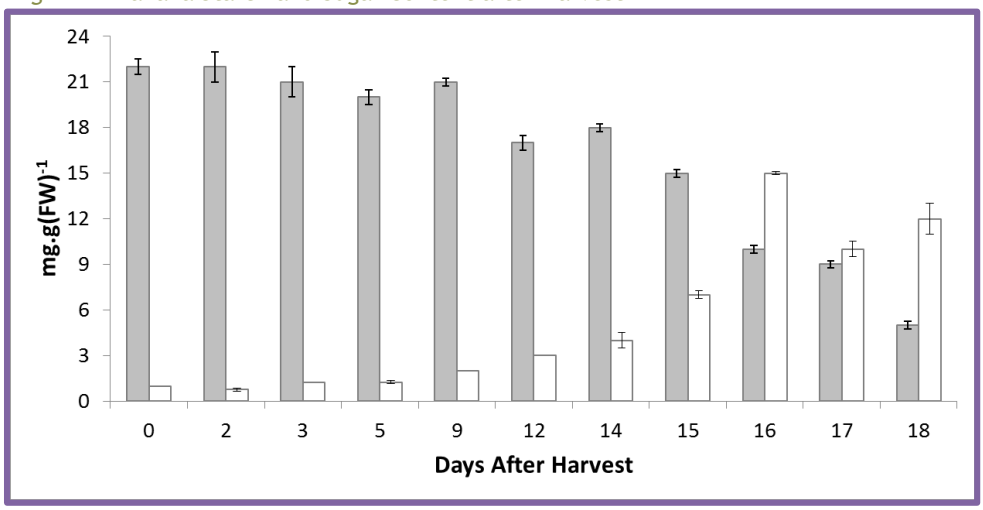
Ssali et al. (2010) studied 18 hybrids of 'Matooke' East African highland cooking bananas in Nakaseke district of central Uganda. They found that sensory evaluation was more important to consumer acceptability than yield or disease resistance was. In a sensory evaluation with a panel of 25 banana farmers, they found that "'Mbwazirume' had a characteristic yellow 'Matooke' color that was matched by 'M10', 'M9' 'M14' and 'M2'. The hybrid 'M10' was not liked because of the pronounced and sticky placentas, an attribute disliked by consumers. Most hybrids were perceived as less soft than 'Mbwazirume', with the exception of 'M3', 'M14' and 'M2' (Ssali, Nowankunda, Barekye Erima et al., 2010)."

Banana/Plantain *(Musa spp.)*: Determinants of Food Texture

Banana and plantain (*Musa acuminata* and *balbisiana* hybrids) are perennial crops with two geographic centers of genetic diversity (IITA, 2009a). Researchers believe their primary origin is in Southeast Asia and a second center of genetic diversity is located in Central Africa. The *Musa* genome has been researched extensively for breeding capability, developing biotechnology techniques, investigating post-harvest quality, and analyzing genotype-by-cropping system interaction in Africa (Vuylsteke, Ortiz & Ferris, 1993).

Banana fruit texture is especially dynamic due to the degradation of starch during fruit ripening. As shown in Figure 5, Peroni-Okita and colleagues found a pattern of starch degradation and conversion to soluble sugar in the days after fruit harvest, as well as differences in the size and shape of starch granules depending on maturity of the banana *(Musa acuminata* AAA cv. Nanicão) (Peroni-Okita et al., 2010). While green banana starch granules had oval and rounded shapes with smooth surfaces, ripe banana had elongated granules with circular depressions and layered striations due to post-harvest degradation. Such dramatic changes in banana texture due to post-harvest ripening are important considerations in the interpretation of measured textural traits.

Figure 5: Banana Starch and Sugar Content after Harvest



Source: Adapted from Peroni-Okita et al., 2010

Physicochemical Properties Related to Texture in Banana/Plantain

Starch structures and other physicochemical properties of many *Musa* genotypes have been researched extensively. Kayisu and colleagues (1981) found that ripe banana fruit contained 1.27% dietary fiber, as determined by the detergent method. Hemicellulose content was higher than in most other fruits and vegetables, while cellulose and lignin contents were lower. The swelling patterns for banana starch were similar to those reported for mung-bean starch, and banana starch solubility was intermediate between potato and tapioca starch. Higher solubility indicates a lower involvement in amylose in crystalline regions (Kayisu, Hood, & Vansoest, 1981).

Bello-Perez & Agama-Acevedo (1999) found that two common varieties of banana in Mexico ("macho" and "criollo") contained different starch structures evidenced by viscosity. The study observed chemical analysis and physicochemical and functional properties, including moisture content, ash, protein and fat measurements. Methods included calculations of total starch, blue values (absorbance at 680 nm; obtained using Gilbert and Spragg method (1964)), clarity, freeze-thaw and water retention, swelling solubility and apparent viscosity methods. Their chemical analysis is summarized in Table 16.

Table 16: Chemical Analysis and Functional Properties of Banana Starches

	λ_{max} (%)*	Blue Value*	Freeze-Thaw Stability (mL)*	Clarity (% *T*)*	Total Starch Content (%)**	Moisture Content (%)	Protein Content (%)***	Fat Content (%)**	Ash Content (%)**
Macho	583±2.0	0.18±0.006	2.4±0.1	12.0±1.1	97.2±2.4	12.9±0.3	2.03±0.15	2.2±0.05	1.3±0.3
Criollo	589±2.0	0.87±0.003	2.5±0.4	11.2±0.1	98.1±1.8	11.1±0.4	1.95±0.2	2.3±0.07	0.43±0.06

* Means of 3 replicates ± standard error.
** Means of 3 replicates ± standard error, dry basis.
*** Means of 3 replicates ± standard error, dry basis, N × 5.85.
Source: Adapted from Bello-Perez & Agama-Acevedo, 1999

Gibert and colleagues (2010) characterized banana texture after boiling using a mechanical approach, with attention to variation in the cooked texture with genotype. Researchers found a strong correlation between initial dry matter content and firmness, as well as differences in cooking behavior among genotypes. Banana has lower starch content than plantain, 81.9% and 86.5% respectively (Gibert, Giraldo, Uclés-Santos et al., 2010).

Another study used kinetic methods to assess color and texture of banana stored at different temperatures (Chen & Ramaswamy, 2002). The study measured puncture force (the maximum force required to puncture the peeled fruits), and found decreasing force measures over time, but slower rates of decrease at higher storage temperatures.

In a series of papers on dessert banana, Bugaud and colleagues related the rheological properties of banana fruit to texture and taste assessments. Their goal was to identify sensory qualities and instrumental relationships so these could be considered earlier in the breeding process (Bugaud, Cazevielle, Daribo et al., 2013). Initial work identified the diversity of sensory qualities in dessert banana varieties (Bugaud, Daribo, Rosalie et al., 2010). They noted important environmental relationships, finding "correlation between rainfall level and fruit firmness (R=0.88) and peel hardness (R=0.80) (Bugaud et al., 2010; Bugaud, Deverge, Daribo et al., 2011)." In a more recent paper, they related some sensory properties to measurable attributes, finding that "textural properties were predicted by titratable acidity and dry matter content (R2 = 0.62)," but that "predictions of mealiness, adhesiveness, and heterogeneity were not efficient (Bugaud et al., 2013)."

Ding (2008) tracked the physicochemical changes that occur as banana ripens. Table 17 shows the trends over six stages of ripening, including decreasing starch granule length, width and fruit firmness.

Table 17: Physicochemical Changes in Berangan Banana Fruit During Ripening

Ripening Stage	Starch Granules Length (µm)*	Starch Granules Width (µm)*	Soluble Solids Concentration (%SSC)	Firmness (kg cm^{-2})
1	29.26**	15.12	2.63**	10.60
2	27.78	13.73	10.25	2.97
3	26.21	12.76	14.00	1.78
4	24.66	12.17	16.61	1.44
5	23.61	12.00	17.53	1.27
6	22.79	11.50	19.67	1.16

* Mean of 100 observations.
** Mean separation within column by DMRT at P ≤ 0.05.
Source: Adapted from Ding, 2008

Duan and colleagues (2008) found a similar rapid decrease in fruit firmness and related ripening with an increase in water-soluble pectin (WSP) and a decrease in acid-soluble pectin (ASP), noting "changes were associated with the depolymerization of pectin polysaccharides." Banana fruit loss of firmness postharvest was related to cell wall-degrading enzymes including polygalacturonase, pectate lyase, pectin methylesterase, ß -Galactosidase, ß-1,3 glucanase (Amnuaysin, Jones, & Seraypheap, 2012).

Table 18: Correlations Between Textural Properties and Color Parameters Over 10-Day Ripening Period

Textural attributes	Color value		
	L	*a*	*b*
Peel Firmness (N)	-0.18	-0.06	-0.27
Peel Toughness (Ns)	-0.13	-0.48	0.01
Fruit Firmness (N/s)	0.09	-0.24	0.10
Pulp Firmness (N)	-0.12	-0.48	-0.08
Pulp Toughness (Ns)	-0.04	-0.40	-0.17
Stickiness (N)	0.08	0.41	0.05

Source: Adapted from Jaiswal et al., 2014

Recently, Jaiswal and team found the correlations among textural properties and color parameters of banana fruit during ripening listed in Table 18 (Jaiswal, Jha, Kaur et al., 2014).

Nwokocha and Williams (2009) compared the content, structure and properties of white and yellow plantain starch as shown in Table 19. They found similar levels of amylose in the two varieties, but distinct physicochemical properties, including weaker granule architecture in the yellow plantain starch, which was characterized by elliptical granules while white plantain starch had irregular biomodal granules. Overall, yellow plantain starch had lower gelatinization temperature, higher peak viscosity, and less stability, while white plantain starch had higher yield stress and cold paste viscosity and withstood shear forces better.

Table 19a: Composition of White and Yellow Plantain Starches[a]

Parameters	White plantain	Yellow plantain
Yield (%)	4.51	6.82
Moisture (%)	8.44±0.014	8.62±0.014
Ash (%)	1.09±0.0001	0.95±0.0002
Protein (%)	0.640±0.0004	0.325±0.0001
Fat (%)	0.276±0.0001	0.403±0.0003
Amylose (apparent) (%)	24.24±0.014	24.36±0.014
Amylose (total) (%)	26.01±0.01	26.13±0.01
Granule size range (lm)[b]	10.00-33.00 (3.74-7.00)[c]	11.22-41.00

Table 19b: Brabender Paste Characteristics of 8% Slurry of White and Yellow Plantain Starches

Parameters	White plantain	Yellow plantain
Pasting temperature (° C)	68	61
Peak viscosity, P (BU)	1000	1160
Temperature at peak viscosity (° C)	95	77
Viscosity at 95° C (BU)	1000	680
Viscosity, 30mins.at 95° C, H (BU)	840	570
Viscosity at 50° C, (BU)	1000	770
Stability ratio = H/P	0.84	0.49
Setback ratio = C/H	1.19	1.35

a Mean of two determinations ± standard deviation.
b Major axis.
c Smaller granules.
BU = Brabender Units

Source: Adapted from Nwokocha & Williams, 2009

Al-Hosni et al. (2010) studied five dessert banana cultivars (Malindi, Somali, Williams, Fard, and Negal) in Oman for postharvest characteristics. They found that Malindi had the firmest pulp, while Negal had the softest fruit tissue, making it susceptible to decay (see Table 20).

Table 20: Peel Color and Pulp Characteristics of Dessert Banana Cultivars

Cultivar	Color values			Pulp firmness	Total soluble solids (%)	Acidity (%)	TSS: Acid ratio	pH
	L	*a*	*B*					
Malindi	65.8	4.58	40.6	4.8	22.0	5.4	3.4	4.9
Somali	64.1	1.20	36.0	4.0	22.1	5.4	5.8	4.8
Fard	69.6	-0.33	38.9	4.3	24.0	7.1	3.2	4.5
Negal	68.3	0.75	38.7	3.2	12.5	7.4	2.9	5.0
Williams	69.5	0.75	45.2	3.9	18.8	5.6	1.7	5.0

Source: Adapted from Al-Hosni et al., 2010

Kheng et al. (2012) conducted analysis on physicochemical qualities of Rastali dessert banana in Malaysia. In terms of pulp firmness, they found that "There was significant interaction between harvesting weeks and days after ripening in pulp firmness as ripening occurred. During ripening, pulp firmness decreased by 90.91% and 96.53% as fruit ripened from day 0 to 5 after ripening, respectively, for banana harvested at weeks 11 and 12. Banana pulp harvested at week 12 was significantly softer than banana pulp harvested at week 11 on days 0 and 1 after ripening. As fruit ripened, softening occurred which may be due to the breakdown of cells and the conversion of starch to sugars during hydrolysis, resulting in loss of turgidity." Table 21 summarizes their findings.

Table 21: Physicochemical Qualities of Rastali Dessert Banana

Factor	Firmness (N)	pH	CO_2 (mL CO_2 kg^{-1} h^{-1})	C_2H_4 (µL C_2H_4 kg^{-1} h^{-1})
Harvesting weeks				
11	43.40	5.38	74.23	1.19
12	32.31	5.40	59.68	1.26
Days after ripening				
0	64.82	5.85	45.17	0.00
1	60.54	6.00	58.69	0.25
3	21.81	5.05	85.79	2.25
5	4.25	4.66	78.17	1.62

Means in same column with same letter are not significantly different by DMRT at P≤ 0.05.
Source: Adapted from Kheng et al., 2012

Alkarkhi et al. (2011) assessed samples of flour prepared from green and ripe Cavendish dessert banana pulp and peel for physicochemical properties. They found that the viscosity of flour made from ripe banana was much higher (67 to 91 mPa s) than that of flour from green banana (35-54 mPa s). The authors suggest that starch gelatinization contributes to viscosity

and texture in green banana flour, while viscosity and texture of ripe peel flour is driven by hemicelluloses and pectin polysaccharides, which are present in dietary fiber (Alkarkhi, bin Ramli, Yong, & Easa, 2011).

Genetic Drivers of Texture in Banana/Plantain

As noted with other RTB crops, characterization of *Musa* germplasm to index and allow for the manipulation of genetic diversity has only recently become a research priority (Christelová, Valárik, Hřibová et al., 2011). To gain a better understanding of *Musa* genetic diversity, Christelová and colleagues worked to develop a platform for genotyping using microsatellite markers. Their platform efficiently characterized genotypes and distinguished between species, subspecies and subgroups of *Musa* accessions, with implications for genetic modification in banana (though textural traits are not specifically discussed).

Earlier work on the *Musa* genome by Pillay and colleagues (2001) analyzed genetic diversity and phylogenetic relationships of 29 East African highland banana cultivars (*Musa spp.*) and two outgroup taxa, *M. acuminate* Calcutta 4 and Agbagba. The authors indicated that RAPD (Random Amplified Polymorphic DNA) markers can "readily dissect genetic differences between the closely related highland bananas and provide a basis for the selection of parents for improvement of this germplasm (Pillay, Ogundiwn, Nwakanma et al., 2001)." Follow-up work by Langhe and colleagues (2006) has categorized morphological and molecular taxonomy of *Musa (spp. AAB)*, the most diverse subgroup of triploid banana. Their study reviewed different efforts in plantain taxonomy and applied numerical taxonomy to morphological descriptors. Continuing efforts have characterized banana germplasm from Thailand, Rwanda, Tanzania, the Democratic Republic of the Congo, and India (Vuylsteke et al., 1997; Crouch, Crouch, Madsen et al., 2000; Ning, Xu, Lu et al., 2007; Nsabimana & Van Staden, 2005 & 2007; Onguso, Kahangi, Ndiritu et al., 2004; Pachuau, Atom, & Thangjam, 2014; Ruangsuttapha, Eimert, Schröder et al., 2007; Wongniam, Somana, Swangpol et al., 2010).

Gupta and colleagues (2006) explored the differential expression of genes during banana fruit development, identifying 22 genes related to ripening. Six genes down-regulated and 16 up-regulated as shown in Table 22 (Gupta, Srivastava, Sane et al., 2006). They observed that "of the defense/stress related genes, β -1,3-glucanase and the isoflavone reductase-like genes are prominent and have a high expression throughout the course of ripening."

Table 22: Differential Expression of Genes during Banana Fruit Development

Clone	Regulation	Transcript Size	Expression (Specificity)	Best Hits (BLASTx)	Acc. No.
H1-4	Up	1.5	FS, RS	Iroquois homeobox protein like (rat and human)	DQ298191
H1-26	Up	1.1	FS, RS	No significant homology	CF542264
H1-35	Up	1.2	ND	ABA stress ripening protein (*ASR2* from tomato) and other plants	DQ298189
H2-10	Down	1.2	FS	Unknown (Arabidopsis)	DQ298195
H3-5	Up	1.35	FS, RS	ß-1,3 Glucanase of *M. acuminata*	CF519299
H3-15	Up	1.45	FS, RS	No significant homology	CF542224
H4-1	Up	1.4	FS, RS	Isoflavone reductase like (*P. communis*)	CF519305
H4-11	Up	0.9	FS, RS	Conserved hypothetical protein (*C. perfringens*)	CF542265
H6-1	Down	1.3	ND	Auxin/Al responsive protein-like from *V. radiata, A. thaliana, G. hirsutum, B. napus*	CF519304
H6-9	Down	1.4	FS	Auxin/Al responsive protein-like from *V. radiata, A. thaliana, G. hirsutum, B. napus*	CF519300
H6-10	Down	0.75	ND	Unnamed product from *H. sapiens*	CF542263
H6-19	Down	0.8	FS	Unknown (Arabidopsis)	DQ298194
H8-19	Up	0.8	RR	Invertase/PME inhibitor from *Platanus x acerifolia*, rice	DQ298193
H9-2	Up	2	RR	Unknown protein (*Bos taurus*)	DQ298190
H9-3	Up	1.6	RR	Conserved protein (Arabidopsis)	DQ298187
H9-5	Up	1.5	FS, RS	Unknown membrane protein from rice	DQ298188
H9-8	Up	1.7	ND	No significant homology	CF569227
H10-1	Up	1.6	RR	Pectate lyase of M. acuminata	CF519302
H12-5	Down	1.8	FS	No significant homology	CF569230
H12-8	Up	1.4	RR	No significant homology	CF542267
H13-2	Up	1.7	RR	Transcriptional co-repressor like/regulatory proteins from Arabidopsis, rice, sorghum	DQ298192
H14-4	Up	0.65	ND	No significant homology	CF542268

FS: fruit specific expression; RS: ripening specific expression; RR: ripening related (for those genes that did not show fruit specific expression or where fruit specific expression study was not performed but nevertheless showed an increase in their transcript levels during ripening); ND: not studied in detail.
Source: Adapted from Gupta et al., 2006

Arvanitoyannis and colleagues (2008a) surveyed current biotechnological approaches for banana and plantain breeding, focusing on the potential to improve disease and pest resistance and drought tolerance through genetic modification. In a follow-up review in 2009, they summarized the physicochemical properties of the major cultivated *Musa* species. Specific genetic markers were not identified, though the correlation between *Musa* genotypes and sensory characteristics including texture was discussed[8] (Arvanitoyannis & Mavromatis, 2009). The authors concluded that biotechnology has the potential to enhance banana starch content, improve the balance of starch components, and increase fiber and antioxidant content.

Continued research on the genetics of ripening noted the complexity of fruit softening by demonstrating the simultaneous expression of multiple genes of the same family of *Musa* during softening. A 2007 paper identified "α-expansin genes, MaEXPA2, MaEXPA3, MaEXPA4 and MaEXPA5 from banana fruit which express differentially during fruit development and ripening (Asha Sane, Sane, & Nath, 2007)." "Expansins are cellular proteins expressed in the course of cell wall loosening during fruit ripening (Y. Wang et al., 2006)." Kesari and colleagues indentifed an additional set of genes involved in ripening and fruit softening (included in Appendix A; Kesari, Trivedi & Nath, 2007). Similarly, Xu and colleagues investigated genes associated with ripening; their work located 26 cDNAs that up-regulated (table included in Appendix A; Xu, Su, & Liu, et al., 2007).

Hippolyte et al. (2012) assessed the allelic distribution of 22 SSR loci for musa (triploid banana and plantain) in an effort to support breeding efforts targeting disease resistance and yield improvements, while maintaining taste and texture. They identified diploid parents conferring desirable traits by determining the closest diploid progenitors of the triploid 'Cavendish' and 'Gros Michel' lines. In concluding, they highlighted a currently incomplete understanding of regulatory mechanisms for genome expression as a salient gap in this area. They pointed to the high level of phenotypic diversity in triploids and suggested that this was not a result of gamete recombination – indicating a continuing need to explore epigenetic mechanisms, rather than solely genetic mechanisms and inherited mutations (Hippolyte, Jenny, Gardes et al., 2012).

A table summarizing textural characteristics, consumer preferred characteristics, physicochemical drivers of textural attributes, and genetic drivers of texture for banana/plantain is provided below:

Table 23: Summary of Determinants of Consumer-Preferred Textural Traits in Banana/Plantain

Trait	Description	Consumer Preferred	Physicochemical Driver	Genetic Driver	Source
Hardness	See Tables 20 & 21	Soft +	Ripening; dry matter content; cell wall-degrading enzymes including polygalacturonase, pectate lyase, pectin methylesterase, β-Galactosidase, β-1,3 glucanase	FHIA-01, FHIA-17, and FHIA-23; α-expansin genes (MaEXPA2, MaEXPA3, MaEXPA4 and MaEXPA5); See Table 22; See Appendix A for table by Xu et al., 2007	Dzomeku et al. (2007a); Nowakunda et al. (2000); Gibert et al. (2010); Gupta et al., (2006) (table included in Appendix A); Xu et al. (2007); Y. Wang et al. (2006); Asha Sane et al. (2007); Amnuaysin et al. (2012); Kheng et al. (2012); Al-Hosni et al. (2010)
Cohesiveness	NA	NA	NA	NA	NA
Viscosity	See Table 19b Intrinsic viscosity of green banana starch 2.00. Green banana flour 40.94 mPa s. Ripe flour 87.88 mPa s.	NA	Starch structure; starch gelatinization; hemicellulose and pectin polysaccharides	NA	Bello-Perez & Agama-Acevedo (1999); Kayisu et al. (1981); Alkarkhi et al. (2011) (table included in Appendix A)
Springiness	NA	NA	NA	NA	NA
Adhesiveness	Gelatinization between 67°C – 60°C	NA	NA	NA	Kayisu et al. (1981)
Particle Size	See Table 19a	NA	NA	NA	Nwokocha & Williams (2009); Bello-Perez & Agama-Acevedo (1999)
Particle Shape	Green: oval and rounded shapes with smooth surfaces Ripe: elongated granules with circular depressions and layered striations	NA	NA	NA	Peroni-Okita et al. (2010)
Moisture Content	See Tables 16 & 19	NA	NA	NA	Nwokocha & Williams (2009); Bello-Perez & Agama-Acevedo (1999)
Fat Content	See Tables 16 & 19	NA	NA	NA	NA

[8] A table from this review summarizes the physicochemical properties of various banana cultivars in detail and is included in Appendix A.

Cassava: Highlights

- Cassava processing procedures can vary greatly, from simple processing (peeling and boiling) to more complicated procedures for pounded products, including peeling, grating, pressing, fermenting, sifting, and roasting. Industrial uses of cassava starch are becoming increasingly common.
- Important sensory characteristics for cassava include smoothness, aroma, and color (creamy-white, grey, and yellow are all preferred colors).
- Cassava texture is largely driven by the quantity and quality of starch (chemical composition, physicochemical properties, morphology and molecular structure).
- Cassava leaves and tubers contain the cyanogenic glycosides linamrin and lotaustralin, which can decompose into cyanide hydroxide if not removed during processing. For this reason (and consumer preferences) cassava is often fermented to prepare food dishes and cassava flour.

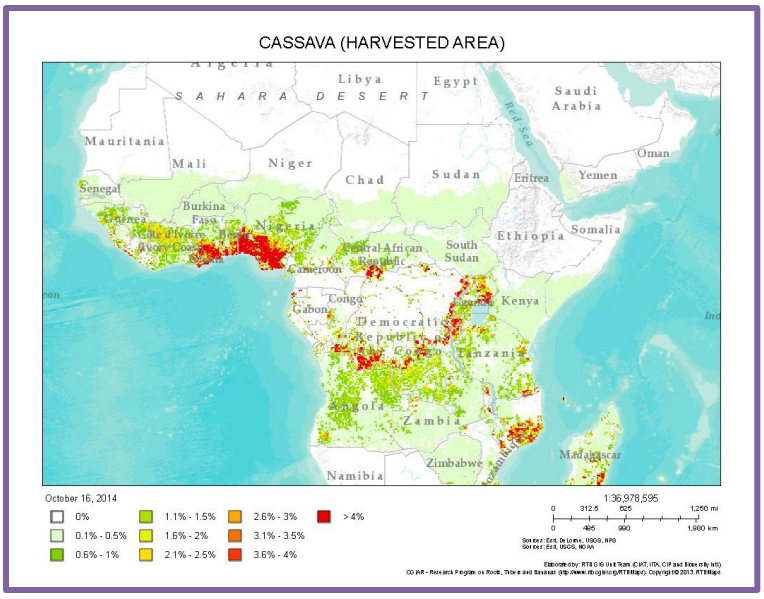
Cassava (*Manihot esculenta* Crantz): Food Texture Preferences

The tuberous root of cassava is the fourth most important food source of carbohydrate in the tropics after rice, maize, and sugar cane; it is a staple food for more than 500 million people due to its high starch content (Moorthy, 2002; Davis, Supatcharee, Khandelwal et al., 2003; Tonukari, 2004; Blagbrough et al., 2010). In almost all cases today cassava is a vegetatively propagated food crop, valued because it grows well in poor soils with limited labor requirements and produces roots that can be harvested between six months and three years after planting.

In SSA, cassava is primarily a subsistence crop grown by smallholder farmers. Surplus cassava is sold, and it grows well in resource-poor soils and is relatively non-labor intensive (IITA, 2014). Cassava can be intercropped with a wide range of other crops such as vegetables, coconut, oil palm, coffee, yam, sweetpotato, melon, maize, rice, groundnut, and other legumes (IITA, 2014). In 2013, Africa accounted for 56% of all cassava production; Nigeria (where cassava is the top-produced commodity) is the world's largest producer at 54 million tonnes (FAOSTAT, 2013). Annual per capita consumption of cassava is estimated at 80 kilograms per year in Africa, and it is estimated that 37% of all dietary energy comes from cassava (IITA, 2014). IITA has played a role in developing improved cassava varieties that are drought resistant and high-yielding, have low cyanide content, and fight green mite, mealybug, cassava bacterial blight, anthracnose disease, root rot, and cassava mosaic disease (CMD). Improved varieties are now grown in most cassava-growing countries in SSA (IITA, 2014).

Cassava is used in many products ranging from sweeteners to glues, plywood, textiles, paper and drugs. Cassava chips are widely used in animal feed (IITA, 2009b). Cassava starch is suitable for specialty uses in food processing, textiles, and paper (Blagbrough, Bayoumi, Rowan et al., 2010). Cassava varieties of poor cooking quality and high cyanogenic potential can be used for production of starch, glucose, adhesives, fuel alcohol and other industrial materials. (Aryee, Oduro, Ellis et al., 2006).

Map 4: Cassava Area Harvested



Common Preparation of Cassava in SSA

Cassava is harvested over a wide geographic area in Sub-Saharan Africa (see Map 4), with concentrations throughout West, Central and East Africa and in Madagascar. It must be processed due to the presence of cyanide, a toxic substance to humans (Hahn & Keyser, 1985). As Hahn & Keyser explained, cassava processing procedures can vary greatly, from simple processing (peeling and boiling) to more complicated procedures for pounded products, including peeling, grating, pressing, fermenting, sifting, and roasting. In some areas of Africa, cassava leaves are consumed as vegetables. Fresh cassava must be processed or transported quickly because fresh roots rot within days of harvest. Common names for cassava products include *gari* (a fermented, roasted cassava pulp), *lafun* (fermented, dried cassava pulp, also referred to as *cossettes* in Democratic Republic of Congo and Rwanda, *kanyanga* and *mapanga* in Malawi, and *makopa* in Tanzania),

kumkum (smoked cassava balls), *chickwangue* (fermented pulp consumed in plantain leaves), and *fufu* (fermented, pounded paste product) (Hahn & Keyser, 1985).

Consumer Preference Studies of Cassava: Preferred Characteristics

Important sensory characteristics for cassava include smoothness, aroma, and color (creamy-white, grey, and yellow are all preferred colors).

Franck et al. (2011) conducted a consumer sensory analysis with 15 untrained consumers of boiled cassava in Bénin.[9] The participants considered taste and friability to be the most important attributes indicating quality of boiled cassava. The panel was then trained to assess cassava for textural qualities using a semi-structured 1-10 categorical scale. Figure 6 displays different cultivars and their primary textural attributes as assessed by the panel. Mean sensory friability scores of the boiled cassava ranged between 1.5 for TMS 91/02319 and 8.6[10] for the traditional cultivar, Oluchute. Among the improved cultivars, only one sweet cultivar, BEN 86052, had a friability score above 5. The panelists exhibited high correlation coefficients between mean panel score and individual scores.

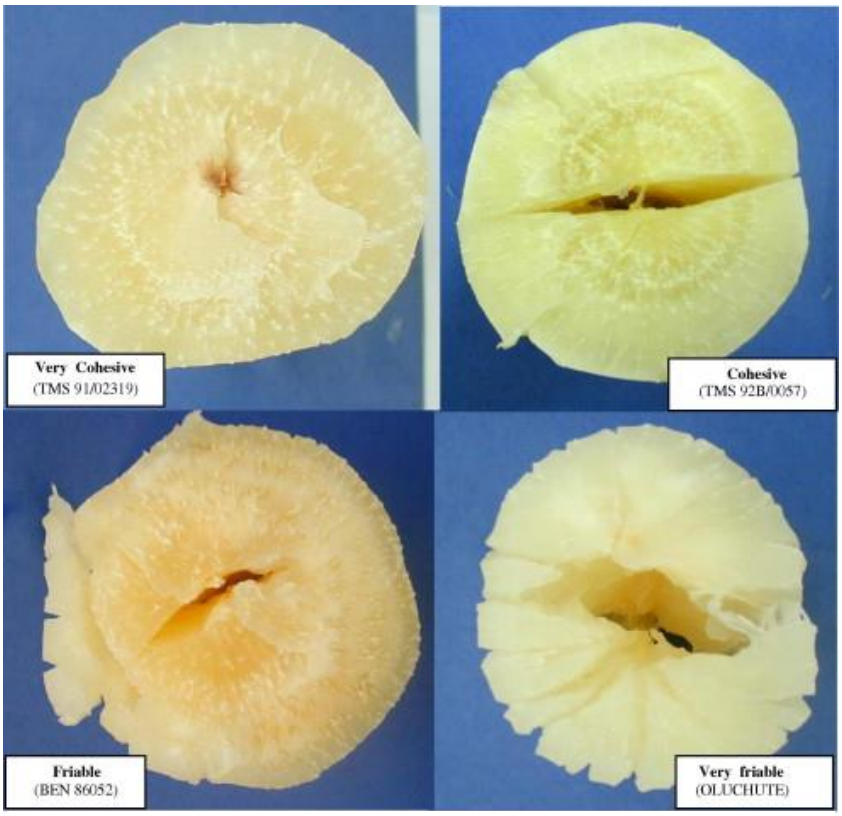


Figure 6. Examples of Cassava Texture (Franck et al. 2011)

Tomlins and colleagues (2007) conducted consumer preference research for fermented cassava flour (*fufu*) in Nigeria, specifically in Lagos (n=91), Ibadan (n=121), and Abeokuta (n=99). Sixty percent of respondents were male, and 82% were between 20 and 39 years old. The majority of the 311 participants indicated that they were willing to purchase cassava and that they most frequently ate *fufu* at home. The forms of *fufu* typically purchased varied considerably by region. For example, in Abeokuta, 92% of participants purchased cooked *fufu*, whereas only 4% of participants in Ibadan purchased cooked *fufu*. The authors found that men preferred *fufu* more than women did (a 6.0 average score for men versus 5.6 for women), and that older consumers demonstrated slightly higher preference than younger consumers (17-30 year-olds gave an average rating of 5.7, while those aged 50 and over gave an average rating of 6.1). Additionally, consumers rated fermented cassava flour as "sticky" in texture, and pastes as "soft" in texture. Notably, the authors stated that "*fufu* acceptance varies widely among consumers and is related to preferences for distinct *fufu* flavor profiles (Tomlins, Sanni, Oyewole et al., 2007)."

In contrast, Jumah et al. (2008) found that consumers did not identify significant differences in sensory characteristics among *fufu* flour brands sold in a major supermarket in Ghana. The authors claimed that "the lack of significant differences in the respondents' evaluation of the sensory characteristics of the *fufu* flours could stem from the fact that all the producing companies use protocols that are very similar, given that almost all the *fufu* flour producing companies in Ghana have benefited directly or indirectly from research work on *fufu* flour production by the Food Research Institute (FRI) of Ghana."

[9] However, these panelists had previously been trained for taste attributes of yam thick paste.
[10] On a 10-point hedonic scale.

Consumer Preference Studies of Cassava: Variety Preference

Only two relevant studies of consumer preferences for improved and traditional varieties of cassava were found through this review, both conducted in West Africa in the late 1990s and early 2000s.

Oyewole & Afolami (2001) found that consumer preference for *lafun*, a cooked, fermented cassava flour popular in Nigeria, was highest for the local variety,"Isunikankoniyan", and a clone, TME 1. The authors used a 10-point hedonic scale for sensory analysis and found that consumers rated *lafun* highly when it had low odor, white color, "good" texture, and did not stick to their hands. Texture among cassava varieties varied significantly in physicochemical analysis: cooked *lafun* made from TMS 4(2) 1435 was found to be significantly different from other varieties in appearance and taste, while the only significant differences between the cooked products of "Isunukankoniyan" and TME 1 were texture and smoothness. TMS 4(2) 1425 was found to be the least acceptable overall to consumers.

In Table 24 below, various cassava cultivars processed into *gari* were evaluated by a trained sensory panel on a 1-6 categorical scale. According to the authors, all cultivars except cultivar 3044, which had a low swelling capacity, possessed good sensory attributes.

Table 24: Sensory Evaluation of *Gari* Processed from Six New Cassava Cultivars

Cultivar	Texture	Color	Taste	Overall acceptability
TMS 3055	4.5	3.6	3.8	15.4
TMS 30572	3.4	3.5	3.4	13.6
TMS 40944	3.1	3.2	3.0	12.9
TMS 3572	4.4	3.7	4.6	16.3
TMS 3044	2.3	3.5	2.5	11.8
HTV	4.0	3.5	4.0	15.1

Source: Adapted from Achinewhu, Barber, & Ijeoma, 1998

Cassava (*Manihot esculenta* Crantz): Determinants of Food Texture

Physicochemical Properties Related to Texture in Cassava

Charoenkul and colleagues (2006) predicted the most important factor influencing cassava texture as "the quantity and quality (chemical composition, physicochemical properties, morphology and molecular structure) of starch" (Charoenkul, Uttapap, Pathipanawat, & Takeda, 2006). Researchers have published widely on the basic qualities and characteristics of cassava starch. Blagbrough et al. (2010) reported that starch comprises 65-75% of cassava carbohydrate. They describe the starch as low in mucilage and latex in contrast with that of other crops and as such, suitable for use in food processing, textiles, and paper. It is also associated with good thickening and textural qualities, a clear and stable gel and the following breakdown of components: amylose content between 14% and 24%, fiber 0.10-0.15%, lipid 0.11-0.22%, and phosphorus 0.007-0.012% (Blagbrough et al., 2010). In another study, Aryee et al. (2006) evaluate flours from 31 cassava varieties and report starch content between 67.92% and 88.11%, amylose between 10.9% and 44.3%, and low swelling power across all samples.

Cassava is commonly fermented to prepare flour. Aloys and Zhou (2005) find that longer fermentation of raw cassava is associated with higher yield of flour, density, dispersibility, crude fiber, and pasting temperature, but lower pH, starch, cyanide content, peak viscosity, paste viscosity, and water retention. Wet fermentation is also associated with greater reductions in residual cyanide and higher yields, pasting temperature, density, and dispersability in this research.

Cassava viscosity is influenced by factors including granule shape, size, swelling power, and amylose and amylopectin granular interaction (Sanchez, Dufour, Moreno et al., 2010). Swelling power, a metric of hydration capacity, is itself a function of amylose and amylopectin ratio, chain length, and molecular weight distribution, as well as the branching structure of the granule. One study found that the season in which cassava is planted and harvested also can influence the swelling power of the starch (Anggraini, Sudarmonowati, Hartati et al., 2009).

Makanjuola et al. (2012) analyzed cassava from eight processing centers in South-West Nigeria for physicochemical and sensory characteristics. They compared their results to the Gari Regulation of 1980 thresholds of acceptability for moisture content, fat content, acidity, swelling index, water absorption capacity, hydrocyanic acid and particle size distribution. Findings included a positive relationship between particle size (after grating, dewatering, fermenting and sieving) and moisture content when roasted, i.e., large aggregate sizes were associated with higher moisture content and thus implied challenges related to storage. Overall particle size was found acceptable. Fat content was below the threshold of

acceptability even with the addition of palm oil; however other quality characteristics including fibre, ash, acidity and hydrocyanic acid were in the acceptable range (Makanjuola, Ogunmodede, Makanjuola et al., 2012).

Charoenkul et al. (2006) hypothesized that cassava texture is influenced by the "quantity and quality (chemical composition, physicochemical properties, morphology and molecular structure) of starch." Other relevant factors include quantity and quality of other root components, macro-structure of cassava root, as well as cell organization and arrangement. They concluded that the molecular structure of starch was not related to textural appearance. Notably, this study relied on a visual assessment of texture rather than an instrumental method, but the authors did not elaborate on the approach. This research team later explored physicochemical properties of cassava flours including chemical composition (protein, lipid, fiber, ash), pasting properties, firmness of gel, thermal properties, morphology and granular size distribution, and also crystalline pattern of starches, and reported finding no relationship between texture and these properties (Charoenkul et al., 2011).

Cassava starch has been reported to possess variable gelatinization temperatures. Asaoka et al. (1992) measured gelatinization temperatures of around 50.7°C -57.77°C for four cassava varieties, while Perez et al. (1998) observed approximately 62.5°C, and Defloor et al. (1998) reported a range of 53.9°C to 62.17°C. Aryee et al. (2006) found gelatinization temperatures between 66.8°C to 70.4°C, with peak temperatures varying between 73.1°C and 84.5°C. Overall, gelatinization temperature does not appear to be influenced by granule size.

Cassava deteriorates after harvest, with hydroxycoumarins, scopoletin (and its glucoside) and eculetins accumulating in root tissue at this time, leading researchers to assume that these compounds play a role in the deterioration (Blagbrough et al., 2010; Tanaka, Data, Hirose et al., 1983; Buschmann, Rodriguez, Tohme et al., 2000; Riley et al., 2008). Saka et al. (1998) reported a significant correlation between glucoside level and bitter taste (r=0.77) in 246 cassava samples from the 10 most common cultivars grown in Nkhata Bay District, Malawi. Franck and colleagues (2011) explored the quality of boiled roots of seven cassava cultivars harvested at 10, 12, and 14 months in three different seasons. In this study, sensory taste of boiled flesh appeared uncorrelated with sucrose content and cyanide potential, though both influence taste. The age of cassava plants and the environmental conditions experienced during the growing season were suggested by past research to affect texture (in particular friability) and taste; however, improved cultivars demonstrated lower friability regardless of plant age. Franck et al. also suggested that the interaction of cultivar and environmental effects with pectin (improved cultivars have higher pectin content) drives vegetable mealiness (Franck, Christian, Noel et al., 2011).

Genetic Drivers of Texture in Cassava

There is a paucity of research on cassava genetics, particularly related to texture (Nyaboga, Njiru & Nguu et al., 2013). Ceballos and colleagues (2004) reported that "evaluations at early stages of selection allow for estimates of general combining ability effect or breeding values of parental lines. Inbreeding by sequential self-pollination facilitates the identification of useful recessive traits, either already present in the *Manihot* gene pool or induced by mutagenesis." However, there appears to be little literature linking these breeding techniques and genetic knowledge with textural traits.

Genetic factors such as the heterozygous nature of the crop and parental lines and poor flowering ability have made it difficult to identify cassava parents with good breeding values and to successfully cultivate (Ceballos, Iglesias, Perez et al., 2004; Blagbrough et al., 2010). These challenges make biotechnological approaches to cassava appealing (Liu, Zheng, Ma et al., 2011; also see Appendix B). Genetic modification to delay post-harvest deterioration, to improve nutritional value, and to support disease resistance has been the target of an international consortium, BioCassava Plus, whose efforts have resulted in field trials in Nigeria involving transgenic cassava (Blagbrough et al., 2010; http://biocassavaplus.org/).

Still, in earlier research, Munyikwa et al. (2001) identified genes critical in the synthesis of starch, an important component of texture. In an experiment crossing the cassava cultivars TMS 30572 and CM 2177-2, the authors isolated the AGPase S and AGPase B genes, which are localized on the female-derived linkage groups E and P, respectively. The two genes are expressed in all cassava tissues, but in particular AGPase B is associated with higher steady state mRNA levels and higher expression in leaf and tuber tissue. Also, AGPase enzymes were found to be more active in young cassava leaves than in older leaves and tubers.

Yuen et al. (2009) identified two genes involved in the synthesis of cassava starch as well as a variety of other metabolic functions. These genes, MeAATP1 and MeAATP2, encode for putative ATP/ADP translocases. Suppression of the genes also was found to result in decreases in starch content and changes in tuber characteristics, as well as increased pathogenic resistance, although the pathways are not clearly understood.

In a study of genetic variation and morphological characteristics among starch samples from the roots of cassava genotypes from Indonesia, Anggraini et al. (2009) found that amylose content varied from 17.1 to 21.3%. Mean particle size was 7.3 to 9.7 µm and gelatinization onset temperature was in the range of 63.5°C-66.1°C. Median granule size of a subset of the genotypes was between 7.7-10.8 µm and phosphate content varied from 23.5-25.3 nmol/mg starch. Regarding textural

dimensions specifically, gel strength, which may serve as an indicator of adhesiveness, cohesiveness and elasticity, was found to be fairly uniform.

A table summarizing textural characteristics, consumer preferred characteristics, physicochemical drivers of textural attributes, and genetic drivers of texture for cassava is provided below:

Table 25: Summary of Determinants of Consumer-Preferred Textural Traits in Cassava

Trait	Description	Consumer Preferred	Physicochemical Driver	Genetic Driver	Source
Hardness	NA	Soft +	NA	NA	Tomlins et al. (2007)
Cohesiveness	NA	Mealy +	Pectin	NA	Franck et al. (2011)
Viscosity	NA	Viscous +	Granule shape, swelling power, amylose and amylopectin granular interaction	NA	Sanchez et al. (2010)
Springiness	NA	NA	NA	NA	NA
Adhesiveness	Gelatinization 50.7˚C to 70.4˚C	Non-sticky +	NA	NA	Aryee et al. (2006); Oyewole & Afolami (2001); Anggraini et al. (2009); Asaoka et al. (1992); Perez et al. (1998); Defloor et al. (1998)
Particle Size	7.3 to 9.7 μm	NA	Moisture content	NA	Anggraini et al. (2009); Tomlins et al. (2007); Oyewole & Afolami (2001); Makanjuola et al. (2012)
Particle Shape	NA	NA	NA	NA	NA
Moisture Content	NA	NA	NA	NA	NA
Fat Content	0.11-0.22%	NA	NA	NA	Blagbrough et al. (2010)
Cyanogenic Potential	0.58 to 20.0mg HCN per 100 g	NA	NA	CYP79D1/D2	Aryee et al. (2006); Blagbrough et al. (2010)
Texture	NA	NA	Quantity and quality of root components, macro-structure of cassava root, organization of cells, arrangement of tissue (hypothesis)	TMS 3055; TMS 3572	Achinewhu, Barber, & Ijeoma (1998); Charoenkul et al. (2006)
Starch Content	67.92% to 88.11%	NA	NA	MeAATP1 and MeAATP2; AGPase S and AGPase B genes	Yuen et al. (2009); Munyikwa et al. (2001); Aryee et al. (2006)

Potato: Highlights

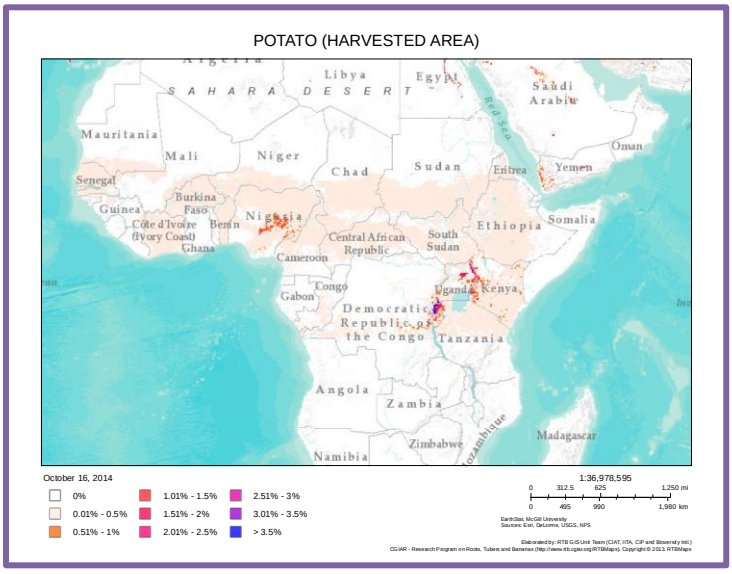
- In consumer preference studies conducted mostly outside of Africa, high dry matter appears to be an important physicochemical driver of preferred textural traits in potato.
- Potato texture is known to be both genetically and environmentally determined; in one study, potato grown in sandy soil was found to possess higher dry matter.
- Five genes have been shown to drive starch structure and cell wall biosynthesis, which may explain differences in the textural traits of potato tuber varieties.
- Pectin methyl esterase (PME) activity and the PEST1 gene play an important role in processed tuber textural properties.

Potato (*Solanum tuberosum*): Food Texture Preferences

Potato (*Solanum tuberosum*) originated in the Andes mountains of South America and is part of the *Solanaceae* family (CIP, 2014). Until the early 1990s, most potato was grown and consumed in North America, Europe, and the former Soviet Union (FAO, 2010). Recently, there has been a significant increase in potato production and demand in Asia, Africa, and Latin America: the combined potato output for these regions increased from less than 30 million tonnes in 1960 to more than 165 million tonnes in 2007 (FAO, 2010). Potato is now considered the third most important crop grown for human consumption with more than 4,000 edible varieties cataloged and additional non-edible varieties that contain potentially useful genetic material (CIP, 2014). Their global importance has led to extensive study of potato crops, the research methods and findings of which may relate to other RTB crops. In Sub-Saharan Africa, potato has been described as an important crop for food security; Prakash (2010) found that price inflation for potato and other root crops was less widespread during global price spikes in 2007 and 2008 in comparison with major cereals in the most food-insecure countries in the world. In part, this is due to the fact that potato is a thinly traded crop – only a fraction of total production enters international markets – thus insulating it from major international food shocks (Prakash, 2010). According to FAO, low and lower-middle income countries have now surpassed high-income countries in potato production (FAO, 2014). Sub-Saharan Africa is projected to lead the expansion in potato production in the coming decade (FAO, 2010).

Common Preparation of Potato in SSA

Map 5: Potato Area Harvested



Potato production in Africa is diffuse but increasing. Top producers in SSA include Malawi, Kenya, Tanzania, Rwanda, Ethiopia, Nigeria, Uganda, South Africa, and Angola. Egypt, Algeria, and Morocco also produce large quantities of potato (FAOSTAT, 2013). The literature on potato preparation in Africa is sparse compared with Latin America, where potato comprises a significant portion of the diet in many countries. According to the International Potato Center (CIP) in 1991, potato makes up a minor portion of the average daily intake in Sub-Saharan Africa, however, it is eaten more regularly in Central, East, and parts of Southern Africa. According to more recent sources, FAO (2008) reports that quantity of potato consumption is varied among the top potato producing countries, with Rwanda and Malawi exhibiting the highest per capita potato consumption.

CIP (1991) reports that in rural households potato is typically boiled, while in urban centers it is eaten as potato fries at restaurants. In some select countries like Burundi and Madagascar, potato comprises the majority of household food reserves in the pre-harvest season while awaiting maturation of other basic staples (CIP, 1991). For a more recent assessment of common preparation, CIP (2014) reports a wide range of food and non-food uses for potato, not specific to Africa, indicating that global consumption of potato is "shifting from fresh potatoes to added-value, processed food products."

Consumption of potato spans socioeconomic strata in Sub-Saharan Africa, however low-income consumers eat potato less frequently, and often only for special occasions (CIP, 1991). Urban consumption in Rwanda is higher due to production increases and new roads, which have lowered the price of potato in major cities and towns. Overall, high potato prices

discourage more widespread use (CIP, 1991). According to recent reports from FAO (2010), potato has potential to increase food security. However, no literature was found concerning sensory evaluation of potato or variety preference for top potato-consuming countries in SSA.

Consumer Preference Studies of Potato: Preferred Characteristics

Important sensory traits for potato among consumers and farmers in sub-Saharan Africa include low sugar content, high starch content, floury texture, high dry matter content, mealiness, creaminess, butter taste, adhesiveness, hardness, moistness, no greening, no sprouting, smooth skin texture, absence of blemishes, and light skin color (Katandu, Hendriks, Bower et al., 2007; Katandu, Hendriks, Bower et al., 2010; Seefeldt, Tonning, Wiking et al., 2010). Of these characteristics, starch content, floury texture, mealiness, adhesiveness, hardness, and skin texture are all classified by Szczesniak (1963) as primary or secondary textural traits. Katandu et al. conducted a sensory evaluation of potato after different storage times (2007), and evaluated organic potato (2010).

While potato preferences are relatively well-studied in developed countries (relative to other RTB crops), the literature for sensory consumer preferences of potato in Africa is sparse. Some studies conducted outside of Africa indicated that texture (in general) is the sensory characteristic that most influences consumers in both trained and untrained consumer panels (Montouto-Grana, Cabanas-Arias, Porto-Foho et al., 2011). Furthermore, related textural properties such as hardness and adhesiveness have been found to be the most important quality descriptors among boiled, oven-fried, and mashed potato products, indicating that texture is important across different preparation methods (Seefeldt, Tonning, & Thybo, 2011). There are a number of studies conducted in North America and Europe on value-added potato products such as packaged, fried, and organic potato products, which may not be relevant to the African context (see for example Beltran, Selma, Tudela et al., 2005; Gilsenan, Burke, & Barry-Ryan, 2010). Studies oriented towards consumers in North America and Europe and studies linking textural and/or genetic variation to sensory qualities are prevalent.

Consumer Preference Studies of Potato: Variety Preference

Arvanitoyannis et al. (2008b) conducted an exhaustive review of all consumer preference studies by potato variety. Nearly all of the consumer preference studies for potato were conducted by trained panelists, and the hedonic scales used vary considerably (from 1-4 to 1-15). In Appendix C, their findings are provided in table format. However, nearly all of these studies were conducted in North America or Europe, and thus have less relevance to the African context specifically.

Studies in Tanzania examined farmer preferences for potato varieties with respect to other agronomic properties and market concerns (Mpogole & Kadigi, 2012; Namwata, Lwelamira, & Mzirai, 2010). Mpogole & Kadigi (2012) reported that the following varieties are common among smallholder round potato farmers in the Southern Highlands of Tanzania (n=510): Kikondo (CIP 720050), Arka, Kagiri, Kidinya, Tigoni, Malita, Msafiri/Mtega, and Sasamua/Baraka. Forty-one percent of farmers reported growing two or more varieties. Reasons for round potato selection varied. Sensory properties were not an explicit part of this study; however, market demand and suitability for home consumption were included as variables, as seen in Table 26 (Mpogole & Kadigi, 2012). Within home consumption, sensory attributes could be included in this overall evaluation, but it is impossible from the data given to assess sensory information.

Table 26: Farmers' Criteria for Potato Variety Selections

Main reason for variety selections	Njombe	Mbeya	Nkasi
High selling price for the variety	15.9%	23.5%	0.0%
High yielding variety	11.2%	2.4%	10.6%
Most demanded in the market	37.6%	32.9%	7.1%
Resistant to pests and diseases	.6%	.6%	.6%
Seed tubers availability/most available	19.4%	33.0%	63.5%
Recommended by extension officers	1.2%	.0%	1.2%
Suitability for home consumption	2.9%	7.6%	3.5%
Common practice	11.2%	0.0%	13.5%

Source: Adapted from Mpogole & Kadigi, 2012

A European study found through Principal Component Analysis (PCA) that 45% of the variation in the 15-19 sensory descriptors used by a trained panel was related to variety differences, which was ascribed to variation in descriptors for appearance, dry matter content, and texture. Growing location was also found to significantly affect appearance and texture (Seedfelt, Tonning, & Thybo, 2011). In particular, the authors found that potato grown in sandy soil possessed higher dry matter content in comparison with varieties grown in clay soils. Dry matter content is classified as a textural property (Szczesniak, 1963).

Studies conducted in SSA have largely focused on farmer preferences related to other agronomic properties and marketing concerns, rather than sensory or varietal preferences for consumers.

Potato (*Solanum tuberosum*): Determinants of Food Texture

Of the RTB crops reviewed, potato has the most substantial scientific literature on determinants of texture. Potato texture is influenced by multiple factors including starch content and distribution, starch swelling pressure, cell size, cell wall structure and composition, and breakdown of the cell wall when heated during cooking (reviewed in Taylor et al., 2007).

Physicochemical Properties Related to Texture in Potato

Many studies examine the physicochemical and sensory traits of potato, allowing for a better understanding of relationships between textural traits and physicochemical properties. Early studies linked firmness and cohesiveness to starch, pectin and cell size (Kaur, Singh, Singh Sodhi et al., 2002). Changes in textural traits due to cooking are also associated with cell wall and middle lamella structure and the gelatinization of starch (Kloosterman, Oortwijn, uitdeWilligen et al., 2010).

Multiple studies found that glycoalkaloid content in potato can lead to low sensory consumer preference ratings (Morris & Lee, 1984; Phlak & Sporns, 1992; Grunenfelder, Hiller, Knowles et al., 2006; Katandu et al., 2007). Glycoalkaloids are associated with bitterness, and their levels can increase with storage time and cooking, affecting taste (Katandu et al., 2007). Little is known about the link between glycoalkaloids and texture, and Katandu et al. (2007) recommended that future research analyze glycoalkaloid content and textural characteristics.

A study of Japanese cultivars related physicochemical properties of 13 potato varieties to their sensory traits (Jitsuyama, Tago, Mizukami et al., 2009). Table 27 presents correlation coefficients, relevant to relationships between starch content and tasting traits. The authors found starch content to be strongly negatively correlated with sweetness and smoothness and slightly positively correlated with potato taste. The tasting trait smoothness was positively related to phosphorous and potassium content and tuber cell size[11].

Table 27: Correlations between Traits of Potato Tubers

Traits	Sweetness	Potato Taste	Smoothness	Deliciousness	Starch Content
Potato Taste	-0.745[a] **b	-			
Smoothness	0.495 †	-0.665 *	-		
Deliciousness	0.896 ***	-0.797 **	0.540 †	-	
Starch Content	-0.584 *	0.541 †	-0.761 **	-0.633 *	-
Pulp Hardness	-0.608 *	0.478 †	-0.337 ns	-0.559 *	0.468 ns
pH	-0.734 **	0.440 ns	-0.222 ns	-0.767 **	0.572 *
Potassium Content	0.180 ns	-0.249 ns	0.591 *	0.108 ns	-0.546 †
Phosphorus Content	0.457 ns	-0.379 ns	0.694 **	0.265 ns	-0.698 **
Silicon Content	-0.307 ns	0.574 *	-0.304 ns	-0.313 ns	0.030 ns
Cell Size	0.394 ns	-0.281 ns	0.584 *	0.474 ns	-0.533 *
Weakness of Cell Wall Bind	0.478 †	-0.499 †	0.195 ns	0.455 ns	-0.114 ns

Source: Adapted from Jitsuyama et al., 2009

Kaur and colleagues (2002) related the dry matter content of Kufri Jyoti and Kufri Badshah potato cultivars to assessments of mealiness. Previous work found that mealy potato tended to have higher dry matter content and that starch granules from mealier potato gelatinized at lower temperatures (Kaur et al., 2002). Table 28 summarizes the dry matter content, texture profiles, and stress relaxation measures of Kufri potatoes relative to the low-mealiness Pukhraj cultivar. Cultivars with high mealiness scores showed higher Maxwell elastic moduli, hardness, fracturability, cohesiveness and adhesiveness.

Table 28: Sensory Panel Results from Potato Cultivars

	Pukhraj	Kufri Jyoti	Kufri Badshah
Fracturability (Newton)	3.91a	4.80b	4.85b
Hardness (Newton)	7.00c	9.54b	11.42c
Cohesiveness	0.1049a	0.1124b	0.1078a
Adhesiveness (Joules)	2.167×10^{-4}a	6.8341×10^{-4}b	8.991×10^{-4}c
Springiness (Meter)	0.0012b	0.0009a	0.00104b
Gumminess (Newton)	0.7343a	0.8475a	1.231b
Chewiness (Joules)	0.00128b	0.00076a	0.00128b
Dry matter content (%)	13.20a	16.40b	18.20c
Water uptake (%)	3.03a	5.21b	5.1b
Total solids loss (%)	3.54a	5.8c	5.7b
Taste panel scores	0.9a	3.0c	2.75b

Values followed by the same letter within row do not differ significantly ($P<0.05$).
Source: Adapted from Kaur et al., 2002

[11] Additional tables from Jitsuyama et al. (2009) are in Appendix C.

In the same study the authors further reported that the "cooking properties of potatoes, such as cooking time, compression force, total solids loss and water uptake values, were found to be related to their textural properties (Kaur et al., 2002)."

An earlier paper by Pardo and colleagues summarized the physicochemical and sensory characteristics of seven varieties of potato. Table 29a shows the average physicochemical and sensory parameters of the potato varieties, while Table 29b shows their correlations. Overall, this research found that solid content, pH level, and moisture varied minimally. However, firmness was highest in the varieties with low moisture content and lowest in varieties with high moisture content (Pardo, Alvarruiz, Perez et al., 2000).

Table 29a: Physicochemical Traits and Sensory Parameters in Potato

						Raw Potato	*Fried Potato*		*Boiled Potato*	
Variety	Type (skin color)	pH	Soluble Solids (Brix)	Moisture (%)	Firmness (kPa)	External Appearance	Flavor	Texture	Flavor	Texture
Bartina	reddish	5.95 ab	6.22 b	82.82 b	775 a	1.07 bc	1.79 b	1.66 c	0.00a	0.66 a
Caesar	reddish	5.93 a	5.30 a	82.30 b	838 b	1.28 bc	1.03 a	1.21 bc	0.10 a	0.72 ab
Desiree	reddish	6.00 ab	6.34 b	78.73 a	977 d	0.21 a	0.45 a	0.24 a	1.41 bc	1.41 ab
Agria	yellow-white	6.05 b	6.32 b	80.10 a	877 bc	1.21 bc	1.45 b	0.48 ab	1.14 bc	1.14 ab
Edzina	yellow-white	5.97 ab	6.20 b	81.52 ab	885 bc	1.62 c	1.48 b	1.79 c	0.72 ab	1.07 ab
Monalisa	yellow-white	5.92 a	5.50 a	81.80 ab	905 c	2.48 d	1.59 b	1.62 c	1.34 bc	1.31 ab
Victoria	yellow-white	6.01 ab	5.80 ab	79.32 a	965 d	0.83 ab	1.76 b	1.34 c	1.62 c	1.62 b

Hedonic scale ranged from (-4: dislike extremely) to (+4: like extremely). Each value is the mean of the 48 and 50 samples in physical-chemical and sensorial parameters, respectively. Means followed by the same letter within column sections do not differ significantly at $P<0.05$.
Source: Adapted from Pardo et al., 2000

Table 29b: Correlation Coefficients among Physicochemical Traits and Sensory Parameters in Potato

					Raw Potato	*Fried Potato*		*Boiled Potato*	
	pH[1]	Soluble Solids[1]	Moisture[1]	Firmness[1]	External Appearance[2]	Flavor[2]	Texture[2]	Flavor[2]	Texture[2]
pH	-								
Soluble Solids	0.61***	-							
Moisture	-0.41***	-0.30***	-						
Firmness	0.06	-0.01	-0.73***	-					
Appearance	-0.12	0.22**	0.27***	-0.12	-				
Fried Flavor	-0.01	-0.01	0.12	-0.07	0.11	-			
Fried Texture	-0.10	-0.09	0.24***	-0.05	0.25***	0.44***	-		
Boiled Flavor	0.11	0.08	-0.31***	0.33***	-0.01	0.10	0.11	-	
Boiled Texture	0.09	0.07	-0.17*	0.19**	0.08	0.23**	0.23**	0.51***	-

[1] n= 48×7= 336; [2] n= 4×7= 28.
*, **, and *** represent significant differences at the 0.05, 0.01, and 0.001 levels, respectively.
Source: Adapted from Pardo et al., 2000

A study of potato tuber texture comparing Nicola and Panda varieties used instrumental measurements of texture to explore changes due to cooking time and temperatures. Nicola has a lower starch content (16-17%) than Panda (19-21%) (Blahovec & Esmir, 2001). At higher temperatures, the rate of softening for the Panda variety increased faster than the rate of softening for the Nicola variety, indicating that starch content is important to cooked tuber texture.

Van Marle and colleagues compared the extracted cell wall material structures of Nicola and Irene potato cultivars. They found more branched pectic polysaccharides were solubilized for the Irene variety, indicating that the Nicola variety has a less compact primary cell wall structure (Van Marle, Recourt, Dijk et al., 1997).

Finally, Liu and colleagues researched how potato starch varies over growing time, comparing three cultivars of white round potato, Shepody, Snowden, and Superior. They found that dry matter content increased over time and peaked between 64 and 71 days. Peak measures were 19.2% for Superior tubers at 64 days, 24.2% for Shepody tubers at 71 days, and 24.0% for Snowden potato at 71 days. The highest starch contents were 80.4% for Superior potato at 84 days, 78.1% for Shepody potato at 91 days, and 78.4% for Snowden at 91 days. As growing time increased, average starch granule size increased, while amylose content and gelatinization temperatures decreased. The authors concluded that factors such as granule size, phosphorous content, and amylose content can affect the functional properties of starch (Liu, Weber, Currie et al., 2003).

Genetic Drivers of Texture in Potato

As mentioned above, genetic studies of textural properties of tubers focus largely on the role of starch. For example, Lorberth et al. (1998) studied the phosphorylation of starch in potato. They sought to characterize proteins involved in starch metabolism - isolating the R1 protein and identifying it as a driver of phosphate content. They noted that transgenic plants are associated with starches very low in phosphate content, i.e., 10-50% of wild-type levels in both leaf and tuber. The reduced R1 protein and phosphate content were also associated with impacts on pasting properties, and further with reductions in starch degradation during cold storage. Ritte et al. (2002) further characterized the R1 protein as an α-glucan, water dikinase, finding that it catalyzed phosphorylation of starch-like glucans. This team noted the need for additional work to distinguish the actual target structures which R1 would recognize as phosphorylation sites.

A study of starch behavior in transgenic potato varieties by Aksenova and colleagues (2010) found that the expression of *rol* transgenes may change the dimensions of starch granules. Further, they found that *rolC* plants had elevated starch melting temperatures of crystalline lamella and low melting enthalpy of starch, suggesting imperfect structures in the starch of *rolC* expressing plants (Aksenova, Wasserman, Sergeeva et al., 2010).

Research by Munyikwa and team (2001) on potato plants transformed with an antisense of the AGPase gene found that this alteration led to more tubers, lower starch content, and higher levels of soluble sugars than control plants.

One especially promising study by Ducreux and colleagues (2008) used microarray techniques to identify tuber gene expression profiles that correspond to potato flavor and texture (Ducreux, Morris, Prosser et al., 2008). The researchers compared two *Solanum tuberosum* group Phureja cultivars and two *S. tuberosum* group Tuberosum cultivars. Table 30 shows genes involved in tuber quality traits. The authors identified five genes that explain cell wall biosynthesis and one gene that explains starch structure. Differential expression of these genes may explain differences in the textural traits of potato tuber varieties.

Table 30: Genes Involved in Tuber Quality Traits

Quality trait (process)	Gene Description	Higher in	Potato Oligo Chip Initiative (POCI) Array Identification	Top Hit Accession Number
Flavor	Branched chain amino acid aminotransferase	Phureja	MICRO.2772.C2_1399	AAF07191
Flavor	Sesquiterpene synthase	Phureja	MICRO.8755.C3_977	AAX40666
Flavor (nucleotide formation?)	Ribonuclease	Phureja	MICRO.5716.C1_596	AAD50436
Flavor (glutamate biosynthesis)	Glutamate ammonia ligase	Phureja	MICRO.3959.C1_623	NP_190886
Flavor (glutamate biosynthesis)	Glutamine synthetase I	Phureja	STMDI41TV_515	CAB63844
Flavor (glutamate biosynthesis)	GABA transaminase subunit 3	Tuberosum	MICRO.15425.C2_1257	AAO92257
Flavor (methionine biosynthesis)	Cystathione c synthase I	Tuberosum	MICRO.1118.C2_1798	AAF74981
Flesh color	Carotene b-hydroxylase	Phureja	MICRO.7880.C2_1119	ABI23730
Texture (cell wall biosynthesis)	Pectin acetylesterase	Phureja	MICRO.4427.C3_1465	CAA67728
Texture (cell wall biosynthesis)	Xyloglucan endotransglycosylase	Phureja	MICRO.4152.C1_825	AAG00902
Texture (cell wall biosynthesis)	NAD-dependent epimerase	Phureja	bf_arrayxxx_0046b02.t7m.scf_638	ABE78360
Texture (cell wall biosynthesis)	Nucleotide-rhamnose synthase	Phureja	MICRO.444.C1_634	NP_564806
Texture (cell wall biosynthesis)	Pectin methylesterase	Tuberosum	MICRO.4403.C1_728	AAF23891
Starch structure	ß-amylase	Phureja	MICRO.13823.C1_1872	AAK84008
Tuber life cycle	Chitinase	Phureja	MICRO.15095.C1_874	CAA54374
Tuber life cycle	FRIGIDA	Phureja	MICRO.1851.C1_1	CAM06912
Tuber life cycle	ent-Kaurene oxidase	Tuberosum	MICRO.10720.C2_566	AAO85520
Tuber life cycle	Dimethylallyl transferase	Tuberosum	MICRO.2151.C3_724	CAA59170

Source: Adapted from Ducreux et al., 2008
Note: Genes were identified by microarray analysis as being differentially expressed between Phureja and Tuberosum cultivars.

Ross and colleagues followed up on Ducreux's findings, concluding that the PEST1 gene consistently expressed at significantly higher levels in Tuberosum tubers than in Phureja tubers. This work supports the finding that pectin methyl esterase (PME) activity and the PEST1 gene have an important role in cooked potato texture (Ross, McDougall, Vincent et al., 2010). Further exploration of this relationship in two additional studies found that in "tubers containing a higher level of total PME activity, there was a reduced degree of methylation of cell wall pectin and consistently higher peak force and work done values during the fracture of cooked tuber samples, demonstrating the link between PME activity, the degree of methylation of cell wall pectin and cooked tuber textural properties (Ross et al., 2011b)." In genetic manipulation of the PEST1 gene, Ross and colleagues found that "over-expressing lines indicated that the changes in PME activity resulted in a decrease in pectin methylation" and that "processed tuber texture demonstrated that the reduced level of pectin methylation in the over-expressing transgenic lines was associated with a firmer processed texture," further confirming the

important role of "PME activity, pectin methylation and processed tuber textural properties (Ross, Morris, Ducreux et al., 2011a)."

In related research appearing in a brief prepared by Wayne Morris of the SCRI Living Technology group, Morris and colleagues commented that "major differences in the expression levels of genes involved in cell wall biosynthesis (and potentially texture) were also identified by microarray analysis including genes encoding pectin methlyesterase and pectin acetylesterase. Quantitative PCR assays were performed to confirm the microarray expression patterns. Enzyme activity of pectin methlesterase was measured using an in-gel enzyme assay. PME activity was consistently higher in Tuberosum compared with Phureja. Transgenic plants overexpressing the PME gene exhibited a firmer texture compared to wild type controls whereas antisense lines had a softer texture (Morris, Ducreux, Hedley et al., N.D.)"

Research by Kloosterman and colleagues implemented RNA sample pooling strategies to locate a candidate tyrosine and lysine rich cell wall proteins (TLRP) gene. They found that the presence of an allelic variant of TLRP was negatively correlated with tuber mealiness (Kloosterman et al., 2010). The study noted that the same gene has been identified in tomato and tobacco. A complete list of genes up-regulated and down-regulated in potato with different textures is in Appendix C.

In research on tuber taste, van Dam et al. (2003) considered the role of genetics in driving glycoalkaloid content and consequently bitterness. They reviewed ISSR (Inter-Simple Sequence Repeat) primers and Cleaved Amplified Polymorphic Sequence primers (CAPS), ultimately demonstrating a genetic influence on glycoalkaloid synthesis in tetraploid potato tubers. Using regression they optimized a model consisting of an interaction between two loci in addition to a single locus effect. Notably, 28% of variation in glycoalkaloid content was explained.

In a separate research thrust, Kandemir et al. (2010) looked at 191 samples of the landrace cultivar Başçiftlik Beyazi from Turkey, a potato prized for its taste. Using SSR analysis, the researchers established that these samples arose from 23 different genotypes indicating high genetic variability given clonal propagation, information that could be directly useful to breeders. However, 150 of the plants did share a common marker profile.

Skrabule et al. (2013) compared 20 potato genotypes grown under organic versus conventional systems in Latvia. They found significant genetic influence on concentrations of Vitamins C, B1 and B2, along with glycoalkaloids, and confirmed the Kandemir et al. (2010) finding of high genetic diversity. Organic cultivation was associated with enhanced levels of B1, while conventional cultivation was associated with negative correlation between vitamin C and yield. Traits such as starch content and boiled tuber taste were not found to be correlated with the vitamin and glycoalkaloid levels.

A 2011 study used quantitative trait loci (QTL) methods to identify and quantify loci for flower color and five agronomic traits: dry matter content, specific gravity, foliage maturity, skin texture, and yield (McCord, Sosinski, Haynes, et al., 2011). Specific gravity and dry matter are strongly correlated traits of interest for potato texture; however their independent handling in this analysis enabled the identification of QTL that were not co-located. Five markers were found to explain variation in dry matter content. Specifically, QTL for dry matter were detected on chromosomes II, III, V, and VIII in the same regions as QTL for specific gravity, but also on chromosome XI and the major subgroup of group VII, where no specific gravity QTL were detected. These results corroborate other research but also contribute new findings (McCord et al., 2011).

Arvanitoyannis et al. (2008b) reviewed existing studies pertaining to textural traits of potato varieties, including through genetic modification. Starch, pectic substances and cell size are associated with basic properties of firmness, cohesion, sogginess, stickiness, and gumminess, while texture after cooking has been linked to a tuber's content in terms of amylose, dry solids, sugars, protein, nitrogen, as well as specific gravity (Linehan & Hughes, 1969; Reeve, 1972). Physicochemical analysis of potato cultivars and results from the Arvanitoyannis et al. (2008b) review of literature through 2008 are available in Appendix C.

Finally, of further importance to breeding-programs are studies of genotype and environment interactions. A 2013 study of five potato cultivars used multi-environmental trials to improve the understanding of environment and genotype interactions (El-Sharkawy & El-Aal, 2013), a potentially important method to improve the understanding of how environmental factors contribute to observed phenotypes.

A table summarizing textural characteristics, consumer preferred characteristics, physicochemical drivers of textural attributes, and genetic drivers of texture for potato is provided below:

Table 31: Summary of Determinants of Textural Traits in Potato

Trait	Description	Consumer Preferred	Physicochemical Driver	Genetic Driver	Source
Hardness	See Tables 27, 28 & 29	Hard +	Starch, pectin, cell size, low moisture content	Nicola variety (less compact primary cell structure)	Pardo et al. (2000); Kaur et al. (2002); Van Marle et al. (1997); Katandu et al. (2007, 2010); Seefeldt et al. (2010); Arvanitoyannis et al. (2008b)
Cohesiveness	See Table 28	Mealy +	Starch, pectin, cell size, high dry matter content	Pectin methyl esterase (PME) activity; PEST1 gene	Kaur et al. (2002); Katandu et al. (2007, 2010); Seefeldt et al. (2010); Kaur et al. (2002); Ross et al. (2011b); Arvanitoyannis et al. (2008b)
Viscosity	See Table 28	NA	NA	NA	Kaur et al. (2002)
Springiness	See Table 28	NA	NA	NA	Kaur et al. (2002)
Adhesiveness	See Table 28	Adhesive +	Starch, pectin, cell size	NA	Kaur et al. (2002); Katandu et al. (2007, 2010); Seefeldt et al. (2010); Arvanitoyannis et al. (2008b)
Smoothness	See Table 27	Creamy + Smooth skin +	Cell size, phosphorous and potassium content	NA	Jitsuyama et al. (2009)
Particle Size	21 – 26 µm	Floury +	NA	ß-amylase; expression of *rol* transgenes may change dimensions of starch granule	Liu et al. (2003); Aksenova et al. (2010); Katandu et al. (2007, 2010); Seefeldt et al. (2010); Ducreux et al. (2008)
Particle Shape	NA	NA	NA	Expression of *rol* transgenes may change dimensions of starch granule	Aksenova et al. (2010)
Moisture Content	78.73-82.82% See Table 29	Moist +	NA	NA	Pardo et al. (2000)
Fat Content	NA	NA	NA	NA	NA
Starch Content	See Table 27	High Starch Content +	NA	AGPase; R1 gene	Katandu et al. (2007, 2010); Seefeldt et al. (2010); Munyikwa et al. (2001); Lorberth et al. (1998); Ritte et al. (2002)
Dry Matter Content	See Table 28	High Dry Matter Content +	Grown in sandy soil	Chromosomes II, III, V, VIII, XI, VII subgroup, pectin acetylesterase, xyloglucan endotransglycosylase, NAD-dependent epimerase, nucleotide-rhamnose synthase, pectin methylesterase	Katandu et al. (2007, 2010); Seefeldt et al. (2010); McCord et al. (2011); Ducreux et al. (2008); Blahovec & Esmir (2001); Kaur et al. (2002)

Literature Review Methods

This review was conducted using Scopus, Google Scholar, Science Direct, and the University of Washington Online Libraries, and by consulting experts (geneticists, plant breeders, and scholars) via telephone and email. The expert contact list and affiliations are found below. Regarding our literature review methods, combinations of search terms from the following list were used in each of these search engines: *consumer preference, biochemistry, food, texture, crop, preferences, Africa, genetics, genome, polymorphism, lipid, physicochemical, physiochemical, processes, measurement, breeding, instrumental, microstructure, starch, yam, root, tuber, potato, cereal, banana, plantain, cassava, rice, sweetpotato, dioscorea.* To ensure that a comprehensive search was conducted, we finalized our search using Scopus, using systematic permutations of search terms that included textural traits (i.e., brittle, crumbly, crunchy, etc), accompanied by each crop's common and scientific name to confirm that no key studies were missed. The following table summarizes search results including Scopus keyword searches and number of articles returned for each keyword combination:

Scopus Search Results		
Scopus Search Terms	Total Number of Articles Referencing Textural Attributes	Consumer Preferences Studies[1]
TITLE-ABS-KEY((yam OR dioscorea) AND (cohesiv* OR hard* OR crumbly OR crunchy OR brittle OR chewy OR mealy OR mealiness OR gummy OR viscous OR adhesiv* OR sticky OR tacky OR gritty OR grainy OR coarse OR fibrous OR cellular OR crystalline OR floury OR flouriness OR taste OR textur*))	421	46
TITLE-ABS-KEY((cassava OR manihot) AND (cohesiv* OR hard* OR crumbly OR crunchy OR brittle OR chewy OR mealy OR mealiness OR gummy OR viscous OR adhesiv* OR sticky OR tacky OR gritty OR grainy OR coarse OR fibrous OR cellular OR crystalline OR floury OR flouriness OR taste OR textur*))	787	123
TITLE-ABS-KEY((“sweet potato” OR sweetpotato OR ipomoea) AND (cohesiv* OR hard* OR crumbly OR crunchy OR brittle OR chewy OR mealy OR mealiness OR gummy OR viscous OR adhesiv* OR sticky OR tacky OR gritty OR grainy OR coarse OR fibrous OR cellular OR crystalline OR floury OR flouriness OR taste OR textur*))	571	80
TITLE-ABS-KEY((banana OR plantain OR musa) AND (cohesiv* OR hard* OR crumbly OR crunchy OR brittle OR chewy OR mealy OR mealiness OR gummy OR viscous OR adhesiv* OR sticky OR tacky OR gritty OR grainy OR coarse OR fibrous OR cellular OR crystalline OR floury OR flouriness OR taste OR textur*))	1,171	146
TITLE-ABS-KEY((potato OR solanum) AND (cohesiv* OR hard* OR crumbly OR crunchy OR brittle OR chewy OR mealy OR mealiness OR gummy OR viscous OR adhesiv* OR sticky OR tacky OR gritty OR grainy OR coarse OR fibrous OR cellular OR crystalline OR floury OR flouriness OR taste OR textur*)) AND (LIMIT-TO (SUBJAREA , "AGRI"))[2]	2,551	371

[1] Refined search for consumer preferences studies adds *AND ("consumer preference" OR sensory)* to the search terms listed.
[2] Owing to the unusually large number of developed country food processing papers discussing textural attributes of potato, the code *AND (LIMIT-TO (SUBJAREA , "AGRI"))* was included in the potato searches to reduce the number of irrelevant responses.

Please direct comments or questions about this research to Leigh Anderson at eparx@u.washington.edu.

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Appendix A. Summary Tables – Banana

Physicochemical Properties of Various Banana Cultivars

Banana cultivars	Ripening stage of	pH	Chromatometric parameters L*	a*	b*	Moisture content (g/100 g FW)	Textural (N/g FW)	Vitamin C (mg/ 100 g FW)	Sugars (%FW)	Sucrose	Glucose	Fructose	Proteins (mg/ 10g FW)	ash (g/ 100 g DM)	References
Spanish Enana (Canary islands) AAA	Yellow-green, 70:30	4.74	60.1	1.2	26.1	73.24	6.68	33.5	10.2	6.93	1.95	1.32	2.87		Cano et al., 1997
Spanish Gran Enana (Canary islands) AAA	Yellow-green, 70:30	4.91	67.1	2.9	24.0	74.04	6.13	33.2	11.1	5.53	3.55	2.28	2.66		Cano et al., 1997
Latin-American Enana (Colombia)AAA	Yellow-green, 70:30	4.83	59.3	−3.1	20.6	76.05	5.53	29.3	8.23	5.91	1.34	0.97	0.46		Cano et al., 1997
Pequena Enana (Tenerife) AAA	Yellow					77.75		10.16	17.9	11.27	3.45	3.16	156 FW	l	Forster et al., 2002
Gran Enana (Tenerife) AAA	Yellow					77.45		9.69	16.83	10.84	3.13	2.86	1.61	0.97	Forster et al., 2002
Gran Enana (Equador) AAA	Yellow					77.5		8.29	16.04	10.14	2.69	2.42	1.15	0.7	Forster et al., 2002
Bluggoe ABB	Dark green					68							30.1 DM	26.3 DM)	Yomeni et al., 2004
Dwarf Kalapua ABB	Dark green					58.44							13.9	20.9	Yomeni et al., 2004
French Sombre AAB	Dark green					59.62							26.2	16.9	Yomeni et al., 2004
Bluggoe ABB	Pale green with yellow tips					67.48							27.9	26.1	Yomeni et al., 2004
Dwarf Kalapua ABB	Pale green with yellow tips					57.99							18	21.3	Yomeni et al., 2004
French Sombre AAB	Pale green with yellow tips					58.20							36.9	19.1	Yomeni et al., 2004
Bluggoe ABB	more Green than yellow					68.2							30.6	26.1	Yomeni et al., 2004
Dwarf Kalapua ABB	More green than yellow					57.27							29.9	21.2	Yomeni et al., 2004
French Sombre AAB	More green than yellow					59.6							37	18.5	Yomeni et al., 2004
Bluggoe ABB	more Yellow than green					69.22							33.3	27.1	Yomeni et al., 2004
Dwarf Kalapua ABB	More yellow than green					58.25							21.6	18.8	Yomeni et al., 2004
French Sombre AAB	More yellow than green					61.94							40.4	19.3	Yomeni et al., 2004
G rande Naine AAA	Green	5.95	59.9	−20.1	35.5	74.05	Pulp firmness 1.65								Dadzie, 1998
W illiams AAA	Green	6.02	57.3	−20.6	34.8	76.62	1.67								Dadzie, 1998
Banana hybrid FH IA-01 AAAB	Green	5.77	57.3	−18.8	35.1	76.1	0.86								Dadzie, 1998
Banana hybrid FH IA-02 AAAB	Green	5.98	58	−20.9	36.6	76.21	1.30								Dadzie, 1998
Plantain hybrid FH IA-21 AAAB	Green	6–6.3				68–71	1.6–1.9								Dadzie, 1998
Plantain hybrid FH IA-22 AAAB	Green	6–6.4				66–70	1.7–1.9								Dadzie, 1998
Horn Plantain Cuerno AAB	Green	6–6.5				61–67	1.9–2.5								Dadzie, 1998
Cooking banana hybrid FH IA-03 AABB	Green	6–6.5				74–76	1.3–1.6								Dadzie, 199

(Arvanitoyannis & Mavromatis, 2009)

Musa Cultivars and Agronomical and Quality Traits

Type or species (genomic group)	Cultivar	Agronomical and quality traits	Cavendish (AAA)
Dwarf Cavendish		Accepted sensory & physicochemical traits	Mediate fruit size
Robusta (AAA)	Valery	Large bunches of high quality fruit	
Lacatan (AAA)	Pisang	High aromatic	Sweet pulp
Cavendish Nana		Good quality traits, high yielded	Sensitivity to choke throat, sensitivity to *Fusarium oxysporum*
Giant Cavendish	Williams	Very good quality traits	Sweet taste, long size fruits
	Grand Naine	High yielded, very good quality traits	Sensitivity to *Mycosphaerella fijiensis*
Plantain (AAB)	French	Cooking bananas	Horn
Musa balbisiana (ABB)	Bluggoe	Drought tolerance	Long size fruits
Dwarf Prata (*AAB*) × SH 3142 (*AA*) (AAAB)	Gold finger	Tolerance to low temperatures, drought tolerance, resistance to *Fusarium oxysporum*	Fruit acidity, small fruit size

(Arvanitoyannis et al., 2008)

Density, Dry Matter and Edible Fraction of Selected Musa Varieties

Type and use	Variety name	Group	Subgroup	Fruit density (g/ml)	Pulp density (g/ml)	Edible fraction (MS, kg)	Dry matter (DM)
Dessert diploitre	Ney Poovan	AB	Sucrier	0.98±0.11	1.01±0.12	2.31	31.85±0.65
Diploid BB	M.B. Tani	BB	Balbisiana	0.85±0.07	0.77±0.08	1.73	21.24±1.22
Dessert postre	Gros Michel Guayabo	AAA	Gros Michel	1.16±0.11	1.02±0.10	3.35	28.98±1.54
	Yangambi Km3	AAA	Ibota	1.02±0.06	1.04±0.12	2.79	33.25±0.85
	Bocadillo Chileno	AAA	Gros Michel	1.01±0.04	1.28±0.21	5.99	26.64±0.31
	Dwarf Cavendish	AAA	Cavendish	1.0±0.08	1.32±0.14	2.32	28.90±0.99
	INDIO (Primitivo)	AAA	Cavendish	0.95±0.07	1.05±0.20	3.43	29.73±2.47
	Banano Chico	AAA	Gros Michel	1.22±0.12	1.36±0.21	2.37	33.02±2.52
	Tafetan Rojo	AAA	Red Dacca	1.05±0.06	1.08±0.12	1.87	24.87±0.60
	Banano 2	AAA	Gros Michel	1.12±0.12	1.16±0.32	2.68	29.33±0.76
Cooking bananas	Guineo	AAA	Mutika	0.95±0.06	1.07±0.18	2.95	25.26±0.64
Dessert plantain	Pisang Ceylan	AAB	Mysore	0.98±0.12	1.12±0.19	4.33	31.34±2.03
Cooking	Mbindi	AAB	Plantain	1.04±0.03	1.13±0.05	3.84	40.02±1.10
	Africa 1	AAB	Plantain	1.02±0.05	1.13±0.07	3.64	36.76±1.24
	Cachaco sin Bellota	ABB	Bluggoe	1.03±0.03	0.88±0.11	1.58	34.82±0.29
	Cachaco Espermo	ABB	Bluggoe	0.95±0.04	0.79±0.09	1.23	35.07±0.61
	Saba	ABB	Saba	0.92±0.04	0.91±0.14	1.87	31.84±1.14
Dessert	FHIA 17	AAAA	Hybrid	0.95±0.06	0.99±0.10	4.66	22.44±0.96
	ICAFHIA 110	AAAA	Hybrid	0.86±0.04	0.99±0.15	4.83	28.61±2.34
	FHIA 1	AAAB	Hybrid	1.1±0.13	1.3±0.22	2.92	27.52±1.03

(Hoyos-Leyva et al., 2012)

Up-regulated Genes during Banana Fruit Ripening Identified by Suppression Subtractive Hybridization

Clone	Gene Bank accession no.	Size (bp)	*E*-Value	Annotation	Predicted function[a]
7.1	DQ493956	122 (2)	4E−14	Osmotin-like protein (*Fragaria ananassa*) AAF13707	SDD
7.2	DQ493957	221	1E−08	Prolyl-4-hydroxylase alpha subunit-like (*Oryza sativa*) BAD82590	SDD
7.3	DQ900659	387	6E−38	Voltage-dependent anion-selective channel protein (*Solanum tuberosum*) P42055	MT
7.4	DQ493958	312	5E−14/3E−12	Nitrilase-associated protein, AAG52493/spiral1-like, NP_974209 (*Arabidopsis thaliana*)	CA
7.5	DQ663586	272 (2)	1E−110	β-1,3-Glucananse (*Musa acuminata*) AF001523	SDD/CWL
7.7	DQ493959	317 (2)	1E−45	Vacuolar ATP synthase subunit H (*O. sativa*) NP_910644	SDD/MT
7.8	DQ493960	158		Unknown	
7.9	DQ900660	551	8E−91	Farnesyl pyrophosphate synthetase (*Lupinus albus*) P49351	SPP
7.10	DQ493961	318	4E−08	Ferredoxin (*Lycopersicon esculentum*) CAB65696	SDD/FAB
7.12	DQ493962	488	7E−30	Phosphatidylinositol transfer protein (*O. sativa*)	ST
7.13	DQ493963	267		Unknown	
7.14	AY651065	550 (4)	1E−80	Isoflavone reductase related protein (*Pyrus communis*) AAC24001	SDD/SPP
7.17	DQ493964	230	5E−14	Tetratricopeptide-like helical (*Medicago truncatula*) ABE85139	TTR
7.20	DQ497410	257	1E−38	*S*-Adenosyl-L-homocysteine hydrolase (*Triticum aestivum*) P32112	EB/TTR/SPP
7.21	AY651063	791 (2)	2E−108	Betaine aldehyde dehydrogenase (*Gossypium hirsutum*) AAR23816	SDD
7.22	DQ497409	215	2E−22	PHD finger protein-like protein (*A. thaliana*) NP_177849	TTR
7.23	DQ497411	322 (2)	1E−111	Metallothionein-like protein (*M. acuminata*)	SDD
7.24	DQ497412	308 (2)	5E−05	Bundle sheath defective protein 2 (*Zea mays*) AAD28599	TTR/SDD
7.25	AY651066	279 (2)	3E−114	Cytochrome P450 (*M. acuminata*)	SDD
7.27	DQ497413	174	1E−09	Translation initiation factor eIF-1A (*Beta vulgaris*)	TTR/SDD
7.28	DQ497414	213		Unknown	
7.33	DQ663581	552		Unknown	
7.34	AY651067	279 (2)	4.7	Ubiquitin-conjugating enzyme E2 (*O. sativa*)	TTR/SDD
7.35F	DQ663582	189 (2)	1E−09	Pathogenesis-related protein 1, PR1 (*Z. mays*) ABA34060	SDD
7.35S	DQ663583	207		Unknown	
7.37	DQ663584	168	3E−24	*S*-Adenosylmethionine synthetase (*M. acuminata*) AAB71138	EB/SDD
7.38	DQ663585	114	2E−12	β-1,3-Glucananse (*M. acuminata*) AAF08679	SDD/CWL
7.39	DQ663587	314		Unknown	
7.41	DQ663588	171		Unknown	
7.42	DQ663589	361	1E−61	Isoprenoid biosynthesis-like protein (*O. sativa*) AAO72576	SDD/SPP
7.43	DQ663590	179		Unknown	
7.44	DQ663591	304 (2)	1E−169	ACC oxidase 1 gene (*M. acuminata*) AJ223232	EB/SDD
7.45	DQ663592	268	2E−05	RNA-binding protein homologous to eukaryotic snRNP (*A. thaliana*) NP_199804	TTR
7.46	DQ900661	496	2E−38	Nucleoside diphosphate kinase (*Flaveria bidentis*) P47920	SDD
7.47	DQ663593	526	3E−93	Cell wall invertase (*M. acuminata*) AAO21213	SM
7.48	DQ663594	394	3E−62	Pectate lyase 1 (*M. acuminata*) AAF19195	CWL
7.50	DQ663595	209	3E−25	Stearoyl-ACP desaturase, chloroplast precursor (*Helianthus annuus*) P22243	SDD/FAB

[a] EB, ethylene biosynthesis; SDD, stress defense and detoxification; CWL, cell wall hydrolysis; CA, cytoskeleton associated; FAB, fatty acid biosynthesis; SM, sugar metabolism; MT, metabolite transport; TTR, transcription translation regulation; SPP, secondary plant product biosynthesis. Values in bracket in column "Size (bp)" represent frequency of Uni-EST in ripening up-regulated genes in this study.

(Kesari et al., 2007)

Up-regulated Genes at an Early Stage of Postharvest Ripening of Bananas

SSH Clone number	BLAST homologues[a]	Accession number	Numbers of clones in the SSH library	Ratio of signal intensity[b] (fluorescence units) 2 DPH/0 DPH
SSH-24	Alcohol dehydrogenase A (*Washingtonia robusta*)	ABA39598.1	1	2.4276
SSH-266	Complete chloroplast genome (*Acorus calamus*)	AJ879453.1	2	2.3894
SSH-53	ATP synthase CF1 epsilon chain (atpE) gene (*Yucca schidigera*)	DQ069396.1	3	2.3877
SSR-170	Metallothionein-like protein (*Musa acuminata*)	AF268393.1	7	2.2410
SSH-60	ATP synthase CF_0 C chain (*Yucca schidigera*)	DQ069384.1	1	2.1013
SSH–61	ABA- and ripening-inducible-like protein (*Oryza sativa*)	AF039573.1	1	2.0181
SSH-64	No homologues		1	2.0481
SSH-47	Granule-bound starch synthase (*Pennisetum glaucum*)	AAQ06271.1	1	2.0735
SSH-145	Putative polyphosphoinositide binding protein (*Arabidopsis thaliana*)	AAL86320.1	1	1.9702
SSH-184	Hypothetical protein (*Deinococcus radiodurans*)	F75297	1	1.9317
SSH–93	Putative protein (*Arabidopsis thaliana*)	CAB78914.1	3	1.8455
SSH-269	Senescence-associated protein-like (*Oryza sativa*)	XP_481260.1	1	1.8117
SSH-95	MADS-box transcription factor (*Asparagus virgatus*)	BAD83772.1	1	1.8012
SSH-196	Endochitinase (*Musa acuminata*)	AF416677.1	4	1.6689
SSH-9	No homologues		1	1.6508
SSH-76	DNA-directed RNA polymerase alpha chain (PEP) (*Australopyrum velutinum*)	CAB01381.1	1	1.6508
SSH-198	No homologues		1	1.5990
SSH-110	ATP-dependent clp protease (*Arabidopsis thaliana*)	NM_114746.2	1	1.5778
SSH-3	Unknown protein (*Arabidopsis thaliana*)	NP-568066.1	1	1.5640
SSH-256	Putative serine/threonine-protein kinase (*Oryza sativa*)	XP_467323.1	1	1.5566
SSH-271	No homologues		1	1.5425
SSH-105	Expressed protein (*Arabidopsis thaliana*)	NP_568066.1	1	1.5309
SSH-21	Ribosomal protein L22 (*Panax ginseng*)	YP_087005.1	1	1.5251
SSH-219	Endo-1,4-beta-D-glucanase (*Populus tremuloides*)	AY535003.1	4	1.5110
SSH-27	No homologues		1	1.5091
SSH-161	No homologues		1	1.5063

[a] BLASTN and BLASTX searches were conducted to determine homologous genes and putative functions of the cDNAs in the SSH library. The cut-off *e*-value used was 10^{-5} . Sequences with no significant hits were labeled "no homologues"

[b] Ratios of signal intensities were determined by cDNA microarray as described in Materials and methods ($P < 0.05$)

(Xu, Su, Liu, Wang, & Jin, 2007)

Descriptive Statistics for Selected Physicochemical Properties of Banana Flour

Parameter	Green (G-peel)				Ripe (R-peel)			
Min		Max	Mean[c]	Std[d]	Min	Max	Mean[c]	Std[d]
(a) Cavendish peel flour								
pH	4.3	5.33	4.8	0.42	4.86	5.69	5.47	0.24
TSS (°Brix)	1.53	1.9	1.73	0.12	3.2	3.63	3.46	0.14
L∗ value	34.83	48.73	40.88	4.46	32.43	41.08	37.62	3.07
a∗ value	3.79	6.42	5.2	0.78	4.77	6.34	5.55	0.39
b∗ value	21.01	27.07	23.27	1.94	11.02	14.01	12.47	0.88
WHC40[a]	4.14	5.2	4.91	0.36	5.39	6.55	6.1	0.33
WHC60[a]	4.81	5.85	5.23	0.33	5.59	6.72	6.34	0.33
WHC80[a]	5.15	6.5	5.88	0.34	6.65	9.26	8.19	0.68
OHC40[b]	0.69	0.85	0.76	0.04	0.78	1.06	0.93	0.08
OHC60[b]	0.68	0.8	0.76	0.03	0.92	1.05	0.98	0.04
OHC80[b]	0.95	1.17	1.03	0.06	1.07	1.39	1.28	0.08
Viscosity (mPa s)	46.73	60.07	54.24	4.38	66.8	83.9	76.47	5.56
BEF (N)	32.7	40.91	37.29	2.53	35.94	63.24	50.68	8.73
(b) Cavendish pulp flour								
	Green (G-pulp)				Ripe (R-pulp)			
pH	4.37	5.65	5.06	0.52	4.76	5.6	5.13	0.29
TSS (°Brix)	1.03	1.43	1.22	0.12	3.77	4.57	4.26	0.24
L∗ value	64.37	79.25	74.18	4.62	67.12	74.86	70.85	2.53
a∗ value	1.57	3.67	2.53	0.78	2.42	5.07	3.22	0.8
b∗ value	14.69	21.69	17.36	2.32	11.51	20.23	14.15	2.59
WHC40a	3.72	4.08	3.94	0.12	1.08	1.69	1.37	0.18
WHC60a	5.37	5.99	5.66	0.17	1.56	1.88	1.71	0.1
WHC80a	6.03	6.53	6.31	0.17	3.99	5.03	4.67	0.41
OHC40b	0.64	0.91	0.8	0.09	0.69	0.87	0.79	0.05
OHC60b	0.42	0.64	0.5	0.07	0.73	0.87	0.82	0.04
OHC80b	0.71	0.97	0.85	0.06	0.94	1.15	1.05	0.07
Viscosity (mPa s)	35.07	47.47	40.94	3.65	84.13	91.67	87.88	2.18
BEF (N)e	0.54	0.81	0.67	0.07	1.97	2.72	2.32	0.2

a Water holding capacity (g water/g dry sample); b Oil holding capacity (g oil/g dry sample); c n = 12; d Standard deviation; e Back extrusion force

(Alkarkhi et al., 2011)

Appendix B. Summary Table – Cassava

Progress and Current Status of Genetic Transformation in Cassava

Explant	Regeneration mode	Gene-transfer technique	Plasmid (marker genes)	Selection	Target traits	Integration/ expression	Reference
Somatic cotyledon	SO	*Agrobacterium*	pTOK233 (*hpt*, *uid*AInt, *nptII*); pBinGusInt(*nptII*, *uid*AInt)	Hygromycin	–	SAP, NAP, GAP	Li et al. 1996
Suspension	SE	Particle bombardment	pILTAB313 (*nptII*, *uid*A)	Paromomycin	–	SAP, GAP	Schöpke et al. 1996
Suspension	SE	Particle bombardment	pJIT100 (*luc*, *pat*); pJIT64 (*luc*)	Luciferase	–	SAP	Raemakers et al. 1996
Suspension	SE	Particle bombardment	pHB1 (*luc*, *AGPase*); pJIT100 (*luc*, *pat*)	Luciferase and ppt	–	SAP, NAP	Munyikwa et al. 1998
Suspension	SE	*Agrobacterium*	pMON977 (*nptII*, *uid*AInt)	Paromomycin	–	SAP, GAP	González et al. 1998
Somatic cotyledon	SE	*Agrobacterium*	pGV1040 (*nptII*, *bar*, *uid*A)	ppt	Herbicide resistance	SAP, GAP	Sarria et al. 2000
Somatic cotyledon	SO	Particle bombardment	pTZR5 (*hpt*, *uid*AInt)	Hygromycin	–	TGB, SAP, RAP, GAP	Zhang et al. 2000a
Suspension	SE	*Agrobacterium*	pHMG (*uid*AInt, hpt, pmi)	Hygromycin, mannose	–	SAP, NAP, GAP	Zhang et al. 2000b
Suspension	SE	Particle bombardment	pHMG (*uid*AInt, hpt, pmi)	Hygromycin, mannose	–	SAP, NAP, GAP	Zhang and Puonti-Kaerlas 2000
Suspension	SE	*Agrobacterium*	pCP15GUS; pCP54GUS (*uid* AInt, hpt)	Hygromycin	Root-specific promoters	SAP, NAP, GAP	Zhang et al. 2003b
Suspension	SE	*Agrobacterium*	pCASP1 (*uid*AInt, hpt)	Hygromycin	Improved protein content	SAP, NAP, GAP, WAP	Zhang et al. 2003a
Somatic embryo	SE	*Agrobacterium*	Cab1-CYP79D1/CYP79D2 (*nptII*)	Paromomycin	Reduced cyanogen content	SAP, RAP	Siritunga and Sayre 2003
Somatic embryo	SE	*Agrobacterium*	patatin-CYP79D1/D2 (*nptII*)	Paromomycin	Reduced cyanogen content	SAP, RAP	Siritunga and Sayre 2004
Somatic embryo	SE	*Agrobacterium*	pKYLX-HNL (*nptII*)	Paromomycin	Reduced cyanogen content	SAP, WAP	Siritunga and Sayre et al. 2004
Suspension	SE	*Agrobacterium*	pILTAB9001 (*nptII*)	Paromomycin	CMD resistance	SAP, NAP	Chellappan et al. 2004
Suspension	SE	*Agrobacterium*	pPZPasAC1, pPZPasAC2, pPZPasAC3 (*hpt*)	Hygromycin	CMD resistance	SAP, NAP	Zhang et al. 2005
Suspension	SE	*Agrobacterium*	GBSS-as2 and GBSS-as7	Luciferase	Improved starch	NAP	Raemakers et al. 2005
Somatic cotyledon	SO	*Agrobacterium*	E35S::antisense CYP79D1 /E35S:: antisense CYP79D2 (*nptII*)	G418	Reduced cyanogen content	GAP	Jørgensen et al. 2005
Somatic cotyledon	SE	*Agrobacterium*	3D (*nptII*)	Paromomycin	Improved starch content	SAP, RAP	Ihemere et al. 2006
Suspension	SE	*Agrobacterium*	pRNAi-dPro (*hpt*)	Hygromycin	CMD resistance	SAP, NAP	Vanderschuren et al. 2007a
Suspension	SE	*Agrobacterium*	pRNAi-dsAC1 (*hpt*)	Hygromycin	CMD resistance	SAP, NAP	Vanderschuren et al. 2009

continued.

Explant	Regeneration mode	Gene-transfer technique	Plasmid (marker genes)	Selection	Target traits	Integration/ expression	Reference
Somatic cotyledon	SO	*Agrobacterium*	pMAT21; pEXM2; pIPT5 (*ipt*)	Kanamycin	marker-free	SAP, RAP, GAP GAP	Saelim et al. 2009
Suspension	SE	*Agrobacterium*	pCP2	Hygromycin	tissue-specific promoter	SAP, GAP	Beltrán et al. 2010
Somatic cotyledon	SO	*Agrobacterium*	pSG529 (*nptII*)	Paromomycin	prolonged leaf life	SAP, RAP	Zhang et al. 2010
Suspension	SE	*Agrobacterium*	pILTAB600; pILTAB601 (*nptII*)	Paromomycin	Improved protein content	SAP, WAP	Abhary et al. 2011
Suspension	SE	*Agrobacterium*	p35S::GBSSI-RNAi; p54/1.0:: GBSSI-RNAi (*hpt*)	Hygromycin	waxy cassava	SAP, RAP, WAP	Zhao et al. 2011
Suspension	SE	*Agrobacterium*	RNAi FL-CP (*nptII*)	Paromomycin	CBSVD resistance	SAP, NAP	Yadav et al. 2011

AGPase, ADP-glucose pyrophosphorylase; *bar*, bialaphos resistance gene; GAP, beta-glucuronidase analysis positive; *hpt*, hygromycin phosphotransferase gene; *ipt*, isopentenyl transferase gene; *luc*, luciferase gene; NAP, Northern analysis positive; *nptII*, neomycin phosphotransferase II gene; *pat*, phosphinothricin acetyl transferase gene; *pmi*, phosphomannose isomerase gene; RAP, reverse transcription–polymerase chain reaction analysis positive; SAP, Southern analysis positive; SE, somatic embryogenesis; SO, shoot organogenesis; TGE, transient gene expression; *uid*A, beta-D-glucuronidase gene; *uid*AInt, *uid*A with intron; WAP, Western analysis positive.

(Liu et al., 2011)

Appendix C. Summary Tables – Potato

Up- and Down-regulation in Firm Tuber Bulks

Up-regulated in Firm Tuber bulks				
Feature	**GeneName**	**ProbeName**	**Description blastX**	**CLASS**
13194	bf_mxlfxxxx_0012e02.t3m.scf	bf_mxlfxxxx_0012e02.t3m.scf_192	proteinase inhibitor isoform [Solanum phureja]	not assigned.unknown
32244	bf_ivrootxx_0011c10.t3m.scf	bf_ivrootxx_0011c10.t3m.scf_313	thiohydroximate S-glucosyltransferase [Brassica rapa subsp. pekinensis]	misc.UDP glucosyl and glucoronyl transferases
30141	bf_mxflxxxx_0067a07.t3m.scf	bf_mxflxxxx_0067a07.t3m.scf_260	NA	not assigned.no ontology
29512	bf_arrayxxx_0091c12.t3m.scf	bf_arrayxxx_0091c12.t3m.scf_96	NA	development.unspecified
28240	bf_mxflxxxx_0031a10.t3m.scf	bf_mxflxxxx_0031a10.t3m.scf_113	NA	not assigned.unknown
20886	bf_mxflxxxx_0075c01.t3m.scf	bf_mxflxxxx_0075c01.t3m.scf_452	Peptidase A1, pepsin [Medicago truncatula]	not assigned.unknown
35560	MICRO.14952.C1	MICRO.14952.C1_416	MtN3 [Medicago truncatula]	development.unspecified
31532	**MICRO.187.C2**	MICRO.187.C2_212	NA	secondary metabolism.flavonoids.flavonols
43932	bf_mxlfxxxx_0064b03.t3m.scf	bf_mxlfxxxx_0064b03.t3m.scf_587	NA	not assigned.unknown
35076	MICRO.9973.C2	MICRO.9973.C2_755	serpin-like protein [Citrus x paradisi]	stress.biotic.PR-proteins.proteinase inhibitors
16669	MICRO.9408.C1	MICRO.9408.C1_459	putative ripening-related protein [Vitis vinifera]	misc.invertase/pectin methylesterase inhibitor family protein
12938	bf_mxlfxxxx_0007c06.t3m.scf	bf_mxlfxxxx_0007c06.t3m.scf_78	NA	not assigned.unknown
7721	bf_mxlfxxxx_0005g01.t3m.scf	bf_mxlfxxxx_0005g01.t3m.scf_94	metal ion binding [Arabidopsis thaliana]	metal handling.binding, chelation and storage
36775	bf_arrayxxx_0029c03.t7m.scf	bf_arrayxxx_0029c03.t7m.scf_463	putative receptor-like serine-threonine protein kinase [Solanum tuberosum]	not assigned.unknown
4579	MICRO.9519.C2	MICRO.9519.C2_740	acid phosphatase [Arabidopsis thaliana]	misc.acid and other phosphatases
31844	bf_mxlfxxxx_0039g03.t3m.scf	bf_mxlfxxxx_0039g03.t3m.scf_351	NA	not assigned.unknown
8896	MICRO.12232.C1	MICRO.12232.C1_599	cytochrome P450 [Petunia x hybrida]	misc.cytochrome P450
40044	SSBT003F21x.scf	SSBT003F21x.scf_410	Protein LE25	development.late embryogenesis abundant
39867	MICRO.11150.C1	MICRO.11150.C1_316	cytochrome P450 [Petunia x hybrida]	misc.cytochrome P450
35220	MICRO.17343.C1	MICRO.17343.C1_526	NA	not assigned.unknown
487	bf_stolxxxx_0038d02.t3m.scf	bf_stolxxxx_0038d02.t3m.scf_42	NA	protein.synthesis.misc ribosomal protein

2057	TBSK04052FB08.t3m.scf	TBSK04052FB08.t3m.scf_172	NA	not assigned.unknown
1685	MICRO.11070.C1	MICRO.11070.C1_334	Acidic endochitinase precursor	stress.biotic.PR-proteins
1645	bf_mxlfxxxx_0020b10.t3m.scf	bf_mxlfxxxx_0020b10.t3m.scf_405	calcium-binding protein [Olea europaea]	signalling.calcium
21105	SDBN003O04u.scf	SDBN003O04u.scf_595	CYP98A33v1 [Nicotiana tabacum]	secondary metabolism.phenylpropanoids.lignin biosynthesis.C3H
15838	MICRO.13583.C1	MICRO.13583.C1_1703	vacuolar citrate/H+ symporter [Citrus sinensis]	transport.unspecified cations
20514	BF_LBCHXXXX_0046A06_T3M.SCF	BF_LBCHXXXX_0046A06_T3M.SCF_351	NA	not assigned.unknown
33507	MICRO.249.C17	MICRO.249.C17_543	NA	not assigned.unknown
13057	STMCQ90TV	STMCQ90TV_391	cytochrome P450 [Petunia x hybrida]	misc.cytochrome P450
12356	MICRO.12441.C1	MICRO.12441.C1_593	ethylene-responsive late embryogenesis-like protein [Lycopersicon esculentum]	development.late embryogenesis abundant
29799	STMGZ78TV	STMGZ78TV_542	Auxin Efflux Carrier [Medicago truncatula]	hormone metabolism.auxin.signal transduction
27813	MICRO.12705.C2	MICRO.12705.C2_1576	aromatic amino acid decarboxylase 1A [Lycopersicon esculentum]	amino acid metabolism.degradation.histidine
29400	MICRO.12329.C2	MICRO.12329.C2_874	Tm-2 ToMV resistance protein [Lycopersicon esculentum]	not assigned.unknown
20275	POCBC15TV	POCBC15TV_292	putative O-linked N-acetyl glucosamine transferase [Oryza sativa (japonica cultivar-group)]	not assigned.no ontology
10875	bf_arrayxxx_0031e11.t7m.scf	bf_arrayxxx_0031e11.t7m.scf_404	ASR3 [Lycopersicon chilense]	not assigned.unknown
38374	STMGF96TV	STMGF96TV_987	NA	not assigned.unknown
39303	MICRO.2033.C9	MICRO.2033.C9_164	NA	stress.biotic.PR-proteins.proteinase inhibitors
36404	bf_cswbxxxx_0065f12.t3m.scf	bf_cswbxxxx_0065f12.t3m.scf_278	unknown [Solanum tuberosum]	not assigned.unknown
42256	bf_stolxxxx_0033D02.t3m.scf	bf_stolxxxx_0033D02.t3m.scf_413	ATEXLB1 (ARABIDOPSIS THALIANA EXPANSIN-LIKE B1) [Arabidopsis thaliana]	cell wall.modification
9442	bf_swstxxxx_0004h12.t3m.scf	bf_swstxxxx_0004h12.t3m.scf_435	NA	not assigned.unknown
26621	MICRO.16894.C1	MICRO.16894.C1_421	putative peroxidase [Solanum tuberosum]	misc.peroxidases
29314	MICRO.1262.C13	MICRO.1262.C13_1015	extensin-like protein - cowpea (fragment)	not assigned.unknown
11515	MICRO.16774.C1	MICRO.16774.C1_533	Avr9/Cf-9 rapidly elicited protein 137 [Nicotiana tabacum]	stress.biotic.misc

32516	MICRO.2069.C2	MICRO.2069.C2_648	putative NAD dependent epimerase [Trifolium pratense]	cell wall.precursor synthesis.GAE
29213	bf_mxlfxxxx_0020b06.t3m.scf	bf_mxlfxxxx_0020b06.t3m.scf_665	vetispiradiene synthase [Solanum tuberosum]	secondary metabolism.isoprenoids.terpenoids
2509	MICRO.2608.C15	MICRO.2608.C15_780	putative acid phosphatase [Hordeum vulgare subsp. vulgare]	misc.acid and other phosphatases
28129	STMGF79TV	STMGF79TV_401	F21J9.20-like protein [Euphorbia esula]	not assigned.unknown
36439	PPCBE53TH	PPCBE53TH_170	Multicystatin (MC)	protein.degradation.inhibitors
35866	MICRO.6554.C2	MICRO.6554.C2_508	TNY; DNA binding / transcription factor [Arabidopsis thaliana]	RNA.regulation of transcription.AP2/EREBP, APETALA2/Ethylene-responsive element binding protein family
6124	MICRO.17165.C1	MICRO.17165.C1_525	late embryogenesis abundant protein [Catharanthus roseus]	development.late embryogenesis abundant
7502	MICRO.13319.C1	MICRO.13319.C1_813	Arabidopsis thaliana CLC-d chloride channel protein (GB:Z71450)	not assigned.unknown
26817	MICRO.10505.C1	MICRO.10505.C1_380	hypothetical protein OsJ_019403 [Oryza sativa (japonica cultivar-group)]	not assigned.unknown
20678	MICRO.6277.C1	MICRO.6277.C1_146	abscisic stress ripening protein	stress.abiotic.drought/salt
9132	bf_stolxxxx_0041h12.t3m.scf	bf_stolxxxx_0041h12.t3m.scf_321	NA	not assigned.unknown
12355	MICRO.708.C12	MICRO.708.C12_635	SGRP-1 [Solanum commersonii]	RNA.RNA binding
36188	MICRO.13587.C1	MICRO.13587.C1_1154	CRT/DRE binding factor 1 [Hevea brasiliensis]	stress.abiotic.drought/salt
41096	MICRO.12312.C1	MICRO.12312.C1_759	Os06g0653000 [Oryza sativa (japonica cultivar-group)]	secondary metabolism.wax
32047	STMGN40TV	STMGN40TV_239	NA	not assigned.unknown
41885	MICRO.10309.C2	MICRO.10309.C2_1776	4-coumarate-CoA ligase/ fatty-acyl-CoA synthase [Arabidopsis thaliana]	secondary metabolism.phenylpropanoids
2274	MICRO.5360.C2	MICRO.5360.C2_480	NA	not assigned.unknown
20005	STMCC32TV	STMCC32TV_522	blight resistance protein RGA3 [Solanum bulbocastanum]	not assigned.unknown
17060	MICRO.11161.C1	MICRO.11161.C1_603	MFL8.1/MFL8.1 [Arabidopsis thaliana]	protein.degradation
Down-regulated in Mealy Tuber bulks				
Feature	**GeneName**	**ProbeName**	**Description blastX**	**CLASS**
23108	MICRO.8925.C1	MICRO.8925.C1_986	amidase/ glutamyl-tRNA(Gln) amidotransferase [Arabidopsis	tetrapyrrole synthesis.glu-tRNA synthetase

			thaliana]	
3681	MICRO.5947.C1	MICRO.5947.C1_1031	putative strictosidine synthase [Lycopersicon esculentum]	secondary metabolism.N misc.alkaloid-like
31598	MICRO.9908.C2	MICRO.9908.C2_1014	unknown protein [Arabidopsis thaliana]	not assigned.no ontology
9116	MICRO.13334.C2	MICRO.13334.C2_659	auxin-repressed protein-like protein [Nicotiana tabacum]	not assigned.unknown
13135	MICRO.9271.C1	MICRO.9271.C1_1049	chloroplast post-illumination chlorophyll fluorescence increase protein [Nicotiana tabacum]	not assigned.unknown
43927	BPLI17J17TH	BPLI17J17TH_709	hypothetical protein OsJ_030302 [Oryza sativa (japonica cultivar-group)]	not assigned.unknown
38330	MICRO.7102.C1	MICRO.7102.C1_317	unknown protein [Arabidopsis thaliana]	not assigned.unknown
19884	MICRO.4152.C2	MICRO.4152.C2_482	xyloglucan endotransglycosylase LeXET2 [Lycopersicon esculentum]	cell wall.modification
32993	STMHV65TV	STMHV65TV_595	aldehyde oxidase [Lycopersicon esculentum]	hormone metabolism.abscisic acid.synthesis-degradation
41303	SDBN006P07u.scf	SDBN006P07u.scf_462	unknown protein [Arabidopsis thaliana]	not assigned.unknown
30247	MICRO.2611.C3	MICRO.2611.C3_1435	Apyrase precursor (ATP-diphosphatase) (Adenosine diphosphatase) (ADPase) (ATP-diphosphohydrolase)	nucleotide metabolism.degradation
16043	POABE12TP	POABE12TP_387	zinc-finger protein [Petunia x hybrida]	stress
5100	STMCB53TV	STMCB53TV_77	NA	not assigned.unknown
23769	MICRO.5374.C1	MICRO.5374.C1_449	cyclopropane fatty acid synthase [Gossypium hirsutum]	lipid metabolism.Phospholipid synthesis
15178	MICRO.5245.C2	MICRO.5245.C2_1714	putative serine/threonine protein kinase [Nicotiana tabacum]	protein.postranslational modification
24788	MICRO.6624.C2	MICRO.6624.C2_589	NA	not assigned.unknown

(Kloosterman et al., 2010)

Starch Content, Morphological Traits of Starch Granules and Pulp Hardness of 13 Potato Cultivars

Cultivars	Starch content (g/100gFW)		Morphological traits of starch granules			Pulp hardness (gw)	
			Flatness	Size (μm^2)			
Irish Cobbler	14.4	bcde[a]	1.31	632	ab	72.4	bcd
Waseshiro	15.5	abcde	1.30	414	b	76.5	abcd
Kita-akari	14.4	bcde	1.26	516	b	59.2	e
Okhotsk Chip	16.0	abcd	1.29	679	ab	66.3	de
Toyoshiro	16.3	abc	1.39	599	b	78.5	abcd
IWA-5	14.5	bcde	1.38	1,006	a	73.4	bcd
Sayaka	13.5	cde	1.32	543	b	76.5	abcd
Hokuiku-8	12.8	e	1.35	773	ab	66.3	de
May Queen	14.0	bcde	1.32	629	ab	70.4	cd
Norin-1	14.1	bcde	1.23	572	b	71.4	cd
Konafubuki	16.7	ab	1.35	798	ab	86.7	a
Hokkaikogane	13.4	de	1.25	403	b	82.6	abc
Konyu-2	17.9	a	1.31	563	b	83.6	ab
ANOVA[b]		***	ns		**		***

Mean of three replications for each cultivar.

[a] Values with different letters are significantly different at the 5% level by Tukey-Kramer's test.

[b] **and *** significant at 0.01 and 0.001 probability, respectively.

ns not significant.

(Jitsuyama et al. 2009)

Four Tasting Traits in Steamed Tubers of 13 Potato Cultivars

Cultivars	Sweetness[a]		Potato taste		Smoothness		Deliciousness	
Irish Cobbler	2.70	abc[b]	2.84	abc	3.24	abc	2.78	a
Waseshiro	2.63	abc	2.86	abc	3.52	abc	2.66	ab
Kita-akari	2.89	ab	2.38	c	3.84	a	2.82	a
Okhotsk Chip	2.64	abc	2.78	bc	3.04	bcd	2.55	ab
Toyoshiro	2.50	abc	2.87	abc	2.97	cd	2.45	abc
IWA-5	2.16	bc	3.12	abc	3.23	abc	2.16	bc
Sayaka	2.68	abc	2.75	bc	3.63	ab	2.83	a
Hokuiku-8	2.96	a	2.94	abc	3.72	a	2.67	ab
May Queen	2.87	ab	2.86	abc	2.97	cd	2.81	a
Norin-1	2.22	bc	3.18	ab	3.41	abc	2.32	abc
Konafubuki	2.32	abc	3.11	abc	3.18	abcd	2.29	abc
Hokkaikogane	2.60	abc	2.55	bc	3.77	a	2.48	ab
Konyu-2	2.13	c	3.55	a	2.60	d	1.86	c
ANOVA[c]		**		**		***		***

Mean of three replications for each cultivar.

[a] Values represent the magnitude of each tasting traits that evaluated at five evaluative marks (strong: 5; medium: 3; weak: 1) by comparing with the standard sample of 'Irish Cobbler' as mark of '3'.

[b] Values with different letters are significantly different at the 5% level by Tukey-Kramer's test.

[c] ** and *** are significant at 0.01 and 0.001 probability, respectively.

(Jitsuyama et al. 2009)