



# Breeding and end-use quality traits of roots, tubers, and bananas (RTB) crops for authentic African cuisines—a review

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**Abstract** The breeding of improved varieties of root, tuber, and banana (RTB) crops has led to the release of several varieties with excellent agronomic performances, such as high yield and disease resistance. However, farmers and end users have hampered the adoption of these improved varieties of RTB crops over the years due to their processing capacity and final product quality. Across the RTB crops, the key quality and adoption criteria differ for different products. The vital quality traits that can enhance the adoption of these improved varieties have been identified for cassava, yam, and banana/plantain. Some significant traits cassava farmers and consumers prefer are early-bulking, non-bitter roots, in-ground storability, drought tolerance, good pounding capabilities, and excellent cooking and sensory qualities. The acceptance of improved yam varieties is driven by

good yield, resistance to pests, good cooking quality, and admirable textural attributes for both boiled and pounded yams. Also, for banana/plantain *Musa* spp., farmers and end users prefer varieties with appealing sensory properties and good agronomic attributes. Farmers' and end-users' most desired traits are high yields, good cooking qualities, and climate resilience. Though the quantification of some of these quality traits is challenging, the synergized work of breeders and food scientists with the use of standardized protocols during the breeding, selection, and evaluation stages will enhance the production of cultivars that will meet the preferences of all stakeholders along the food product value chain of the RTB crops.

**Keywords** Cassava · Yam · Banana/plantain · Consumer acceptability · Cooking quality · Breeding

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## Introduction

Root, Tuber, and Banana (RTB) crops and their products are critical in improving households' nutrition and food security in Sub-Saharan Africa (Kawarazuka, 2020). The derived food products from the RTB crops are consumed daily and serve as a source of income for smallholder farmers in Africa (Scott 2021). RTB crops have contributed significantly to Sub-Saharan Africa (SSA) during the last few decades. This advancement has been greatly enhanced by Root, Tuber, and Banana (RTB) breeding programs

by releasing new high-yielding and disease-resistant cultivars of the crops. (Friedman et al. 2018). Cassava products such as gari, fufu, and attiékè are particularly important in West Africa, whereas matooke, boiled cassava, and sweet potatoes are significant in East Africa. These goods are primarily consumed at home or offered for sale in nearby marketplaces to generate income (Teeken et al. 2018).

RTB crops have become essential in Africa due to the increasing population growth and climatic uncertainties such as drought, minimum rainfall, and low-income populations. In developing countries, the total production of RTB crops averaged 840 million metric tonnes (FAOSTAT 2021), where cassava and potatoes increased in output by over 200 million tonnes, while yam went up by nearly 67 million tonnes and banana by over 100 million tonnes (FAOSTAT 2021). The RTB food group, which includes banana and plantain, may be the most complex and consists of sweet or dessert bananas, which are primarily of the Cavendish and Gros Michel varieties; cooking bananas, which are primarily of the East African highlands and beer-making bananas (EAHB). Plantains are also known as cooking bananas (Lescot 2020). RTBs are typically consumed in SSA directly as cooked pieces or mashed to form a smooth, non-sticky, elastic dough consumed with preferred soup. In addition, they are steamed or fried and served with traditional African soups. In Eastern and Southern Africa, cassava is typically cooked by boiling, stewing, or steaming. In West Africa, cassava is typically processed immediately after harvest to create derivative products, such as whole root fermentation and softening through retting (fufu, lafun, bâton, chikwangu); heap fermentation (Kwon) and fermentation/dewatering of the mash after grinding, followed by steam cooking (attiéké), roasting (gari), and (eba). The pattern of consumption and preferences due to location significantly impact the demand for the food quality attributes, which are similarly different. The quality of RTB food products is affected by a variety of elements, including variety; agroecological conditions, crop and product management, and processing stages (Teeken et al. 2018). Depending on their position in the target demand, crop and product users (such as growers, processors, merchants, and consumers) frequently choose many particular qualities (Efisue et al. 2008). Yield, dry matter, and disease/pest resistance were first given top focus in breeding programs for RTB

crops, but there is a need for the breeders to incorporate end-product quality attributes. A major problem with enhanced varieties of RTBs is their processing capacity and final product quality, which can reduce the varietal acceptance rate and the following benefits (Thiele et al. 2021). This review aimed to identify the gaps in the quality characteristics of the RTB crops (cassava, yam, plantain/bananas), which informs consumers' preferences and overall adoption of the crops (Table 1)

### Breeding and end-user quality traits of cassava products

#### Identified quality traits for different cassava products

Cassava breeders have created improved varieties of high yield, reduced cyanogenic content, enhanced tolerance to major diseases and pests, and high dry matter using molecular tools (Ceballos et al. 2004). For instance, a molecular map created in 1997 has been used in quantitative trait loci (QTL) mapping investigations in cassava for several variables, including yield, morphological and quality parameters, and pest and disease resistance. Based on these genotypic characteristics, this gene map has aided in producing better cassava cultivars (Sayre et al. 2011). Nevertheless, the improved varieties developed recently faced low adoption by farmers and end-users because they did not meet market demands or lacked the food product quality expectations from the consumers (Bechoff et al. 2018).

Breeders must have access to interact with post-harvest expertise to understand how end users perceive genetically improved cassava genotypes and how changes in cassava quality traits affect processing capacity, sensory qualities, consumer acceptance and market demands. Breeders must also understand the changes in cassava root processing into different value-added products, which can influence customer acceptability (Bechoff et al. 2018).

Cassava breeding programs need to incorporate end-user traits into the breeding traits selection to improve adoption, which is the ultimate goal of breeding investments. Some of these key quality traits have been identified through surveys and focused group discussions involving farmers, processors and other consumers of the product. For ins.

**Table 1** Summary of End Use Quality Traits of RTB crops (Cassava, yam, plantain) and their products

Crop	Products	End use quality traits	Status of end use traits and preference	References
Cassava	Gari/eba	Color, swelling capacity, particle size, moisture content, texture	<ul style="list-style-type: none"> <li>Higher moisture affects gari storage quality</li> <li>Cassava with high cyanide content might be suitable for industrial use but not for food products like gari</li> <li>Pectin content of cassava root may affect the texture attributes of eba</li> </ul>	Aryee et al. (2006), Makanjuola et al. (2012), Awoyale et al. (2023)
			<ul style="list-style-type: none"> <li>Fibrous fresh roots adversely affect fufu's quality</li> <li>Processing methods alter the quality characteristics of fufu</li> <li>Bulk density of the fufu flour correlates positively and significantly with its hardness</li> </ul>	Otoo et al. (1995), Chijioko et al. (2021), Olalaye et al. (2018), Awoyale et al. (2022b)
			<ul style="list-style-type: none"> <li>Starch granules of raw root influence the quality of the cooked roots</li> <li>Long cooking time is attributed to poor cooking varieties</li> </ul>	Mateves et al. (2012), Hongbete et al. (2011), Add Irigaba et al. 2020
Yam	Boiled yam	Color, water absorption, texture, crumbly, and taste	<ul style="list-style-type: none"> <li>White or yellow appearance characterizes yam cultivars acceptable for boiling</li> <li>The chemical constituents of different fertilizers applied to fresh yam tubers affect the quality of the boiled yam product</li> </ul>	Fakorede et al. (2020), Otegbayo et al. (2021), Kouadio et al. (2011)
			<ul style="list-style-type: none"> <li>The acceptability of fresh yam cultivar is determined by its pounded yam quality</li> <li>Poor pounded yam quality indicates poor yam cultivar</li> </ul>	Akissoe et al. (2006), Otegbayo et al. (2021)
Plantain	Boiled plantain Fried plantain Plantain chips	Taste, aroma, mouth feel, texture and color Taste, aroma, mouth feel, texture and color Taste, mouth feel, color and crunchiness	<ul style="list-style-type: none"> <li>Preparatory methods of plantain products influence the consumers' perception of the quality traits</li> <li>Fruit maturity, dark green peel color, and large fruit size are pertinent traits that drive acceptability</li> <li>Good sensory attributes alongside quality agronomic traits will positively drive the adoption of plantain cultivars</li> </ul>	Gibert et al. (2009), Amah et al. (2021), Ngoh Newilah et al. (2021). Add Khakasa et al. (2021)
			Appearance, textural attributes (stretchability, moldability, stickiness, and smoothness)	

In their research work, Tekeen et al. (2020) revealed that cassava roots' quality characteristics that give quality gari and "eba" are non-woody, non-decaying white-flesh roots, white mash with low moisture and less chaff. They further described that the high-quality attributes of cassava roots during processing that give good-quality products are white flesh roots, mash with high dry matter, and non-coarse gari that gelatinize faster. The researchers (Tekeen et al. 2020) established the quality traits of cassava roots and the finished product (*gari*) from the respondents in rural and small-town segments in Nigeria. Osunbade et al. (2023) added that the most preferred quality characteristics of gari by consumers in the rural area of Benue State, Nigeria, are dry, bright/shiny, white, sweet, dense, fine, cooked aroma, and sour gari. These researchers also add that consumer preferences for gari in Osun State, Nigeria's rural areas, are dry, white, dense, sour, and fine particles.

According to Iragaba et al. (2020), high yield, non-bitter roots, disease resistance, early maturity, drought tolerance, the softness of boiled roots, and in-ground storability are major characteristics determining varietal preference. Preference varied greatly by area and gender for some qualities, such as in-ground storage. About twenty-one descriptions related to the appearance, texture, flavor, and aroma of boiled roots were identified by sensory analysis. The results of this study are essential for breeders to use gender-responsive strategies to create varieties that satisfy end-user wants and preferences. The cyanide content of fresh cassava roots has generated major concerns due to the deleterious health effects when ingested at high concentrations. For instance, for freshly harvested cassava roots to be ingested, the varieties must have less than 50 mg/kg of cyanogenic glucosides on a fresh weight basis, whereas roots from varieties with high levels are processed before consumption to reduce the level of glucosides (Cardoso et al. 2005; FAO 2013; Montagnac et al. 2009).

Noting cassava intended for human food must meet cooking and eating quality requirements, which is also sufficient. Eating quality is complicated since it includes a variety of essential characteristics, such as cooking time, texture, bitterness, and flavor. Each of these characteristics is almost a function of several smaller characteristics, making breeding for end-user quality difficult. The significance of these

qualities and their inclusion in breeding practices are being given more attention. According to a study by Padonou et al. (2005), instrumental characterizations and the findings of the sensory evaluation of boiling cassava for end-user desired qualities showed a good correlation between mealiness for instance, is positively correlated with starch functional properties like viscosity after pasting according to the study. According to Ndjouenkeu et al. (2021), multiple technological processes are used to convert cassava roots into gari, which have high-quality characteristics, including dryness, color, shiny/attractive appearance, uniform granules, and flavor.

The primary textural characteristics of eba, the most popular form of gari (cassava product) consumed in Cameroon and Nigeria, are smoothness, stiffness, stickiness, elasticity, and moldability (Awoyale et al. 2022a). According to Chijioke et al. (2021), appearance, texture, and aroma are the main factors influencing gender-specific consumer preferences for fufu. Fufu's smoothness, lack of stickiness, swallowability, and drawability appear to be key characteristics that influence both men's and women's acceptability. Thus, breeding programs must be implemented using a multidisciplinary approach due to the difficulty of producing high-quality fufu. Its main sensory characteristics are the appearance, color, texture, taste, smell, moldability, and stretchability of eba. For raw cassava roots, large roots and smooth skin are preferred. While specific quality characteristics are substantially determined by a range of traits in eba and cooked fufu dough, others can be altered by altering the processing methods (Udoro et al. 2014; Eje et al. 2015; Olaleye et al. 2018). In addition to the amount of hot water used for reconstitution and the consistency of the stirring process, the same factors that impact the sensory acceptability of uncooked gari and fufu flour also affect that of eba and cooked fufu dough (Awoyale et al. 2022a; 2022b). Cassava Breeders should interact with food processors and scientists to understand these crucial quality traits and intensify efforts to integrate them into their breeding program to improve the adoption of new cassava varieties.

According to Maieyes et al. (2012), cooked and raw cassava varieties with starch granules that are more tightly connected to parenchyma tissues, pectin, and cellulose tend to have a firmer texture, which may have an impact on the gari and eba's quality.

Awoyale et al. (2023) also stated that most of the textural changes in roots and tubers during processing and subsequent preparation for consumption are influenced by the amounts of pectin and the starch content. Also, the rheological and textural behavior of the starch matrix is supported by starch qualities like the water absorption capacity after gelatinization and the amylose/amylopectin ratio, which helps to explain the textural characteristics of gari as well as the pasting properties of eba (Akingbala et al. 2005; Goddard et al. 2015). Hardness, adhesiveness, gumminess, and moldability/cohesiveness are the textural qualities of the cooked gari (eba) and fufu dough that the pectin content of the cassava roots may alter. The direct correlation between the pectin content of various cassava types and the textural characteristics of the cooked gari and fufu dough has not been adequately researched; thus, quantification of starch, pectin, and fiber could help to predict the suitability of cassava roots to produce gari, especially when considering that the age of the plants can influence the starch, pectin, and fiber contents of the product.

On the other hand, Charoenkul et al. (2006) argued that textural qualities have nothing to do with the molecular composition of starch. The observation of Charles et al. (2005), based on a visual assessment of texture rather than instrumental approaches, also corroborated this. Moreover, Makanjuola et al. (2012) discovered a favorable association between the moisture content of gari and particle size. This meant that gari with large particle sizes would be challenged with storage stability because they would have a higher moisture content. Poor cooking quality and high cyanogenic potential cassava cultivars, according to Aryee et al. (2006), might be used to make starch, glucose, glue, gasoline, alcohol, and other industrial materials but not major cassava products like gari.

Important quality traits in cassava food products and implications on breeding.

The production process, varieties used, and climatic conditions, among other factors, influence the quality characteristics of various cassava products. Products will be used to discuss breeding for identified quality traits. These products include boiled and fried roots, dried chips, cassava starch, cassava flour, fufu, lafun, gari, and Attieke (Bechoff et al. 2018).

*Raw, boiled, and fried cassava roots:* The following quality characteristics are typically necessary for fresh root consumption: color, low cyanogenic potential, intermediate dry matter content (depending on the location), and, most importantly, good cooking quality. Softness is an important consideration when evaluating the sensory qualities of cooked cassava roots. Varieties that do not cook well can continue to be hard after a long cooking time, which affects how well the product is received. Favaro et al. (2008) and Hongbete et al. (2011) emphasized that consumers consistently identified friability or mealiness as the most critical component of cooked cassava's quality. Crispness and friability were demonstrated to be important frying cassava quality parameters by Grizotto and De Menezes (2002). According to Vitrac et al. (2001), the amount of oil used in frying affects the color and crispiness of the fried cassava root.

*Dried cassava chips:* In Asia, cassava is chopped and dried for use in industrial applications and animal feed, and in Africa, dried chips and pellets for export are becoming more and more common. In Nigeria, drying cassava roots is another practical method of preserving the root before making fermented flour (lafun) or unfermented flour (high-quality cassava flour-HQCF). The shape and consistency of the chips or pellets and moisture content are crucial factors in determining whether or not cassava chips are acceptable (Falade and Akingbala 2010).

*High-quality cassava flour:* According to Shittu et al. (2007), different HQCF from cassava mosaic virus (CMV)-resistant cultivars have very variable physicochemical characteristics (starch content, viscosity, etc.), which could affect how the flour is used. Therefore, the HQCF's functional property diversity creates prospects for its utilization in various industrial, food, and nonfood applications. The main requirement for HQCF acceptance is that the finished product should be sweet rather than bitter. Because of the texture, varieties with high dry matter content are typically used to produce HQCF (Bechoff et al. 2018).

*Lafun:* This fibrous cassava powder is reconstituted into a dough that resembles fufu flour in Nigeria by adding hot water. Lafun is produced using a different process than fufu. Freshly peeled cassava roots are sliced into bits and soaked for 3–4 days, or until the roots become mushy, in the traditional lafun preparation. Next, the roots are dried in the sun for a few days

before being ground into flour and then reconstituted into a paste with the addition of hot water. Lafun, unlike Fufu, has fibers that give it a coarser texture (Cassava Biz 2005). Lafun meets the same standards for quality as *Fufu*. A quick gelatinization while cooking was also valued. (Bechoff et al. 2018).

*Fufu*: In order to get a uniform dough consistency, the fermented roots undergo a process of filtration and cooking. In some areas of Nigeria, the moist fufu paste is dehydrated into flour to extend its shelf life compared to the fresh fufu. According to IITA (2005), fufu has the second position in terms of significance in Nigeria, following gari. Falade and Akingbala (2010) state that high-quality fufu exhibits a consistent hue and possesses a smooth, mildly adhesive, and elastic texture. Opare-Obisaw et al. (2004) claimed that the ideal taste of fufu was lacking in flavor, whereas other investigations (Oyewole and Ogundele 2004; Tomlins et al. 2007; Falade and Akingbala 2010) showed that consumers appreciated a specific flavor and sourness in fufu. Nevertheless, some fufu drinkers find the intense smell that arises during fermentation unpleasant. Consequently, odorless fufu was developed to cater to the preferences of these consumers (Omodamiro et al. 2012). When 300 consumers in Nigerian metropolitan centers were tested for fufu acceptance, men (artisans and professionals) were likelier to purchase fufu in wet form, but women (younger teachers and students) were more interested in purchasing fufu as flour. (Teeken et al. 2023). This difference, however, may be due to lifestyle differences because this was confounded with gender. It is essential to include the preferences of various customer segments while examining fufu preferences, if feasible. Awoyale et al. (2022b) reported a strong and positive relationship between the hardness of the cooked fufu dough, as measured by sensory texture profile analysis (STPA), and the bulk density of the fufu flour.

*Gari*: Gari is a semolina-like cassava product with a slightly sour taste made by peeling grating roots followed by fermentation and/or pressing, roasting, and drying. Gari is widely consumed in West Africa (Awoyale et al. 2021). Gari is processed in a variety of ways and may have varying levels of fermentation and granular size. In Benin, there are numerous qualities and types of gari; some are made from sweet cassava varieties and are not fermented. (Ndjouenkeu et al 2021). In Nigeria, gari is the main staple of

cassava and accounts for over a third of the cassava produced. Gari can equally be eaten as it is sprinkled on other food, diluted into water/milk with sugar, or reconstituted with boiling water into a thick paste (called eba in Nigeria and piron in Benin). Gari quality is judged by its swelling capacity, color, particle size, moisture content, and a slightly sour taste (Blanshard et al. 1994; Achinewhu et al. 1998; Oduro et al. 2000; Irtwange and Achimba 2009; Ray and Sivakumar 2009; Owuamanam et al. 2010).

*Attieke*: *Attieke* is a semolina-like product made from cassava. The initial preparation steps are similar to gari (peeling, rasping, fermentation, pressing, and sieving), but the latter involves steaming instead of roasting. In order to preserve it for a more extended time, the food can be dehydrated either by exposing it to the sun or by utilizing artificial drying methods. It can then be rehydrated by heating it again when needed. According to Djeni et al. (2011), *Attieke* has a tangy flavor and resembles *couscous* in terms of its visual look. It is trendy in Ivory Coast and consumed in many countries in West Africa. Djeni et al. (2011) reported that quality samples were homogenous (granules of equal sizes), did not have an extraneous matter, were not too sour, had a pleasant odor, and were sweet.

Nimaga et al. (2012) showed that the fermenting conditions (type of starter, the quantity of starter, and fermentation time) significantly influenced the sensory characteristics of the *attieke* and, therefore, its acceptance. More research will be needed to understand the effect of cassava variety on the quality and sensory characteristics of the *attieke*. The leading quality and acceptance criteria differ for different cassava products. The products are found in different forms: dry (gari; lafun, fufu) or wet (fufu, agbelima, chikwangue, *attieke*); paste (fufu, agbelima, gari) or granulous (gari; *attieke*) and flour like (HQCF, starch, fufu and lafun). This may explain why the criteria for acceptance vary. Overall, independently of the product, the two principal quality criteria are lack of extraneous matter and homogeneity (i.e. color, texture, taste). The texture is a fundamental quality criterion for accepting cassava products. Paste or dough is most liked when smooth (or soft), elastic, and sticky. For gari, an important criterion is the ability to swell when made into eba or piron (by adding boiling water). Swelling power is also important for *attieke*. Color criteria (e.g. cream, white or yellow) vary

according to the nature of the product. A gari made with palm oil would have an acceptable yellow color, while a gari made with local roots would be white or cream. To be acceptable to the end-users, flavour and smell should be typical of the product but not too firm because these products are used as staples to accompany food that will give the dish the flavor (vegetable, sauce, meat, fish). In some products and for some consumers, a slight acid taste is appreciated (e.g. gari, attieke). A taste or smell close to neutral is preferred in other products (e.g. fufu) and for other consumers.

Although mechanized processing can reduce labor input, the characteristics of the cassava varieties, such as the ease of peeling and water holding capacity of the variety, may significantly affect the time and labor inputs into the processing (Nweke et al. 1999). In addition, resistance to postharvest physiological deterioration (PPD) and ease of peeling may influence processing waste or product yield. Mechanized harvesting and processing are constrained by cassava roots' irregular shape and size and are influenced by variety, growing environment, and age. These factors may significantly constrain the efficient mechanization of peeling and grating operations. Roots with peels that can be rolled or rubbed off will have fewer wastes and require less labor/time of processing than peels that fix tightly to the flesh and would have to be slashed off. Postharvest processing experts have observed that the cost of drying cassava to make some types of products (such as flour or chips) could be reduced if genotypes with less moisture content are made available (Nweke et al. 1999). The higher the moisture content of cassava root, the lower the product yield, the higher the drying costs, and the lower the quality of processed products. Therefore, the most preferred traits relate to reduced processing time and costs, improved safety, quality, and marketability of the final products, and consequently increased farmers' and processors' profitability and income. Therefore, targeted breeding can contribute to reducing processing costs that arise from high labor needs, long processing times, and high energy inputs (Nweke et al. 1999).

Kamau et al. (2011) showed that the farmer's local variety was rated higher than two improved varieties for their root quality, such as appearance, taste, texture, and fiber qualities, suggesting that the primary producers of cassava (farmers), do consider not only the biological parameters for cassava suitability but

others that the scientist may over-look during experimentation (Kamau et al. 2011). Also, the quality preferences of consumers of the primary processed cassava products and the industrial users (such as adhesive, baked items, ethanol, sweetener, and textile makers) are often not the same. Hence, from the early breeding stages of the breeding cycle, the priority should be on screening a large population of cassava clones combined with developing new varieties for the specific preferences of all the categories of end users.

During in-ground storage, the roots of some cassava varieties may start to rot if left in the ground longer than a certain period of physiological stability. Such periods vary from variety to variety and can occur within 2–4 years (Makambila, 1981). On the other hand, some varieties become lignified or fibrous, and the starch content is reduced. Breeding to introduce genes that prevent the lignification of roots in underground storage will reduce the loss of quality of cassava stored underground. Nevertheless, the storage method has an additional problem of soil availability and utilization.

Tools available for measurements of the key traits and challenges in breeding complex traits

Many cassava varieties have been developed and released through conventional breeding (Malik et al. 2020). Breeding cassava is a challenging task due to the heterozygous genetic makeup of the crop (Ceballos et al. 2004). However, new tools and technologies can potentially improve the efficiency of conventional breeding, especially when several traits are being selected simultaneously (Mbanjo et al. 2021). Several approaches have been used for phenotyping breeding lines and germplasm collections for nutrition (carotenoids, cyanogenic potential), yield and yield components (dry matter content), quality (starch physiochemical and functional properties, texture, and pasting properties), biotic stresses (disease resistance), and root system architecture. The following section details the current phenotyping strategies used in cassava. Some of the tools for measuring and developing some of the cassava quality traits are discussed below:

1. *Carotenoids*: Breeding cassava roots with higher levels of  $\beta$ -carotene, a pro-vitamin A carotenoid,

is a high priority in some breeding programs. This is possible because a positive correlation has been established between the color of the fresh cassava root and the total carotenoid content (Iglesias et al. 1997; Afonso et al. 2017). However, the challenge in this process has been to efficiently differentiate within each color group, as using the human eye is difficult. To overcome this constraint, quantification of total carotenoid content by ultra-violet visible spectrophotometry, as well as identification and quantification of  $\beta$ -carotene and its isomers by high-performance liquid chromatography (HPLC), have been employed (Carvalho et al. 2012; Belalcazar et al. 2016). These approaches are accurate but have many drawbacks, including cost, time needed for analysis, labor-intensive methods, and requirements for laboratory infrastructure and trained technical staff, which are not always available to breeding programs in Africa (Udoh et al. 2017). Alternative portable devices, such as I-Check™ carotene, have been proven helpful for rapid field evaluation and could be valuable in remote areas with no laboratory facilities or electricity (Esuma et al. 2016; Jaramillo et al. 2018). Color instruments designed to quantify the Commission International de l'Éclairage (CIE) color parameters have also been successfully used to efficiently evaluate carotenoid content in cassava root samples (Afonso et al. 2017). Near-infrared spectroscopy (NIRS) is another promising approach explored for carotenoid quantification with demonstrated high prediction accuracy (Sánchez et al. 2014; Ikeogu et al. 2019).

2. **Cyanogenic Potential:** One of the significant setbacks in the consumption of cassava value-added products is the presence of cyanogenic glucosides that release hydrogen cyanide during hydrolysis. Cyanide is toxic when accumulated above 50 mg/kg HCN in the human system. Proper processing of cassava roots reduces their cyanide level to a level the human body can accommodate; thus, the levels of cyanogenic potential must be measured in cassava products. Several approaches have been used to quantify cyanide potential, including the titration method (Moriassi et al. 2017; Iliya and Madumelu 2019), the alkaline picrate method (Fukushima et al. 2016; Moriassi et al. 2017), and the metal-based chemosensors (Tivana et al. 2014). These approaches involved multi-step reactions and necessitated trained personnel. Although easy to use, the picrate method is prolonged (minimum 12 h), and the chemicals used are hazardous. Recently, it was shown that NIRS could efficiently be used to distinguish roots with high or low cyanogenic potential (Sánchez et al. 2014).
3. **Dry Matter Content:** The proportion of fresh root used for value-added products is the dry matter content (DMC). The DMC is commonly measured using either specific gravity through suspension of a root sample in water and air or the oven-drying method, the most widely used method. This is where a representative root sample is weighted wet and then oven-dried to constant weight (Fukuda et al. 2010; Teye et al. 2011). However, the oven-drying method is tedious when working with many samples, and it is also difficult to implement where the source of electricity is unreliable (Teye et al. 2011). Both oven-drying and specific gravity could be substituted by NIRS, which has been shown to predict DMC with high accuracy (Belalcazar et al. 2016).
4. **Cassava starch physiochemical and functional properties:** Physiochemical properties are those properties that have a chemical basis but are determined physically. Thus, the physiochemical properties determine root quality attributes necessary for processing and consumption among cassava varieties. Amylose and amylopectin are the significant starch constituents that affect the physiochemical properties of cassava products, such as retrogradation, gelling, pasting, crystallinity, gelatinization temperature, viscosity, and texture. The amylose/amylopectin ratio also affects cassava roots' cooking, eating, and processing quality (Ayetigbo et al. 2018). The amylose content in cassava has been estimated using iodine colorimetry (Sandoval-Aldana and Fernandez 2013; Boonpo and Kungwankunakorn 2017) or Megazyme amylose/amylopectin assay kit (Chisenga et al. 2019). Iodine colorimetry is prone to inter-laboratory variability due to the complexity of the procedure and relies on the development of a suitable curve of known amylose-to-amylopectin ratios. The functional properties are those properties that affect the end use of both the raw material and the final product.

Examples of the functional properties are swelling power, solubility index, dispersibility, least gelation concentration, bulk density, and water absorption capacity. Swelling power and solubility patterns of cassava flour have been determined using the Leach (1959) and Kainuma et al. (1967) methods, respectively (Chisenga et al. 2019; Ma'Aruf and Abdul, 2020). Starch gelatinization properties (onset, peak, gelatinization temperature, and enthalpy) and retrogradation have been determined using differential scanning calorimetry (DSC). DSC can be run at a rate of four samples per hour (Thirathumthavorn and Trisuth 2008; Tappiban et al. 2020). Crystallinity measurement requires an X-ray diffractometer, a piece of complex and expensive equipment (Chatpapamon et al. 2019). In sweet potatoes, it was shown that NIRS could predict most physiochemical and thermal properties of starch with acceptable precision (Lu et al. 2006). NIRS was sufficiently accurate for determining total starch and amylose in barley in the study of Ping et al. (2013). Meanwhile, using NIRS spectroscopy, Cozzolino et al. (2013) demonstrated that swelling properties and water solubility could be determined in whole-grain barley. NIRS technology could potentially be used to predict the functional and physiochemical properties of cassava or cassava-based products.

5. *Texture and Pasting Properties:* Texture is a critical factor for consumer acceptance of cassava doughy products. Sensory analysis has been used to characterize cassava and cassava-based product texture properties. The sensory descriptors assessed included texture, appearance, odor, taste, and masticability (Akely et al. 2016; Adinsi et al. 2019). The cost associated with training and maintaining a descriptive panel, combined with the low throughput of sensory evaluations, has prompted the development of less costly and less time-consuming approaches. Instrumental methods using a texture analyzer that mimics mastication have been used to evaluate and/or predict the texture of raw, cooked, and processed cassava products. The parameters measured include hardness, springiness, adhesiveness, gel strength, mouldability, elasticity, smoothness, appearance, thickness, and general acceptability (Rodríguez-Sandoval et al. 2008; Maievas et al. 2012; Rosa-

lessoto et al. 2016; An et al. 2019; Ma'Aruf and Abdul, 2020). The pasting properties of cassava products are key determinants of quality. Rapid Visco Analyzer (RVA) has been used to evaluate the pasting properties of cassava accessions, and the parameters estimated include peak viscosity, setback viscosity, final viscosity, pasting temperature, and time to reach peak viscosity. Using RVA, less than five samples can be processed in 1 h (Rosalessoto et al. 2016; Chatpapamon et al. 2019). Although not yet reported for cassava, NIRS has been shown to adequately predict the texture and pasting properties of rice (Meullenet et al. 2002; Chueamchaitrakun et al. 2011) and sweet potato (Lu et al. 2006). Therefore, the ability of NIRS to predict the texture and pasting properties of cassava value-added products should be explored.

#### Next Steps/Recommendation

The following steps may be required to contribute to the understanding of breeding end-user quality traits of cassava products:

1. Can more be learned from past successes in introducing and releasing improved cassava varieties? New knowledge about the successes and failures of farmers in adopting new varieties may provide new insights that can assist breeding programs and understand the impact, which may be related to socioeconomic, gender, and market issues. How would this be measured?
2. Scant information exists regarding the magnitude of the African market for primary cassava products. The writers devised an estimation solely relying on their discoveries. Comprehending the market segment that cassava products currently occupy and predicting future trends can aid in identifying the specific areas where investment in cassava breeding will be directed. For instance, in Africa, there is an increasing inclination towards transforming cassava from a primary food source into starch, syrups, industrial adhesives, beer manufacture, and various other uses. Moreover, freshly discovered innovative varieties have the potential to mitigate vitamin A deficiency, and

their effectiveness will be enhanced if there is a clear understanding of market demand.

3. Plant breeding projects/initiatives must adapt to increasing technology in farming, storage, processing (such as grating, pressing, drying, etc.), and marketing. This will optimize production efficiency and hence reduce post-harvest losses and waste.
4. Gaining a more comprehensive comprehension of rival or competing products in the cassava market region can also assist plant breeders in determining the specific characteristics to prioritize. As urbanization increases, the demand for cassava will intensify, leading to competition with other staple commodities.
5. Socioeconomic and gender analyses may be important to ensure that uptake meets the requirements of local communities and that uptake is equitable. Overall, little work has been reported on the gender differences in the consumer acceptance rating of cassava products. Market interventions must take into account the complex and challenging subject of gendered power relations, which ultimately constrain women's benefits in markets more generally (Forsythe et al. 2015). A thorough gender analysis is required concerning end-user preferences to question assumptions of de facto inclusiveness prevalent in market development narratives.
6. Intellectual property rights issues may be critical so that communities in Africa can benefit from the local knowledge they have.

### Breeding and end-user quality traits of Yam products

Identified quality traits for different products

Yam (*Dioscorea* spp.) is a staple tuber crop that forms the basis of nutrition for some indigenous people in Africa, Asia, South America, the Caribbean, and the South Pacific (Obidiegwu and Akpabio 2017). About 97% of global yam production comes from Africa. Therefore, yam is a significant cash crop in Africa (FAOSTAT 2021). In yam processing, the raw tubers are peeled, washed, sliced and are either fried, roasted, boiled, or steamed to produce boiled yam or pounded to produce pounded yam (Loko et al.

2015), but the most popular forms in which yam is consumed are boiled and pounded yam (Ojokoh and Adeleke 2019); boiled yam being an important breakfast menu in various households (Bakare et al. 2019).

Some desired agronomic traits of yam while growing are giant vines, dense canopy, and pest resistance (Otegbayo et al. 2021). Early maturity period and ability to withstand biotic and abiotic stresses, including nematode resistance, are also preferences that have been reported for raw yam tubers (Aboagye et al. 2015; Mignouna et al. 2020). After harvesting, consumers prefer yams with big heavy tubers, regular tuber form, brown skin color, smooth skin, easy to peel, and stability of color during processing (Otoo and Asiedu 2009; Barlagne et al. 2017; Otegbayo et al. 2021). The color of yam flesh is considered one of the essential attributes of its acceptability and attractiveness. Acceptable yam cultivars for boiling are often characterized by a white or yellow appearance (Fakorede et al. 2020). The color variation of yam tuber flesh results from the enzymatic oxidation of these phenolic compounds (Baah et al. 2009). The color of fresh yam slices and boiled yam must remain white or cream as it greatly influences its acceptability (Tortoe et al. 2014; Otegbayo et al. 2021).

The food quality of yam differs due to its genetic diversity, and this is a major criterion for the acceptability of new cultivars by producers, processors, and consumers (Jeannette et al. 2020). The acceptability of boiled yam, which is an important food product, depends on the quality traits desired by users (Loko et al. 2015). Water absorbed during cooking, texture, color, crumbly, and taste are also important quality traits identified for boiled yam (Kouadio et al. 2011; Bakare et al. 2019; Honfozo et al. 2021). Effah-Manu et al. 2022 reported that yam consumers in Ghana attributed boiled yam quality to whether the fresh yam was grown with fertilizer or not, having a preference for the yam grown without fertilizer because it is judged as sweeter than yam grown with fertilizer.

The other popular form of eating yam is in the form of pounded yam. Boiled yam is processed with either a traditional mortar and pestle or a pounding machine to form thick dough known as pounded yam, which can be eaten with soups (Jahan et al. 2020). Appearance and textural attributes such as stretchability, moldability, stickiness, and smoothness are the desired quality traits by processors and consumers of pounded yam. Therefore, poor pounded yam textural

attributes can negatively impact the acceptability of any yam cultivar by consumers (Akişsoe et al. 2006; Otegbayo et al. 2018; Otegbayo et al. 2021).

Consumers' preference for yams meant for boiling or pounding depends majorly on food quality (Effah-Manu et al. 2022). These quality traits are evaluated by trained panelists consumers using sensory analysis, a method employed in varietal improvement programs to evaluate textural traits of boiled and pounded to aid better consumer adoption (Jahan et al. 2020).

#### Breeding for the identified quality traits

The potential of yam for food security and poverty reduction is imperative in yam breeding. Yam breeding employs sexual and asexual reproductive mechanisms to produce progenies with desirable traits such as yield stability, superior resistance to disease and pests, and higher tuber quality. The progenies that meet the breeding program's objectives are then selected and advanced vegetatively for several generations and across locations before releasing as new varieties (Darkwa et al. 2020a; Norman et al. 2020). Breeding for consumer preferences is important in breeding programs because it improves the adoption and utilization of new yam cultivars. Also, breeding programs will be improved if consumers' preferences for yam and its products are factored into the genetic variation processes (Sanginga & Mbabu 2015; Effah-Manu et al. 2022).

Breeding programs had focused on the development of cultivars with quality traits such as high and stable tuber yield, tubers with high dry matter and regular shapes, resistance to diseases and pests (anthracnose and nematodes), and shrub-like or dwarf plant (Mignouna et al. 2007). However, in recent times, the ultimate goal of yam breeding programs is the development of varieties with preferred traits required for production, processing, and consumption (Asfaw 2016). The breeding of yam varieties primarily focuses on improving tuber quality attributes that align with sensory preferences, such as flavor, color, and texture. Additionally, the breeding aims to enhance yield and create resistance against pests and diseases. These factors collectively determine the acceptability of newly generated yam varieties (Koeper et al. 2016). Bredeson et al. (2022) discovered quantitative trait loci using genomic methods

associated with resistance to anthracnose and other tuber quality parameters. As a result of the immense efforts of yam breeders to meet the desired quality preferences of consumers, the International Institute of Tropical Agriculture (IITA) and its national partner breeding programs in sub-Saharan Africa (SSA) countries have identified and/or listed eighty-nine yam varieties for commercial production in Africa. In comparison, five farmer varieties with preferred sensory and agronomic features have been recognized and registered for commercial distribution in Nigeria (Darkwa et al. 2020b). Also, the collaboration of IITA with the National Root Crop Research Institute, Umudike, Nigeria, and the Crops Research Institute, Ghana, resulted in the release of sixteen varieties that have multiple pests and disease resistance, wide adaptability and good organoleptic properties (Lopez-Montes et al. 2012).

#### Tools available for measurements of the traits

Physico-chemical properties such as dry matter, starch, amylose and textural attributes of yam tubers are essential traits that signify the tuber food product quality and influences end-users acceptance of the product; however, these properties differ based on cultivar differences (Lebot and Malapa 2013). The measurement of these quality traits and rapid measurement is very important because they help the breeders screen out low-quality cultivars in the breeding process. The rejection of low-quality cultivars and acceptance of suitable cultivars will hasten cultivar acceptance when it is eventually released to the general public. Near-infrared spectrophotometric (NIRS) calibration model is a rapid and efficient tool that has been developed for the rapid determination of physico-chemical properties (starch, moisture, ash, and protein and crude fiber) of yam tubers and flour (Lebot and Malapa 2013; Alamu et al. 2019). However, amylose, minerals, and cellulose are difficult to predict (Lebot and Malapa 2013). Rapid measurement methods for other cooking quality parameters such as cooking time, water absorption and texture of yam food products such as boiled and pounded yam are yet to be established. Instrumental texture analysis is a medium throughput method for measurement of the texture of these yam products. However, the methods are destructive of the samples, while recent advances such as hyperspectral imaging techniques

are non-destructive and give rapid quality characterization of the food product (Adesokan et al. 2023).

#### Challenges in yam production and breeding of complex traits

Generally, the production of yam in West Africa has been faced with several challenges, such as the high cost of planting material, high labor costs, poor soil fertility, low yield potential of local varieties, pests, and diseases (on the field and in storage), and shortage of quality yam seed of popular landraces and released varieties (Lopez-Montes et al. 2012). Even though breeding efforts over the past five decades have resulted in the commercial release of improved cultivars, the local cultivars are still dominant in the yam consumption system (Alene et al. 2015). The low market dominance of improved varieties could be due to several factors, such as limited dissemination efforts, limited exposure of the farmers and consumers to the released varieties, or ultimately, lack of customers' preferred quality traits in the improved varieties (Darkwa et al. 2020b). The breeding and distribution of improved varieties to farmers and consumers are also affected by the low multiplication ratio of the yam seed samples because this leads to low yields as seed yams infested by pests and diseases are usually not possible to replace due to short supply of quality seed tubers at affordable prices (Aighewi et al. 2015). However, minisets, microsets/micro-tubers, tissue culture, vine cuttings, aeroponics and bioreactor systems, and semi-autotrophic hydroponics (SAH) technology are methods that have been developed to address the challenge of low multiplication seed tubers because these relatively new methods improve the quality and quantity of yam seeds (Darkwa et al. 2020a).

#### Next steps/recommendation

The future stride of yam breeding programs should be the production of yam cultivars with high yield, resistance to diseases and pests, and good adaptability to adverse environmental conditions as it incorporates consumer-preferred quality traits to enhance the adoption of improved cultivars. *D. praehensilis* have been identified to have outstanding performance in tuber yield, dry matter content, tuber flesh oxidation, tuber size, number of tubers per plant, resistance

to the yam mosaic virus, and plant vigor (Adewumi et al. 2022). Therefore, breeding programs should explore these genotypes to improve white Guinea yam for those traits. Additionally, breeding for excellent texture qualities of boiled and pounded yams should be prioritized because consumers and processors will easily accept yam cultivars with these traits. Breeders must also apply gender-responsive strategies to generate varieties that suit the gender-diverse end-user wants and preferences.

#### Breeding and end-user quality traits of plantain/banana products

##### Identified quality traits for different products

Plantain (*Musa* spp.), also known as banana, is a perennial plant grown clonally worldwide, especially in tropical and subtropical regions (FAOSTAT 2021). Plantain production in sub-Saharan Africa (SSA) occurs majorly in small plots and private gardens, but the crop serves as a source of food and income for millions of stakeholder farmers (Marimo et al. 2019; Lorenzen et al. 2008; Tumuhimbise et al. 2020). Banana fruit can be utilized in multiple ways, from being used as a dessert to being consumed as food after boiling or steaming. The crop is economical as the plant's entire body is useful (Nowakunda et al. 2019), but pathogens and pests risk plantains' economic importance. However, plantain hybrids that are resistant to pests and pathogens have been successfully developed by breeders (Tenkouano et al. 2019). The adoption rates of improved cultivars by farmers are low because they are yet inferior to native cultivars in terms of organoleptic properties (taste, aroma, mouth feel, and color). However, the improved banana cultivars have better economic, agronomic and pest resistance features than the native varieties. This has also led to poor marketability of improved varieties (Kagesi et al. 2012; Akankwasa 2013; Marimo et al. 2020).

Consumers rate plantain genotypes based on quality characteristics, including high yield, disease resistance, and good sensory qualities. Therefore, breeding for these quality characteristics for cultivar selection is crucial as they enhance the acceptance of new cultivars that satisfy both the farmers and the end users (Marimo et al. 2019). In order to satisfy the

requirements and preferences of farmers, new banana cultivars must include robust sensory attributes alongside high productivity and resistance to pests and diseases. There is a lack of comprehensive documentation regarding the choice of plantain cultivars for food use.

The qualities of plantain cultivars which may be grouped as either physical (color, length, size, shape, and texture) or chemical (DM, total soluble solids, pH, and titratable acidity), can be used to distinguish between *Musa* varieties, however, the highest values for these parameters are shown mainly by plantain (Tchango Tchango et al. 1999; Gibert et al. 2009). The important quality traits of fresh plantains are finger size, peel color, ease of peeling, pulp color, tip color, bunch size, maturity, number of fingers, fruit angularity, and good taste;. In contrast, for plantain products, colour, texture (softness, smoothness, firmness, stickiness/gumminess, crunchiness), taste and aroma are germane (Amah et al. 2021). In plantain quality evaluation, it should also be noted that how plantain samples are prepared during cooking can also affect consumers' perception of the quality traits (Gibert et al. 2009). Other factors such as gender and geographic differences that also influence the selection criteria of plantain by end-users in accepting a variety and rejecting the other must be fully understood by the breeders to help them make hybrids that will be more widely adopted and have a more significant impact. Some postharvest quality traits that should be considered in plantain breeding are fruit length and girth, dry matter content, pulp color, pH, and hardness. Fruit maturity, dark green peel color, and large fruit size are pertinent traits that drive acceptability (Ngoh Newilah et al. 2021).

#### Breeding for the identified quality traits

It is critical to choose potential cultivars that will please customers by comprehending how new crop genotypes perform for relevant qualities. Tumuhimbise et al. 2020 evaluated new banana genotypes' bunch mass (BMS) and BMS-related features, resistance to black Sigatoka, and sensory qualities as relevant traits for performance selection. It should be highlighted that choosing banana genotypes that satisfy end-user objectives involves more considerations than only high BMS/yield and disease resistance. The selection of banana cultivars

is primarily influenced by a combination of high BMS/yield, agreeable sensory qualities, and disease resistance. In order to optimize marketing opportunities, it is crucial to examine any possible differences in trait preferences between farmers and other participants in the value chain (Tumuhimbise et al. 2020). When compared to how important they are economical, introduced banana cultivar adoption rates are frequently lower than those of other staple crops (ISPC, SPIA 2014; Ortiz 2011; Walker and Alwang 2015), and this adoption rate of new banana cultivars in sub-Saharan Africa (SSA) have been reported in few studies (Faturoti et al. 2006, 2009; Kagezi et al. 2012; Nkuba 2007). Farmers cite poor marketability relative to regional cultivars, worse taste, and dangers connected with cultivar development as factors contributing to the low acceptance (Kagezi et al. 2012). Local cultivars are preferred by farmers because of their superior consumer qualities (excellent taste, soft food texture, nice aroma, and good/yellow color), even though modern cultivars have greater agronomic features and high resistance to biotic and abiotic challenges (Akankwasa et al. 2013; Barekye et al. 2013; Nwachukwu and Egwu 2008). As a result, new plantain cultivars must have good sensory attributes (alongside high yield and resistance to pests and diseases) to compete with landrace cultivars based on adoption (Tumuhimbise et al. 2020; Sanya et al. 2020; Amah et al. 2021). In a study to evaluate the legal, political, and market context that influences the adoption of plantain hybrids, consumer preferences, agricultural policy, market conditions, and the personal engagement of key actors in the research and private sector play a major role (Garmin et al. 2013). Although the adoption rate of plantain hybrids might be slightly improved by processing them into plantain chips, breeding programs such as Fundacion Hondureña de Investigación Agricola (FHIA) have focused on the development of cultivars that are resistant to pests and diseases while maintaining all the quality traits that drive consumer acceptability (Dita et al. 2013). Also, breeders at the International Institute of Tropical Agriculture (IITA) are working on developing hybrid cultivars that generate increased yield while retaining all other quality attributes. They have also incorporated testing of hybrid cultivars, which have been on farmers' fields to enhance the adoption of the cultivars better (Friedmann et al. 2018).

### Tools available for measurements of the traits

As much as agronomic parameters are important traits considered by plantain producers, the products' sensory quality influences consumers' plantain acceptability (Assemmand et al. 2012). The sensory evaluation of boiled plantain by trained panelists has been employed and reported (Vepowo et al. 2023), as well as the use of instrumental measurement. Instrumental texture analysis is rapid relative to sensory evaluation; hence, it can be used to screen new hybrids in breeding rapidly. In a study conducted on boiled plantain, the regression of the sensory and instrumental texture parameters carried out at 50 °C gave a better prediction model as against analyses done at 60 °C. Instrumental texture parameters can predict firmness, chewiness, mealiness, and moistness (Kouassi et al. 2021).

Evaluating the sensory quality of food products based on a physical is more advantageous regarding speed, cost, and objectiveness than using panelists (Ferris et al. 1999). These textural parameters can be difficult to breed for because breeders need measurable quantitative and qualitative data. As a result, these processor-dependent factors must be translated into measurable physicochemical, thermal, and functional properties for breeders (Marimo et al. 2019). Dry matter and soluble solids content of raw plantain have been reported to be indicators of sensory parameters as high dry matter content translates to better eating quality while soluble solids affect the sweetness of the product (Ferris et al. 1996; Colaric et al. 2005). Soluble solids of plantain cultivars, dry matter, soluble solid contents, and titratable acidity are physicochemical parameters that predict boiled plantain's firmness, chewiness, mealiness, moistness, and sweetness very well with minimal error. The soluble solid content of a Brix value of 2.5° was needed to detect differences in moistness, while a Brix value of 4° resulted in a 2-point increase in sweetness, but to detect the difference in firmness, chewiness, and mealiness, a Brix value of more than 4° is needed (Kouassi et al. 2021).

### Challenges in breeding complex traits

The rate at which improved plantain/banana cultivars are adopted profitably by farmers and end users should be the yardstick for evaluating the achievement

of banana breeding programs (Ortiz 2011). One of the challenges of breeding *Musa* cultivars is the multiplicity of species, which often results in genomic complexities. Also, integrating gender differences in trait preferences could be challenging (Friedmann et al. 2018). Synthesizing and interpreting farmers' tacit descriptions of quality traits can be daunting because the described traits cannot be set as breeding goals; hence, there is a need to cross the hurdle of defining these traits into quantifiable and measurable traits for practical use in breeding programs (Marimo et al. 2019).

### Next steps/recommendation

Plantain breeding programs must incorporate the traits end users consider to accept plantain cultivars, as these will further enhance the acceptance and adoption of the improved cultivars. One of the ways this can be achieved is to use the landrace cultivars that are generally accepted and should be used as checks for the new hybrids. Also, experts such as food scientists should actively translate the complex key quality traits identified by farmers and other end users into quantifiable traits that breeders can easily measure. Furthermore, more standardized protocols must be developed by food scientists for varietal selection. This will ensure that the cultivars to be evaluated are subjected to uniform processing methods because a suitable cultivar that is not processed correctly can be mistaken for a poor cultivar and vice versa. The effects of climate change can be very harsh on *Musa* spp because they are easily affected by adverse weather conditions. Therefore, more advanced genomic tools should be employed for breeding drought-tolerant plantain cultivars, which will be resilient against the effects of climate change.

### Conclusion

This review highlights the quality traits that inform the preferences and overall acceptance of improved RTB crops and their food products and the major challenges faced in integrating them into breeding programs. Aside from excellent agronomic traits that farmers and end users expect, good sensory properties and outstanding cooking qualities are essential to increase the acceptance rate of improved RTB

varieties. Specifically, color, short cooking time, aroma, taste and texture are the most important quality traits across all the RTBs, and consumers desire these. However, some of these traits are challenging for breeders to implement because they are complex traits to quantify using conventional approaches. Therefore, alternative methods must be developed for rapid and convenient phenotyping of these essential qualities for breeding programs to implement into their selection metrics. This results in development process improvement and resource optimization where non-promising candidates are screened out at early breeding stages.

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