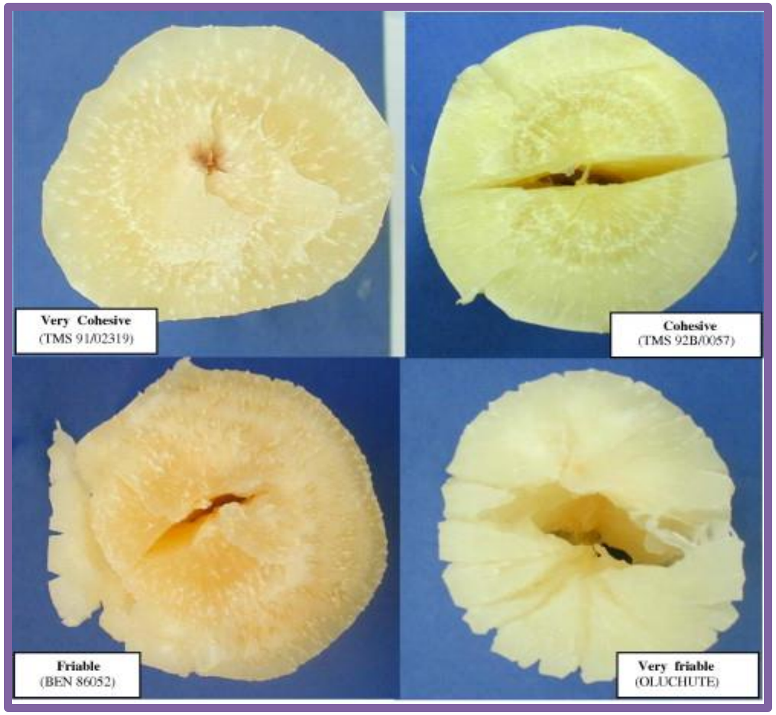

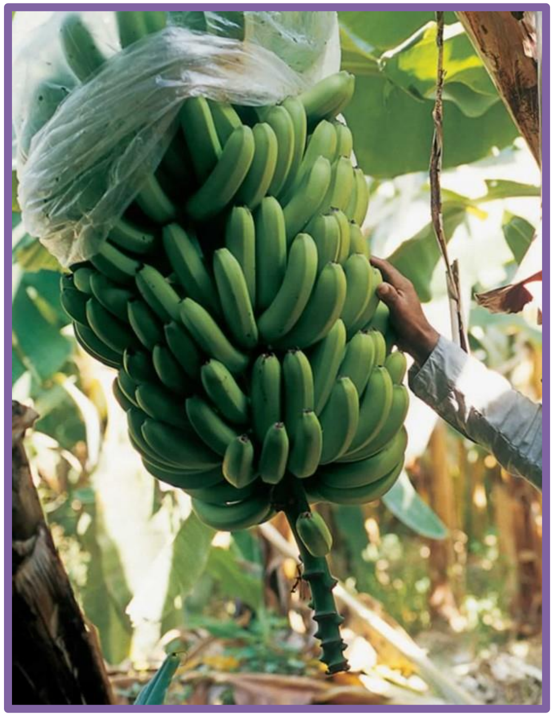
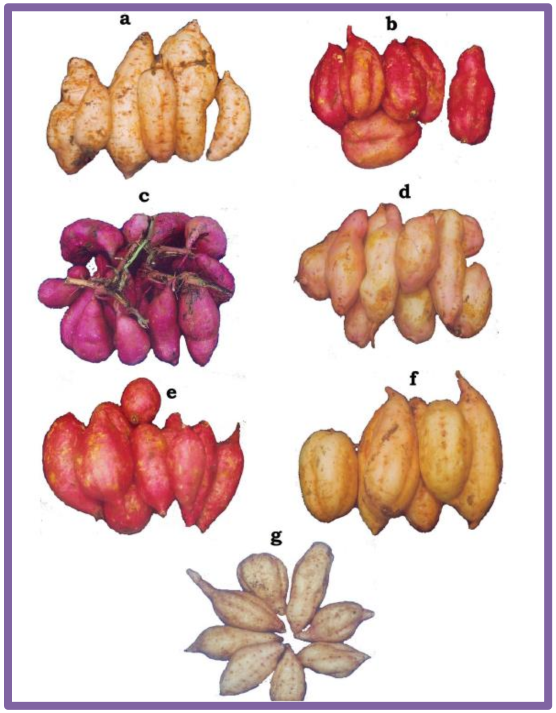

ROOT, TUBER, AND BANANA TEXTURAL TRAITS

A Review of the Available Food Science and Consumer Preference Literature

Full research brief: http://bit.ly/1zSzqNU

Evans School Policy Analysis & Research Group (EPAR)

February 26, 2015

AGENDA

- EPAR Introduction
- Defining Texture
- Classification of Textural Characteristics
- Research Methods
- Drivers of Textural Characteristics
  Role of starch
- Results Summary
  Potato, sweetpotato, yam, cassava, and banana/plantain
- Selected Findings
  Trends, current research priorities and apparent research gaps

Evans School Policy Analysis & Research Group (EPAR), University of Washington

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Evans School Policy Analysis and Research (EPAR)

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

EPAR Brief No. 295

Professors Alison Cullen and Travis Reynolds
Jaron Goddard, Allison Kelly, Katie Panhorst Harris

Prepared for the Agricultural Policy Team of the Bill & Melinda Gates Foundation

Professor Leigh Anderson, Principal Investigator
Professor Mary Kay Gugerty, Principal Investigator

January 9, 2015

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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. 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

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NOTE: The findings and conclusions contained within this material are those of the authors and do not necessarily reflect positions or policies of the Bill & Melinda Gates Foundation.

Link to brief

Provides research and policy analysis to support the Agricultural Development Initiative of the Bill & Melinda Gates Foundation

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Principal Investigator: Professor Leigh Anderson

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Defining Texture

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Research Methods

Drivers of Textural Characteristics
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Selected Findings
Trends, current research priorities and apparent research gaps

Research Purpose

- To review the available literature on consumer preference studies and current food science of texture for root, tuber, and banana (RTB) crops
  - *What are consumer preferences for textural attributes of RTB crops in Sub-Saharan Africa?*
  - *What are the physicochemical and genetic drivers of consumer-preferred textural traits?*

Defining Texture

"the sensory and functional manifestation of the structural, mechanical and surface properties of foods detected through the senses: vision, hearing, touch and kinaesthetic"

(*Civille & Ofteda, 2012*)

- Used to measure readiness for harvest
- Important for food preparation and food consumption; not simply taste or mouth feel, but physical properties
- Texture depends on: *(Sams, 1999; Farag et al., 2009; Konopacka & Plocharski, 2004; Lana et al., 2005)*
  - Genetic make-up (thought to be the primary determinant)
  - Passage of time (e.g., ripening)
  - Environmental factors (e.g., sun exposure, temperature, soil moisture, and climate trends)
  - Postharvest handling and operating conditions such as storage temperature

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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		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*

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Research Methods

- Scientific methods of texture analysis
  - **Subjective methods** identify consumer-preferred traits: surveys, consumer panels
  - **Objective (instrumental) methods** identify drivers of textural traits: Texture Profile Analysis, ultrasound and spectroscopy, mapping quantitative trait loci (QTL), measurements of gene expression, genotyping, microarray analysis
- Literature review methods
  - Academic literature search
  - Interviews of plant breeders and other scientists

Methods of Assessing Texture

Elicit Consumer Preferences for Texture ↔ Conduct Sensory Assessment of Texture ↔ Conduct Instrumental Measurement of Texture ↔ Identify Drivers of Food Product Characteristics ◆ Breed Crop Variety

Overview of Food Product Textural Analysis Process

- **Subjective:** consumer side (green boxes)
- **Objective:** breeder side (purple boxes)

Literature Review Methods

Search terms: texture		Search terms: crops		Number of Articles
(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*))	+	yam OR dioscorea	→	421
		cassava OR manihot		787
		"sweet potato" OR sweetpotato OR ipomoea		571
		banana OR plantain OR musa		1171
		potato OR solanum		2551

Searches: Scopus, Google Scholar, Science Direct, University of Washington Online Libraries, expert consultations

Geneticists, Plant Breeders, and Scholars Contacted

Contacted 37 scientists at 19 institutions, including:

- 6 at University of Washington
- 10 at seven other universities
- 4 in agribusiness
- 11 at CG Centers
- 6 at other research institutions

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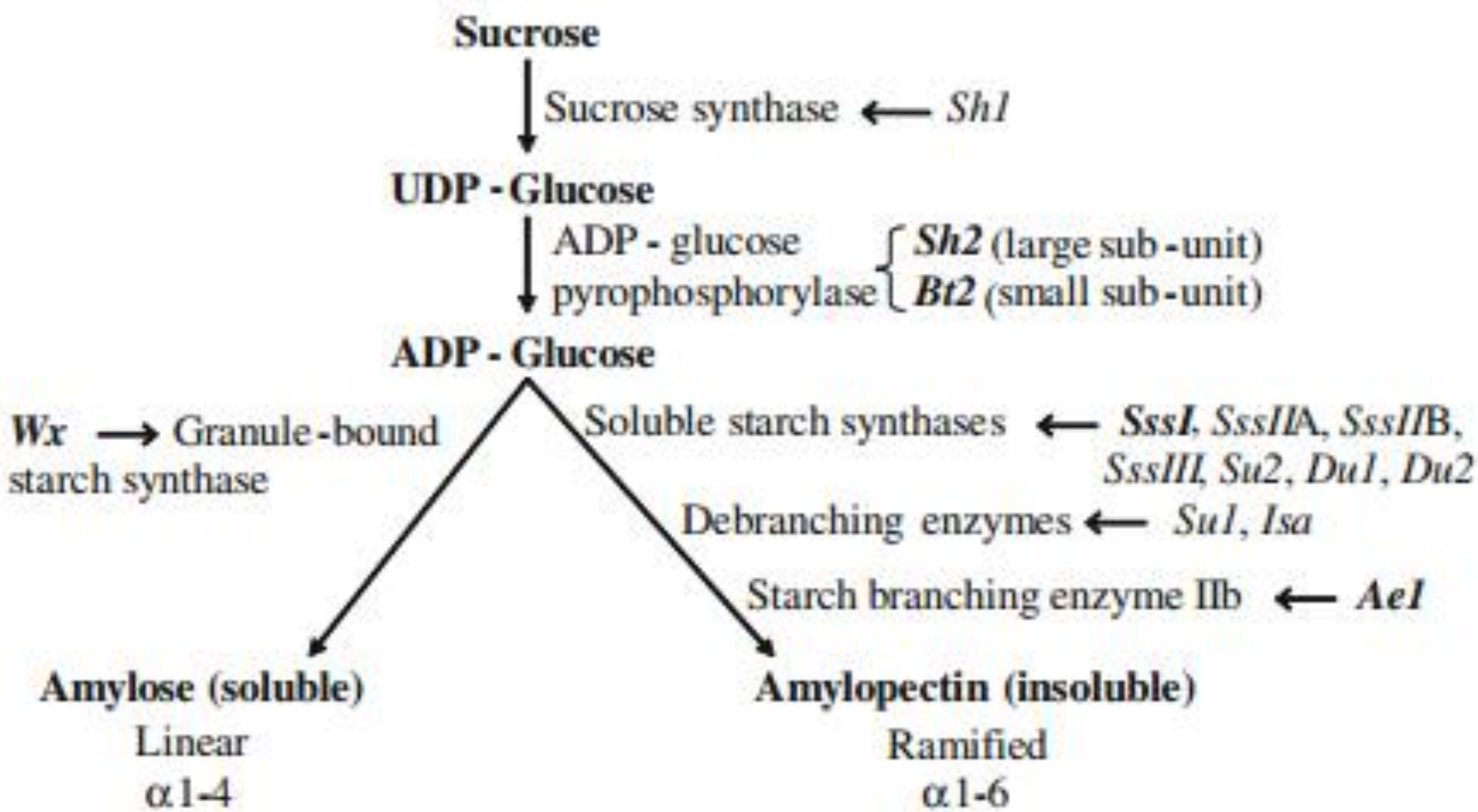
Role of Starch

- Around 80% of dry matter in RTB crops is carbohydrate: starch, mucilage, and sugars
- Starch structures are considered a primary characteristic that affects texture
- Amylose:amylopectin ratio in starch may explain textural traits
- Breeders may manipulate starch granule size
- Research on starch pathways in RTB crops is scarce; can learn from other crops like sorghum, tomato, and maize

Pathways of Starch Synthesis



(*De Alencar Figueiredo et al., 2010*)

Drivers of Textural Characteristics

Owing to the great diversity in textural attributes, there are many genetic, physicochemical, environmental, and processing-related drivers of food texture.

The table shows characteristics with the potential to explain texture.

Measureable Food Product Characteristics
Biochemical characteristics: lipid content, cell wall structure, particle size/shape, moisture content, amylose content, and mechanical properties
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 arrangement of tissue
Physicochemical properties, morphology and molecular structure of starch (amylose and amylopectin content)
Genetic drivers (e.g. polymorphism)
Starch digestibility
Swelling capacity

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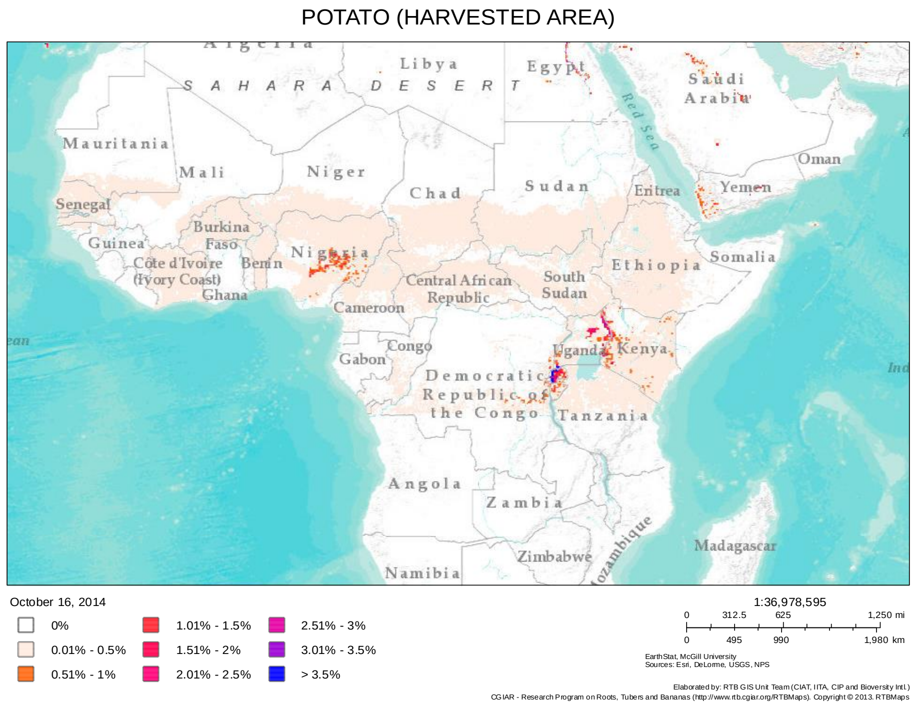
Potato *(Solanum tuberosum)*: Highlights

- Consumer preference studies conducted mostly outside of Africa
- High dry matter an important physicochemical driver of textural traits
- Potato texture is both genetically and environmentally determined
- Five genes are known to drive starch structure and cell wall biosynthesis
- Pectin methyl esterase (PME) and the PEST1 gene important in processing

- Potato production in Asia, Africa, and Latin America increased from 30 million tonnes in 1960 to 165 million tonnes in 2007.
- Potato is an important food security crop in SSA and its production is projected to expand there in the coming decade.
- In SSA, potato is prepared by boiling or consumed as potato fries at restaurants.



Trait	Consumer Preferred	Physicochemical Driver	Genetic Driver
Hardness	Hard +	Starch, pectin, cell size, low moisture content	Nicola variety (less compact primary cell structure)
Cohesiveness	Mealy +	Starch, pectin, cell size, high dry matter content	Pectin methyl esterase (PME) activity; PEST1 gene
Adhesiveness	Adhesive +	Starch, pectin, cell size	NA
Smoothness	Creamy + Smooth skin +	Cell size, phosphorous and potassium content	NA
Particle Size	Floury +	NA	ß-amylase; expression of *rol* transgenes
Particle Shape	NA	NA	Expression of *rol* transgenes
Moisture Content	Moist + (78.73-82.82%)	NA	NA
Starch Content	High Starch+	NA	AGPase, R1 gene
Dry Matter Content	Dry Matter +	Grown in sandy soil	Chromosomes II, III, V, VIII, XI, VII subgroup; pectin acetyl-esterase, xyloglucan endo-transglycosylase, NAD-dependent epimerase, nucleotide-rhamnose synthase

Genes Involved in Tuber Quality Traits in *S. tuberosum* Group Cultivars (*Ducreux et al., 2008*)

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

Correlations Among Traits Related to Starch and Taste

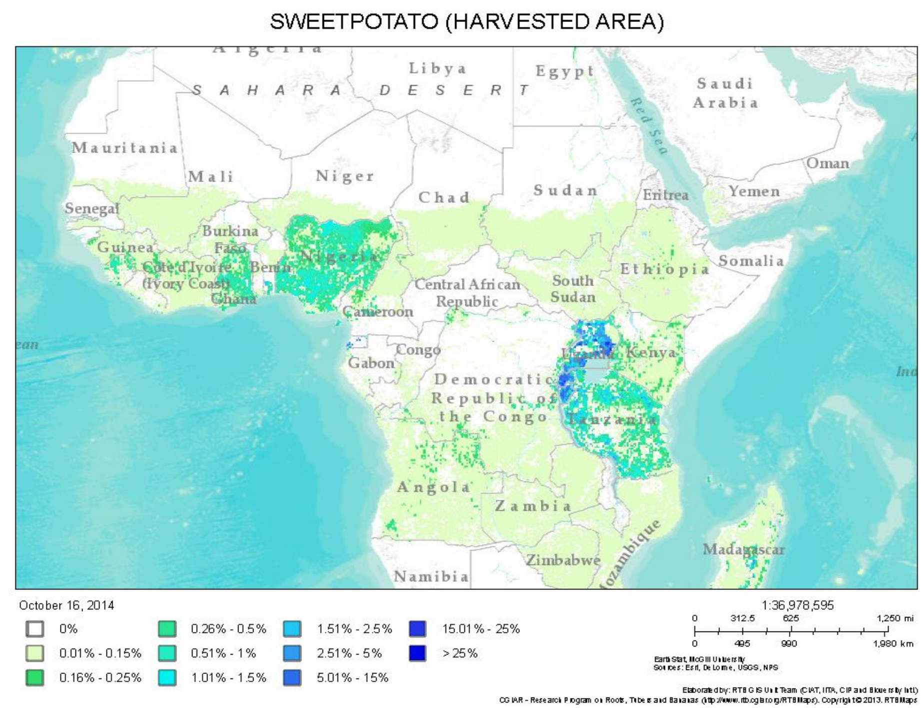
(*Jitsuyama et al., 2009*)

Traits	Sweetness	Potato Taste	Smoothness	Deliciousness	Starch
Sweetness	-				
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

Sweetpotato (*Ipomoea batatas*): Highlights

- Paucity of literature on sensory evaluation of sweetpotato in SSA, but most 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)
- Pasting profiles of sweetpotato starch vary widely across and within varieties

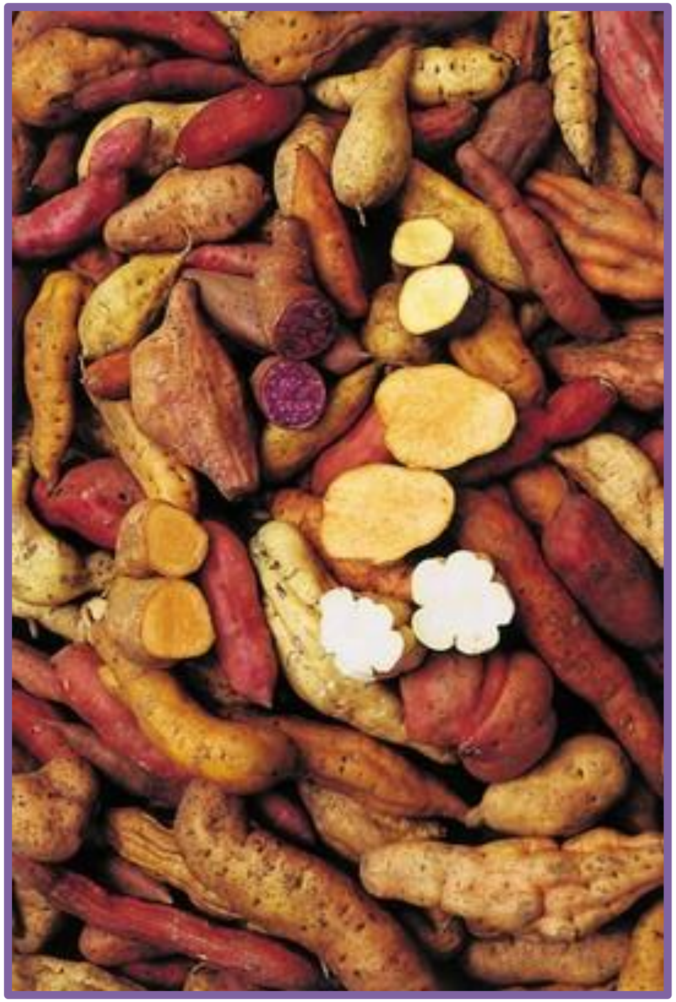
- In SSA, sweetpotato is usually grown on small plots by women.
  - Production is expanding faster than any other major crop in SSA, possibly due to cassava and banana/plantain disease constraints.
- Sweetpotato is the third most important food crop in Eastern and Central Africa and is critical for fighting Vitamin A deficiency.
- In SSA, sweetpotato roots are prepared by boiling or roasting.



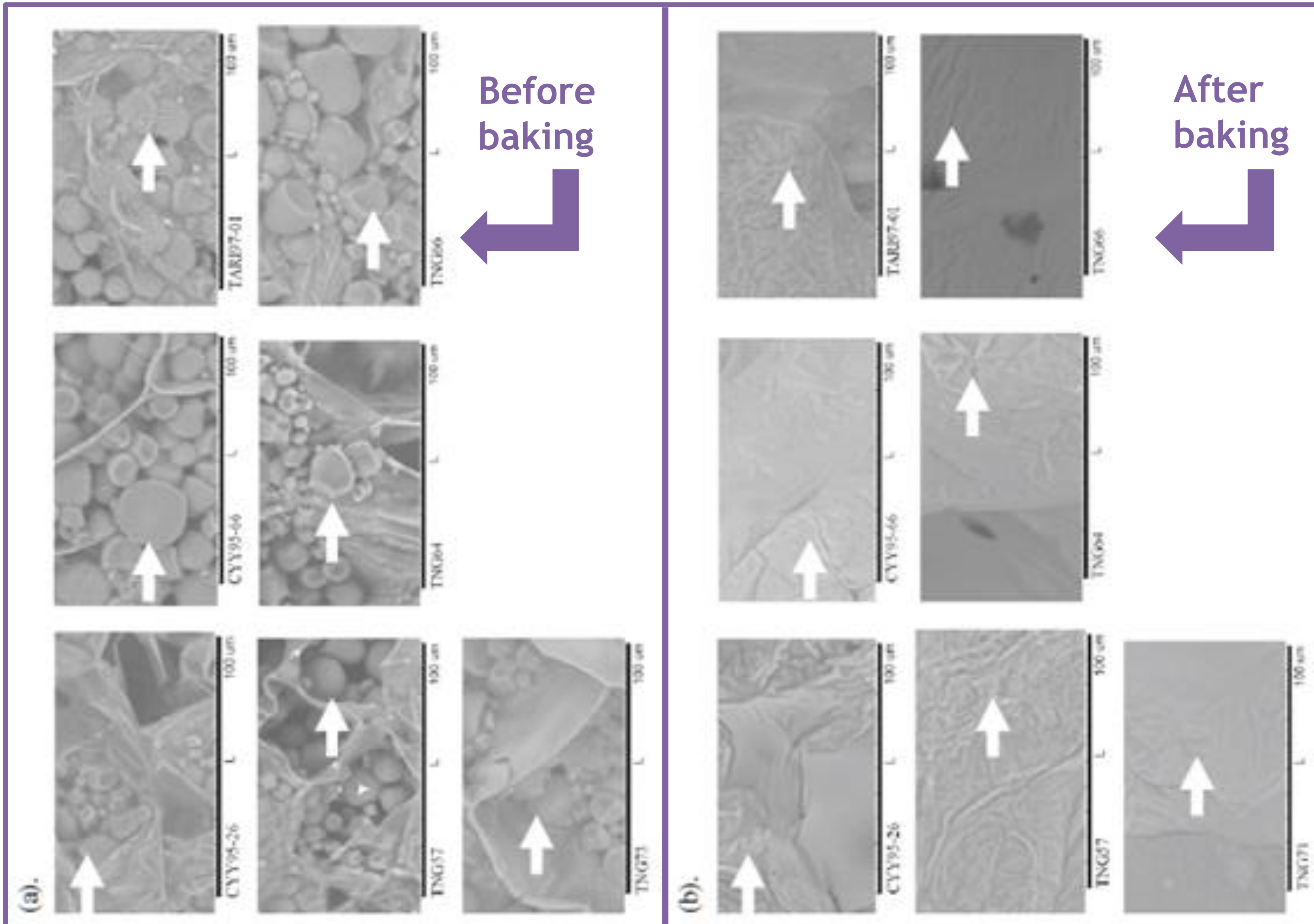
Trait	Consumer Preferred	Physicochemical Driver	Genetic Driver
Hardness	Soft +	NA	NA
Cohesiveness	Chewy +	NA	NA
Viscosity	NA	NA	NA
Springiness	NA	NA	NA
Adhesiveness	Sticky +	Viscosity and setback ratio	See Table 13
Smoothness	Smooth +	NA	NA
Particle Size	Grainy + Floury +	Soil temperature	NA
Particle Shape	Fibrous +	NA	Kanto 116 (this line exhibits abnormal starch granule morphology)
Moisture Content	Moist + Starchy +	High starch content	SPN/0; Polista
Fat Content	NA	NA	NA

Sweetpotato Changes During Preparation

- Though tubers of the same flesh color did not have textural similarity when raw, Principal Component Analysis revealed that they did have similar flesh and flour properties after cooking *(Sajeev et al., 2012)*
- During baking, moisture content (correlated with physicochemical properties) decreases by 5-10% while total sugar content increases by up to 200% as thermal properties induce maltose formation and starch gelatinizes *(Lai et al., 2013)*
- Starch granules gelatinize completely when heated and are rendered invisible in electronic micrographs (image, next slide)



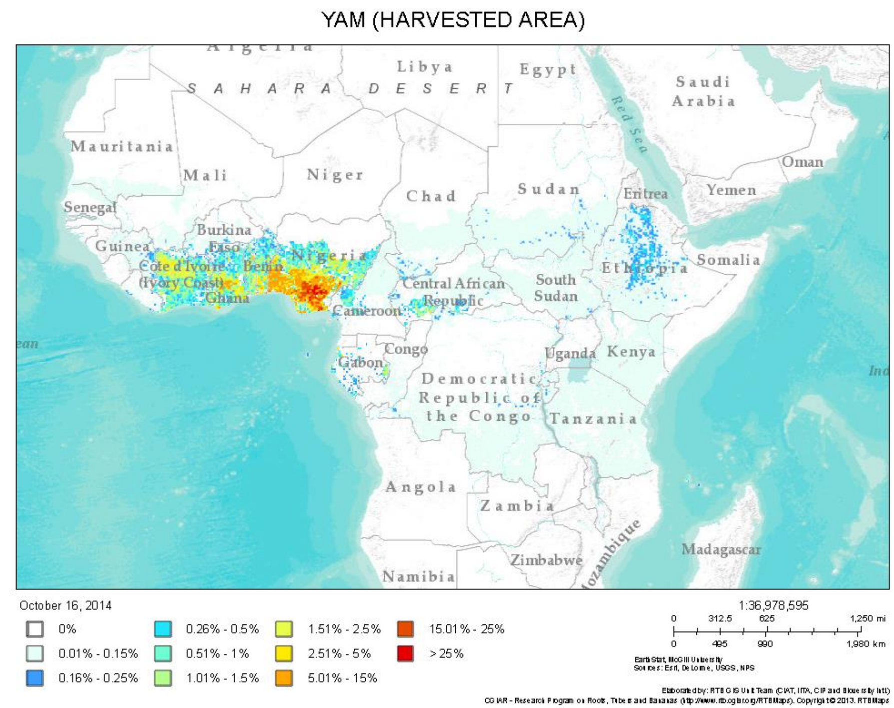
Electronic Micrographs of Sweetpotato *(Lai et al., 2013)*



Tropical Yam *(Discorea spp.)*: Highlights

- Elasticity, non-stickiness, and starch particle size are important for pounded yam products
- Amylose content is a key indicator of texture
- Published work relating physicochemical properties and textural qualities emphasizes the impacts of storage and food preparation on texture

- Africa produces 96% of the world's yam. Nigeria produces more yam than the rest of the world combined.
- Yam is nutritionally superior to other RTB crops and is a better source of protein.
- In West Africa, yam is pounded into pastes called *amala* and *fufu* and is also consumed as dry-slices and flour.



Trait	Consumer Preferred	Physicochemical Driver	Genetic Driver
Hardness	Soft +	Low amylose, soluble starch, dry matter, extracellular integrity	NA
Cohesiveness	Mealiness + Moldable +	Low amylose, cell separation and "rounding off"	NA
Viscosity	NA	Low amylose	NA
Springiness	Elastic +	Low amylose	NA
Adhesiveness	Sticky + Non-sticky + (depends on preparation)	Amylose content and solubility, soluble matter	NA
Particle Size (flour)	150-300µm +	NA	NA
Particle Shape	NA	NA	NA
Moisture Content	NA	NA	NA
Fat Content	NA	NA	NA

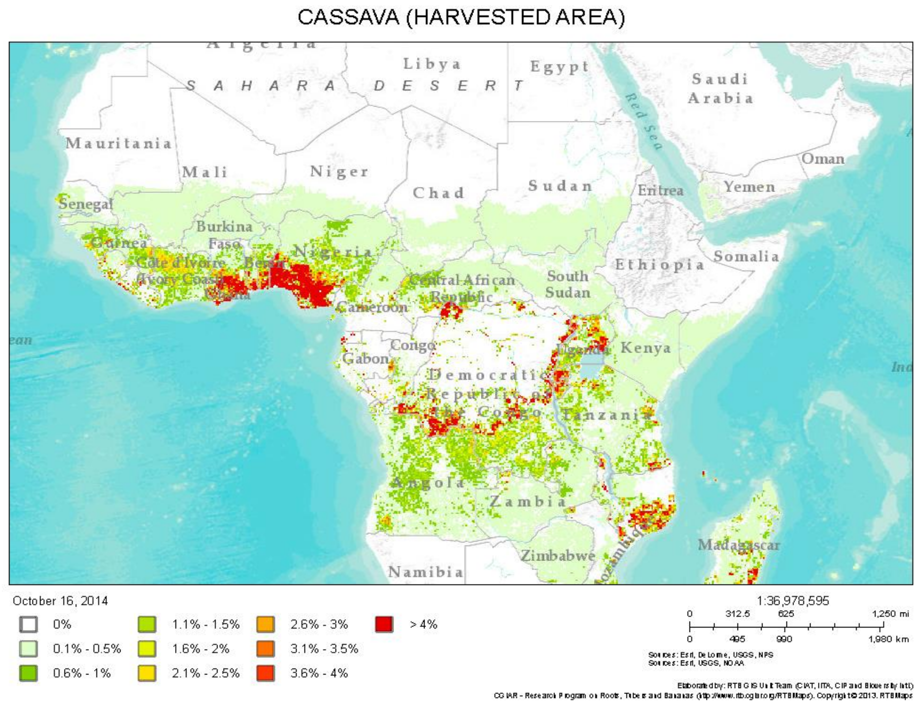
Consumer-preferred Varieties and Characteristics

- Most consumer preference studies asked a trained or untrained panel to rate the two most commonly cultivated yam species, *D. rotundata* and *D. alata*.
- *D. rotundata* is preferred for *fufu* because of its moldability, springiness, and stretchability *(Nindjin et al., 2007, Ekwu et al., 2005)*. Consumers prefer certain textural properties that make food easier to prepare and eat, and others that make food taste good.
- *D. alata* is suitable for *amala* because of pasting properties, high gel strength of its flour, and browning during cooking *(Wireko-Manu et al., 2014)*.
- Though *D. rotundata* is more widely used, *D. alata* has been found to have higher yield, better storage capacity, and higher nutritional value *(Baah, Maziya-Dixon, Asiedu et al., 2009; Wireko-Manu et al., 2014)*; thus scientists recommend diversifying its food uses.
- *D. alata* flour can be mixed with cassava flour and substituted for *D. rotundata* flour. A study found that consumers preferred a 70% *D. alata* – 30% cassava flour mix to 100% *D. rotundata* flour *(Babajide & Olowe, 2013)*.

Cassava *(Manihot esculenta)*: Highlights

- Key sensory characteristics: smoothness, aroma, color (white, grey, yellow)
- Texture driven by physicochemical properties, starch morphology/structure
- Leaves and tubers contain the cyanogenic glycosides linmarin and lotaustralin, which can produce cyanide hydroxide if not removed during processing
- Cassava is often fermented to prepare food dishes and cassava flour

- Cassava is the 4th 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.
- Cassava processing ranges from peeling and boiling to grating, pressing, fermenting & roasting.
- Industrial uses of cassava starch are increasingly common.
- Little published texture research.



Trait	Consumer Preferred	Physicochemical Driver	Genetic Driver
Hardness	Soft +	NA	NA
Cohesiveness	Mealy +	Pectin	NA
Viscosity	Viscous +	Granule shape, swelling power, amylose and amylopectin granular interaction	NA
Adhesiveness	Non-sticky +	NA	NA
Smoothness	Smooth +	NA	NA
Particle Size	NA	Moisture content	NA
Starch Content	NA	NA	MeAATP1 and MeAATP2; AGPase S and AGPase B genes
Texture	NA	Quantity and quality of root components, macro-structure of cassava root, organization of cells, arrangement of tissue	TMS 3055; TMS 3572
Cyanogenic Potential	NA	NA	CYP79D1/D2

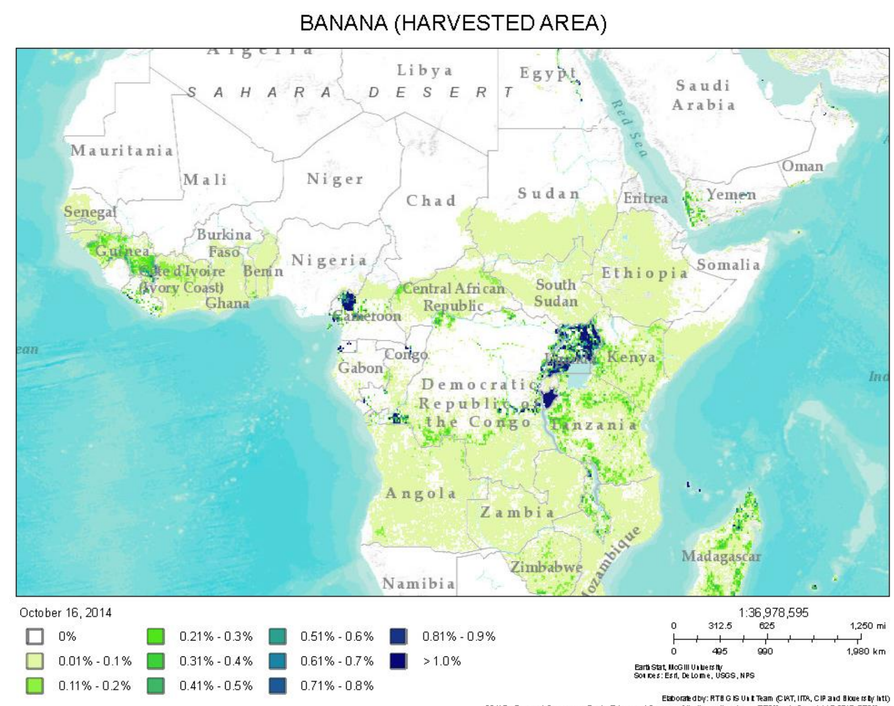
Drivers of Cassava Texture

- "the quantity and quality (chemical composition, physicochemical properties, morphology and molecular structure) of starch" *(Charoenkul et al., 2006)*
  - Starch comprises 65-75% of cassava carbohydrate
  - Cassava starch has good thickening and textural qualities
- Macro-structure of cassava root
- Cell organization and arrangement
- Age of plant
- Environmental conditions during growing season
- Interaction of cultivar and environmental effects with pectin drives mealiness
- Improved cultivars have higher pectin content and lower friability

Banana/Plantain *(Musa spp.)*: Highlights

- Key sensory qualities are softness, sweetness, light yellow color, and ripeness
- Starch structures and other physicochemical properties of many *Musa* genotypes have been researched extensively
- Banana fruit texture changes rapidly as starch degrades during ripening.
- Multiple genes regulate ripening and softening

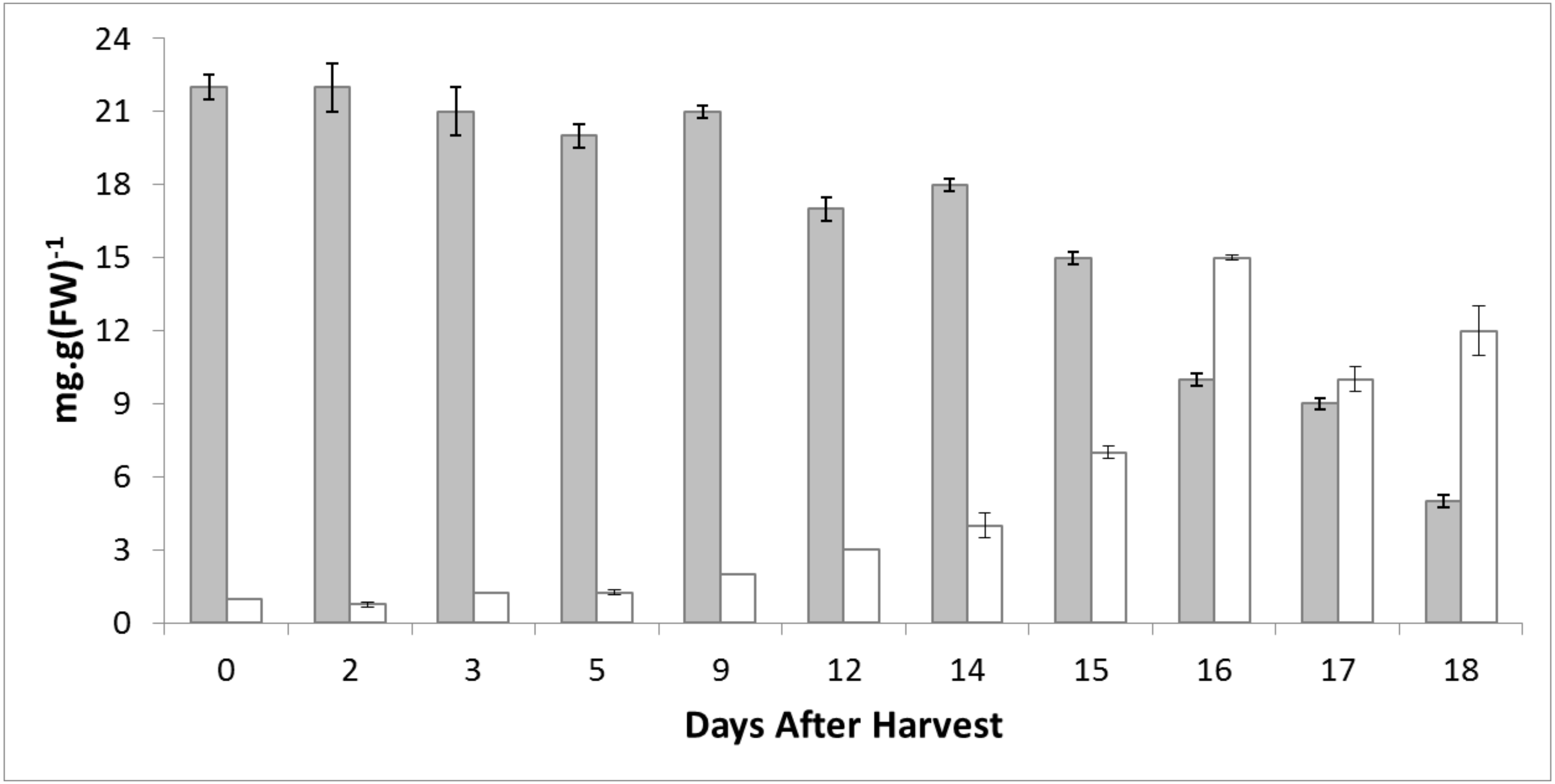
- Africa produces 71% of the world's plantain and 14% of banana.
- Plantain is grown primarily by smallholder farmers in SSA and is valuable for food security.
- Cooking banana is boiled or steamed followed by mashing, baking, drying, or pounding. It can also be served as a sauce or paste.
- Little consumer preference research.



Trait	Consumer Preferred	Physicochemical Driver	Genetic Driver
Hardness	Soft +	Ripening; dry matter content; pectin; 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
Viscosity	NA	Starch structure; starch gelatinization; hemicellulose and pectin polysaccharides	NA
Adhesiveness	NA	NA	NA
Particle Shape	NA	NA	NA

Storage and Crop Deterioration

Banana starch (grey bars) and sugar (white bars) content after harvest



(*Peroni-Okita et al., 2010*)

Storage and Crop Deterioration

- Banana fruit texture is especially dynamic due to the degradation of starch during fruit ripening
- Green banana starch granules have oval and rounded shapes with smooth surfaces
- Ripe banana has elongated granules with circular depressions and layered striations due to post-harvest degradation

Physicochemical changes in banana fruit during ripening (Ding, 2008)

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 $P \leq 0.05$.

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Trait	Potato	Sweetpotato	Yam	Cassava	Banana/Plantain
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

✓ At least one physicochemical or genetic driver known; important for consumer preference

? Drivers unknown but important for consumer preference

- At least one driver known; importance to consumer preference unknown

NA Drivers unknown; importance to consumer preference unknown

Environmental Drivers

- Environmental factors such as sun, temperature, soil moisture, and climate during the growing season determine food product texture *(Sams, 1999)*
- Many sweetpotato textural traits are environmentally determined (or arise from gene-by-environment interactions), which complicates breeding efforts *(Noda et al., 2001)*
- Studies have identified correlations between rainfall level and banana fruit firmness as well as cassava texture *(Bugaud et al., 2010, 2011; Franck et al., 2011)*
- A 2013 study of five potato cultivars used multi-environmental trials to improve understanding of environment-genotype interactions *(El-Sharkawy & El-Aal, 2013)*

Gender and Consumer Preferences

- Otoo & Asiedu (2009) conducted a consumer sensory evaluation of 36 yam genotypes. They found women were more critical than men in ranking texture. Differences may be due to women preparing food.
- Tomlins et al. (2004) conducted a cluster analysis of consumer preference ratings for sweetpotato cultivars over a two-year period. Women gave slightly higher ratings than men did to SPN/0, Ipembe, and Sinia B.
- Dury et al. (2002) found that women in Cameroon have distinct varietal and ripeness preferences that correspond to the cooking method of plantain.
- Tomlins et al. (2007) conducted consumer preference research for fermented cassava flour (*fufu*) in Nigeria. They found that men preferred *fufu* more than women did.

Textural Complexity

- RTB crop texture is influenced by a wide variety of factors including genetics, environment, ripening, and food preparation.
- Textural preference is similarly complex, depending on local tastes and preparation styles.
  - In Ghana, *Musa* hybrids may be accepted by some ethnic groups and rejected by others due to differences in food preparation.
  - Women and men have different preferences for cassava and sweetpotato.
  - Where food is eaten with hands instead of utensils, in-hand texture and on-palate texture both inform preference.
- This complicates breeding efforts.

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RTB Literature Review Available at http://bit.ly/1zSzqNU

EPAR's innovative student-faculty team model is the first University of Washington partnership to provide rigorous, applied research and analysis to the Bill and Melinda Gates Foundation. Established in 2008, the EPAR model has since been emulated by other UW Schools and programs to further support the foundation and enhance student learning.

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