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Tropical roots, tubers and bananas: new breeding tools and methods to meet consumer preferences

Roots, tubers, and cooking bananas (RTBs) play a major role in the diet of tropical populations, particularly in sub-Saharan Africa. More than 3 billion people in the tropics depend on RTBs for their diet, for an annual market value estimated at over $339 billion.[1] The evolutionary origins of RTBs consumed in Africa are very diverse,[2] and the majority are non-native crops, the use of which has increased significantly over the last 50 years. The countries that have the fastest growing RTB production are mainly in Africa and Asia.[3]

Excluding potatoes, which are mainly grown in temperate countries, and dessert bananas, almost 350 million tons of 'tropical' RTBs are processed and consumed in Africa, representing 65% of world production (Table 1). Ninety-eight percent of yams, 72% of cooking bananas, 77% of taros and aroids, and 65% of cassava produced worldwide are consumed in Africa. Roots, tubers, and cooking bananas are an important rural and urban staple food resource, and a critical source of employment and income.

Exotic crops are generally initially well adapted and productive in new habitats, far from native pests and diseases. Nevertheless, due to limited local genetic diversity, and because of crop intensification, and globalization of markets and trade and climate change, growers are often confronted with biological constraints that can have devastating effects on crops and food security (late blight on potatoes in Ireland; anthracnose in yams; weevils, sweetpotato viral disease (SPVD) and *Alternaria* blight in sweetpotatoes; green mite, cassava mosaic disease (CMD), cassava bacterial blight (CBB), and cassava brown streak disease (CBSD) on cassava in Africa; Indian cassava mosaic virus (IMCV) and Sri Lankan cassava mosaic virus (SLCMV) and pink mealybug on cassava in southeast Asia; Banana's *Fusarium* wilt worldwide; tropical race 4 (TR4) is now in almost all producing continents and cercosporiosis and banana viral diseases in all producing countries, and so forth).

In their urgent attempts to develop local varieties that are tolerant or resistant to pests and diseases in new locations, breeders often gave post-harvest quality and consumer preferences a lower priority. They first had to develop varieties that could supply value chains adequately and meet food security challenges. On-farm RTB varietal diversity, the national RTB germplasm, and Consultative Group on International Agricultural Research (CGIAR) genebank platform play a major role in the search for useful diversity for RTB varietal improvement. The inheritance of quality traits from potential RTB parents is generally poorly understood. Low priority was often given in the recent past to consumer/user-preferred traits and to post-harvest aspects, such as those linked to shelf life, women's workloads, and drudgery in processing operations, and this has contributed to the limited uptake of modern varieties targeted toward food use.[4-6]

The RTBfoods project (https://rtbfoods.cirad.fr/) aimed to identify gaps in understanding of varietal traits and local preferences for RTB varieties in terms of processing and consumption characteristics for a range of food products in sub-Saharan Africa. The project also aimed to develop high-throughput phenotyping tools, which breeders urgently need in order to select for user-preferred traits. The RTBfoods methodology includes:

- an evidence review;
- consultations with key informants and rural communities;
- processing diagnosis with experienced processors; and
- consumer testing in urban and rural areas.

Researchers worked with regional stakeholder teams including breeders, social scientists, food scientists, nutritionists, and gender specialists, to design target food product profiles (TFPPs) for each market segment and food product. These TFPPs capture key traits and characteristics of new varieties needed by farmers, processors, and consumers. Quality characteristics were then prioritized by user groups to inform the work of biochemists, chemometricians, and breeders on the development of improved selection tools.[7] Importantly, the methodology is gender intentional – i.e., it incorporates a sampling and conceptual foundation to enable analysis by gender and other social factors, to help crop breeders identify and prioritize specific traits in their breeding programs. This crucial information for breeders was limited in the past and resulted in the release of varieties that lacked the required quality traits, thus leading to low adoption by farmers and consumers.

The survey results using this methodology were published (Table 2), in open access, in March 2021.[8]

The current special issue, 'Tropical roots, tubers and bananas: New breeding tools and methods to meet consumer preferences', shares the methods developed for use in the field and in the laboratory to gather information on priority quality traits for users and consumers of RTBs, mainly in Africa (Table 2). Ten TFPPs, representing the RTB-based foods most widely consumed in the project's target countries, are published in this issue. The methods published in this issue concern:

(1) Biochemical analyses, mainly focusing on starches and parietal compounds and their role in determining the quality of end products, and in particular the texture and mealiness of chunks after steaming or boiling in water.
(2) Diagnostic and control methods for RTB processing unit operations during peeling, cutting or grinding, solid fermentation, and cooking. Among RTBs, cassava is by far the most widely consumed and processed crop, with numerous steps and unit operations, specifically for *fufu*, *gari*, and attiéké.[8] It is

Table 1. Important root, tuber, and banana (RTB) crops worldwide

Common name	Latin name	Center of origin[2]	Main food product in Africa	Production (Mt) World	Production (Mt) Africa (% of world)
Cassava	*Manihot esculenta* Crantz	Amazonian region	Boiled, steamed or stewed cassava, roasted cassava root, gari/eba, attiéké, fufu; batôn, chickwangue	314.8	203.6 **(65)**
White or yellow yam	*Dioscorea cayenensis subsp. rotundata complex*	West Africa	Boiled or steamed yam, pounded yam	75.1	73.5 **(98)**
Greater or water yam	*Dioscorea alata*	New Guinea and Melanesia			
Dessert banana	*Musa acuminata* (Group AAA 'Cavendish' and 'Gros Michel')	SE Asia	Fresh ripe fruit	125.0	22.9 **(18)**
Plantain	*Musa* spp. – (Group ABB)	SE Asia. Secondary center of diversification in West Africa	Boiled, stewed, or roasted plantain, fried green, ripe, over-ripe: tapé-tapé, aloco, tlaco	45.3	32.4 **(72)**
Matooke or mcharé	*Musa* spp. - Group (AAA-EA)	SE Asia. Secondary center of diversification in East Africa	Boiled or steamed banana, matooke		
Sweetpotato	*Ipomea batatas*	Andean and Central America. Secondary center of diversification in SE Asia	Boiled, fried, or stewed sweetpotato	88.9	30.0 **(34)**
Potato	*Solanum tuberosum*	Andean region	Boiled, fried, or stewed potato	376.1	28.1 **(7)**
Taro	*Colocasia esculenta*	SE Asia and Pacific	Boiled or steamed taro	12.4	9.5 **(77)**
Macabo	*Xanthosoma sagittifolium*	Amazonian region and the Caribbean	Boiled or steamed macabo	0.4	NA***
			Total	**1038.0**	**400 (39)**
			Total (excluding potato and dessert banana)	**536.9**	**349.0 (65)**

Source: FAOSTAT (2021): https://www.fao.org/faostat/en/#data/QCL.

estimated that 75% of cassava root processing and transport is carried out by women. Some processing steps can have a major impact on the workload and fatigue of women processors, depending on the genotypes used.[9]

(3) Each TFPP is related to the texture of the ready-to-eat product. Numerous methods were validated for their ability to discriminate among genotypes for texture, and they were correlated with consumer preferences.

(4) A combination of sensory methods was implemented to validate quantitative instrumental evaluation of color, texture, taste, and flavor. These methods and the results of the determination of trait acceptability thresholds are presented for the first time in this special issue.

(5) Methods for machine imaging, automated image analysis, and deep learning were applied to high-throughput prediction of quality traits preferred by consumers and users from raw RTBs. Key methods included infrared fingerprinting using near-infrared spectrometry (NIRS) techniques[10] or hyperspectral imaging cameras.

All these methods have been implemented by the project's partner teams to identify promising genotypes displaying the traits preferred by users and consumers. These genotypes are currently being evaluated by each breeding program for future release to farmers and stakeholder value chains. Many of the publications in this special issue report the results of these on-station or participatory characterizations using different approaches including the mother-baby trial or triadic comparison of technologies approach (TRICOT).

Genome-wide association studies (GWAS) for quality and preferences revealed genetic variability and acceptable heritability for underlying sensory and textural quality attributes, and correlations among them. High broad-sense heritability coupled with sufficient genetic variability in the studied populations indicate good potential for genetic improvement of traits through recurrent selection. The major stable loci that have been identified can be further utilized to improve selection in breeding programs for developing new cultivars with enhanced root/tuber or fruit quality.

This special issue is a pioneering report on the genetic factors underlying boiled and pounded yam food quality and paves the way for marker-assisted selection (MAS) in white Guinea yam. The validated quantitative trait loci (QTLs) will be useful for breeding programs using MAS to improve the quality of several RTBs. A better understanding of the physiological and molecular basis of these important quality traits, combined with knowledge of their genetic control, are critical for accelerating genetic gains.

Table 2. Key quality traits identified as breeding targets and methods developed for trait evaluation

Crop	TFPP's	Target countries	Traits and breeding target	Main quality trait defining TFPPs	Key quality traits identified as breeding targets
Bananas	**Boiled plantain**	Cameroon	Breeding target: Trait evaluation:	https://doi.org/10.1111/ijfs.14812 https://doi.org/10.1002/jsfa.12977	Fruit size, attractively colored pulp, well cooked and soft after boiling (both on touching and in the mouth). Plantain taste and aroma.
	Fried plantain	Nigeria, Côte d'Ivoire	Breeding target: Trait evaluation:	https://doi.org/10.1111/ijfs.14780 https://american-jiras.com/Catherine-Ref11ajira210921.pdf	Fruit size, pulp texture (firmness/softness), color, maturity stage and taste.
	Matooke	Uganda	Breeding target: Trait evaluation:	https://doi.org/10.1111/ijfs.14813 https://doi.org/10.1002/jsfa.13070	Big bunch, big fruits, and quality (soft texture, good taste, good aroma, yellow food).
Cassava	**Boiled or steamed**	Colombia, Benin, Uganda	Breeding target: Trait evaluation:	https://doi.org/10.1111/ijfs.14878 https://doi.org/10.1002/jsfa.13363	Softness of boiled roots and in-ground storability, high yield, non-bitter roots, disease resistance, early maturity and drought resistance.
	Gari/Eba	Nigeria, Cameroon, Benin	Breeding target: Trait evaluation:	https://doi.org/10.1111/ijfs.14790 https://doi.org/10.1002/jsfa.12518	General for cassava: multiple end uses of the roots, size, low water content, maturity, color. Gari: dryness, color, shiny/attractive appearance, uniform granules and taste. Eba: textural properties: smoothness, firmness, stickiness, stretchability and moldability.
	Lafun	Benin Cameroon	Breeding target:	https://doi.org/10.1111/ijfs.14902	Textural and viscoelastic properties and after-cooking storability.
	Fufu	Nigeria	Breeding target: Trait evaluation:	https://doi.org/10.1111/ijfs.14875 https://doi.org/10.1002/jsfa.13400	Appearance, texture, and smell. Smoothness, not sticky, easy to swallow and drawability of *fufu*.
	Attiéké	Côte d'Ivoire	Breeding target: Trait evaluation:	https://zenodo.org/record/6593224 https://doi.org/10.1002/jsfa.13141	Processing: Hard & dry flesh, ease of peeling, 3 days fermentation; Final product: Slightly sweet, non-sticky, not sour taste, hard & round granules
Potato	**Boiled**	Uganda	Breeding target: Trait evaluation:	https://doi.org/10.1111/ijfs.14840 https://doi.org/10.1002/jsfa.12882	Market preferences: Red skin and yellow flesh, big size (processing efficiency) and mealiness (eating quality).
Sweetpotato	**Boiled**	Uganda	Breeding target: Trait evaluation:	https://doi.org/10.1111/ijfs.14792 https://doi.org/10.1002/jsfa.12883	Raw: large roots, sweet taste, smooth skin and hard texture. Processing: ease of peeling and sappiness of raw roots. Boiled: mealiness, sweet taste and good sweetpotato smell.
	Fried	Ghana, Nigeria, Côte d'Ivoire	Breeding target:	https://doi.org/10.1111/ijfs.14764	Raw: hard, smooth skin and no off-odors. Peeled roots: hard to slice and not sticky. Fried: crisp, slightly sugary and mealy, uniform color and not be soggy.
Yam	**Boiled or steamed**	Benin, Nigeria	Breeding target: Trait evaluation:	https://doi.org/10.1111/ijfs.14707 https://doi.org/10.1002/jsfa.12589	Raw: easy to peel, peeled yam discoloration and mucilage. Cooked: white or yellowish, sticky to the fingers, nonfibrous, easy to chew, crumbly/friable, with a sweet taste and a good smell.
	Pounded	Nigeria	Breeding target: Trait evaluation:	https://doi.org/10.1111/ijfs.14770 https://doi.org/10.1002/jsfa.12835	Color and textural quality (smoothness and stretchability), taste, and aroma.

New phenotyping tools developed and deployed through the work of partners in the RTBfoods project have added value and efficiency to RTB breeding programs. High-throughput selection protocols (e.g., water absorption and hyperspectral imagining for boiled cassava; NIRs for different traits in different crops; *in situ* dynamic rheological analysis, etc.) are valuable tools that could allow breeders to overcome logistic limitations that previously prevented the selection of user-preferred traits. A better understanding of quality traits, data management in dedicated databases accessible to all (such as Breedbase, https://breedbase.org/), and a better knowledge of acceptability thresholds, will enable gendered demand-led breeding that takes into account the preferences of users and consumers, ultimately leading to better varietal adoption within RTB value chains.

The objective of the Bill & Melinda Gates Foundation (BMGF) in this project was to give breeding teams for these crops the tools they need to deliver high-yielding and robust new cultivars that include end user-demanded food quality (sensory) profiles. The sub-objectives developed with CIRAD were to have the team interact with producers and end users to define the most important cooked/processed food quality attributes, test their ability to accurately detect those attributes using trained sensory panels, investigate the underlying biochemistry responsible for those attributes, develop high- or medium-throughput assays suitable for detecting the underlying traits in segregating breeding populations, and use the developed tools to understand the genetic architecture of those important traits. The resulting data would be used to in conventional breeding and develop molecular markers for use in genomic selection or genomic prediction to develop efficiently new cultivars that are more likely to match user preferences.

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REFERENCES

1 Scott GJ, A review of root, tuber and banana crops in developing countries: past, present and future. *Int J Food Sci Technol* **56**:1093–1114 (2021). https://doi.org/10.1111/ijfs.14778.
2 Lebot V, *Tropical Root and Tuber Crops: Cassava, Sweet Potato, Yams and Aroids (Crop Production Science in Horticulture)*, 2nd edn. CABI, Wallingford, Oxfordshire, UK, p. 515 (2020) https://www.cabi.org/bookshop/book/9781789243369/.
3 Khoury CK, Achicanoy HA, Bjorkman AD, Navarro-Racines C, Guarino L, Flores-Palacios X *et al*., Origins of food crops connect countries worldwide. *Proc R Soc B* **283**:20160792 (2016). https://doi.org/10.1098/rspb.2016.0792.
4 Bowen AJ and Grygorczyk A, Challenges and opportunities for sensory and consumer science in new cultivar development and fresh produce marketing. *Curr Opin Food Sci* **41**:152–158 (2021). https://doi.org/10.1016/j.cofs.2021.04.009.
5 Thiele G, Dufour D, Vernier P, Mwanga ROM, Parker ML, Schulte Geldermann E *et al*., A review of varietal change in roots, tubers and bananas: consumer preferences and other drivers of adoption and implications for breeding. *Int J Food Sci Technol* **56**:1076–1092 (2021). https://doi.org/10.1111/ijfs.14684.
6 Weltzien E, Rattunde F, Christinck A and Ashby J, Gender and farmer preferences for varietal traits: evidence and issues for crop improvement. *Plant Breed Rev* **43**:243–278 (2020). https://doi.org/10.1002/9781119616801.ch7.
7 Forsythe L, Tufan H, Bouniol A, Kleih U and Fliedel G, An interdisciplinary and participatory methodology to improve user acceptability of root, tuber and banana varieties. *Int J Food Sci Technol* **56**:1115–1123 (2021). https://doi.org/10.1111/ijfs.14680.
8 Béchoff A, Tomlins K, Fliedel G, Becerra Lopez-lavalle LA, Westby A, Hershey C *et al*., Cassava traits and end-user preference: relating traits to consumer liking, sensory perception, and genetics. *Crit Rev Food Sci Nutr* **58**:547–567 (2018). https://doi.org/10.1080/10408398.2016.1202888.
9 Food and Agriculture Organization of the United Nations (FAO), *The State of Food and Agriculture 2010–2011: Women in Agriculture: Closing the Gender Gap for Development*. FAO, Rome, Italy (2011) https://www.fao.org/3/i2050e/i2050e.pdf.
10 Alamu EO, Nuwamanya E, Cornet D, Meghar K, Adesokan M, Tran T *et al*., Near-infrared spectroscopy applications for high-throughput phenotyping for cassava and yam: a review. *Int J Food Sci Technol* **56**:1491–1501 (2021). https://doi.org/10.1111/ijfs.14773.

