















ORIGINAL ARTICLE

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On-farm evaluation of cassava clones using the triadic comparison of technology options approach

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Abstract

The triadic comparison of technology options (tricot) approach to participatory varietal selection has been demonstrated to scale out the on-farm testing of elite candidate crop varieties. In this study, we evaluated elite clones of cassava (*Manihot esculenta* Crantz) using the tricot approach. We sought to (1) synthesize on-farm trial data from two cycles evaluating different sets of elite cassava clones; (2) assess the agronomic performance of elite cassava clones considering sociodemographic and climatic factors; and (3) assess the performance of elite cassava clones for both agronomic and food quality traits. The study involved 10 districts in Uganda, two cycles/seasons of evaluation, 20 elite cassava clones, one check variety, and 294 men and 320 women farmers. Our results indicate that the agronomic performance of elite cassava clones was influenced more by geographic than sociodemographic factors. Our analysis identified the number of days with rainfall higher than 20 mm as the most influencing climatic factor over agronomic performance. Further, the study identified superior elite cassava clones UG110164, UGC14170, and UG120193 as promising candidate varieties for release, targeting food products. Overall, our study emphasizes the important contribution of end-users to crop improvement and provides insights into

Abbreviations: MAP, months after planting; NaCRRI, National Crops Resources Research Institute; PVS, participatory varietal selection; tricot, triadic comparison of technology options; ZARDI, Zonal Agricultural Research and Development Institute.

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use of tricot on-farm testing methodology to evaluate elite cassava clones during cassava variety development in Uganda, which can be used to support decision making for variety release.

1 | INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is a perennial shrub cultivated across tropical and subtropical areas in Africa, Asia, and Latin America, roughly between 30° N and 30° S (Nassar & Ortiz, 2007). It is a multipurpose crop, grown as a staple food for humans, animal feed, and industrial processing (El-Sharkawy, 2004). Although its leaves are sometimes consumed, cassava is mainly grown for its starchy roots (Sánchez et al., 2009). Globally, cassava is a main food source for ~800 million people (Howeler et al., 2013). In Uganda, cassava is the second most important crop after banana (*Musa* spp.) in terms of cultivated area, production and consumption, providing around 60% of basic food requirements of the human population (Bua et al., 2007).

To date, cassava improvement has mainly focused on protecting yield from diseases. This is evidenced by the annual genetic gains for resistance to cassava mosaic and brown streak diseases (Manze et al., 2021; Ozimati et al., 2022). These efforts have led to the introduction of improved varieties to curb challenges that affect the optimal production of the crop such as cassava mosaic and brown streak diseases (Kawuki et al., 2016; Mukiibi et al., 2019). More recently, cassava breeding in Uganda, aiming to integrate end-users' preferences, has considered end-user culinary related traits, which are important for improving adoption rates of improved varieties (Iragaba et al., 2021). Furthermore, the cassava breeding program in Uganda has implemented participatory varietal selection (PVS) (Witcombe et al., 1996) at the end of the breeding pipeline (Kawuki et al., 2011). In Uganda, the mother–baby trials design (Snapp, 2002) has been the most commonly used PVS approach to collect farmers' feedback and on-farm biological performance (Kawuki et al., 2011). The aim of PVS is to select of best performing clones in terms of farmers' preferences (Witcombe et al., 1996). The observations, perceptions, and ratings of candidate varieties gathered from participants during PVS are used to make decisions about variety release, seed multiplication, and promotion.

Uganda has 10 agroecological zones, which are classified based on distinct vegetation type, elevation, and climatic conditions (UBOS, 2018). According to the Uganda Bureau of Statistics, the agroecological zones are aligned to the zonal agricultural research and development institutes (ZARDIs) in Uganda (UBOS, 2018). Considering the importance of cassava in Uganda (Bua et al., 2007), there was need for a method that enables PVS evaluation of elite cassava clones in differ-

ent agroecological zones by end-users mindful of their active participation.

The triadic comparison of technology options (tricot) is an on-farm testing approach supported by citizen science that can be used to implement PVS (van Etten, Beza, et al., 2019). Tricot enables scaling out PVS trials, involving farmers in active roles while generating insights on performance of candidate varieties across different locations. The tricot approach has been used in more than 25 countries in the Global South to test different types of agricultural technologies including crop varieties (de Sousa et al., 2024; van Etten, de Sousa, et al., 2019), food products (Alamu et al., 2023; Moyo et al., 2021; Olaosebikan et al., 2023), and breeding product concepts (Rutsaert et al., 2022).

In tricot experiments, farmers voluntarily contribute as citizen scientists to evaluate agricultural products (varieties, food products, etc.) on-farm to generate data on crop variety performance with higher external validity (de Sousa et al., 2021; van Etten et al., 2020). The tricot approach facilitates this process by randomly allocating the varieties as incomplete blocks of three to make it easier to implement, manage, and evaluate by each farmer. For most traits, farmers are asked to evaluate the varieties in the form of “triadic rankings,” indicating which variety performed best and which performed worst for a given trait (e.g., germination, yield, disease resistance, and overall preference—de Sousa et al. [2024]). As these trials are farmer-managed and relatively simple in format, they can be scaled out for evaluation by a large number of farmers in diverse locations (van Etten, Beza, et al., 2019). As candidate varieties are evaluated by large numbers of farmers, they are tested for adaptability under diverse farming communities by both men and women with different sociodemographic characters (de Sousa et al., 2021; Steinke & van Etten, 2016).

In this way, elite cassava clones adapted across or to specific agroecological zones can be strategically selected and advanced. As the tricot approach also allows collecting data on plot location and sociodemographic characteristics of the participating farmers and their households, additional analyses can be done. The data can be disaggregated in different ways to evaluate if environmental farming conditions (such as climate or soil characteristics) or farmers' sociodemographic characteristics (such as gender or market orientation) influence elite cassava clones performance. Moreover, tricot provides a standardized data collection framework, which allows incrementally combining experiments. The synthesis of tricot trials data is possible through rank-aggregation, as

demonstrated by Brown et al. (2022). Combining data from different experiments is especially relevant when different elite genotypes are tested in different cycles, which is often the case in plant breeding. The cassava breeding program in Uganda adopted the tricot approach to evaluate elite cassava clones with end-users in different agroecological zones. The main objective of our study was to demonstrate the usefulness of the tricot approach for implementing PVS in cassava breeding in Uganda. Specifically, the study aimed to (1) synthesize data from two cycles of evaluating different sets of elite cassava clones, (2) assess the effect of sociodemographic and geographic factors on the agronomic performance of elite cassava clones, and (3) assess the performance of elite cassava clones for both agronomic and food quality traits.

2 | MATERIALS AND METHODS

2.1 | Location of the study

The study was conducted with 294 men and 320 women farmers in Uganda in two production cycles as follows: (1) from April 2019 to June 2020 and (2) from September 2021 to October 2022 (Table 1). The locations (Figure 1) were distributed across six agroecological zones in the vicinity of six ZARDIs in Uganda (Figure S1), namely, Abi, Buginyanya, Bulindi, Mukono, Ngetta, and Serere (Table 1). These locations represent the highest production and consumption areas of cassava in Uganda (UBOS, 2019). Within each agroecological zone, districts were selected based on high cassava production and consumption (Figure S1). In the first cycle, the trials were established in the following six districts: Arua, Dokolo, Kaberamaido, Luwero, Mityana, and Serere (Table 1). In the second cycle, the trials were scaled out to four districts and, consequently, on-farm trials were distributed in eight districts, namely, Arua, Buikwe, Busia, Dokolo, Kibaale, Luwero, Serere, and Tororo (Table 1).

2.2 | Experimental design and genetic material

The on-farm trials were implemented using the tricot approach, which we already introduced in the Section 1. Tricot implements principles of decentralized on-farm testing by randomly assigning technologies, elite cassava clones in our case, to each farm. Each tricot experiment follows the balanced incomplete block design in blocks of three (van Etten et al., 2020; van Etten, Beza, et al., 2019). This ensures A-optimality by connecting all the cassava clones to each other in the complete set (de Sousa et al., 2024). Accordingly, each tricot package was made of an incomplete block comprising three subplots of elite cassava clones labeled with

Core Ideas

- We applied the tricot (triadic comparison of technology options) approach to evaluate elite cassava clones on-farm, exploring how the linked data can be used to advance clones for breeding.
- We used a rank-aggregation approach to assess the on-farm performance of two different sets of elite cassava clones.
- We assessed the effect of sociodemographic and geographic factors on the on-farm agronomic performance of elite cassava clones.
- We assessed the performance of elite cassava clones for beneficial agronomic and food quality traits for consideration in advancement and varietal release.

letters A, B, and C. The elite cassava clone names were masked to anonymize their identity and avoid bias during evaluation. The identity of cassava clones was revealed to farmers at the end of the trial. The experiment was designed using the *ClimMob* platform (Quirós et al., 2024), accessible at <https://ClimMob.net>.

In the first cycle, a total of 11 elite cassava clones and one popularly grown variety (NAROCASS 1, check variety) were evaluated using the tricot approach (Table 2). In the second cycle, nine elite cassava clones and one check variety (NAROCASS 1) were evaluated (Table 2). The genetic material was sourced from the uniform yield trials of cycle 0 and cycle 1, respectively, of the Nextgen cassava breeding population at the National Crops Resources Research Institute (NaCRRI). Four of these clones (MM06/123, MM16/0707, MM16/1627, and MM2018/0054) were provided by the International Institute of Tropical Agriculture cassava breeding program. For an efficient use of resources and to take advantage of the availability of new candidate varieties from the crop improvement process, different genetic materials were evaluated in each cycle. We included a common check, NAROCASS 1, in the two cycles, which makes it possible to aggregate the data from the two cycles (Figure 2).

2.3 | Recruitment of local facilitators and farmers

Data were collected according to the tricot approach by the local facilitators from farmer-facing organizations (van Etten et al., 2020). As the first step, a scoping study was conducted to select extension agents to be the local facilitators of the tricot evaluation. The extension agents were supported by

TABLE 1 Location of cassava on-farm trikot trials, growing cycles, and disaggregation of participants by gender.

District	ZARDIs ^a	Number of participants							
		Growing cycle							
		2019–2020		2021–2022		2019–2020		2021–2022	
		Men	Women	Age (mean)	SD	Men	Women	Age (mean)	SD
Arua	Abi	27	13	36.3	10.3	26	21	34.3	9.01
Buikwe	Mukono					21	26	41.6	11.3
Busia	Buginyanya					21	27	40.4	10.8
Dokolo	Ngetta	21	19	40.2	10.4	25	23	39.9	10.2
Kaberaimaido	Serere	19	20	42.5	12.9				
Kibaale	Bulindi					19	25	43.8	9.7
Luwero	Mukono	15	25	42.6	10.6	19	26	45.4	13
Mityana	Mukono	25	14	43	15.3				
Serere	Serere	15	26	39.9	8.8	25	23	46.9	47.5
Tororo	Buginyanya					16	32	44.1	9.8
Total		122	117			172	203		

Abbreviations: SD, standard deviation; ZARDIs, Zonal Agricultural Research and Development Institutes.

^aAccording to UBOS (2018, 2019).

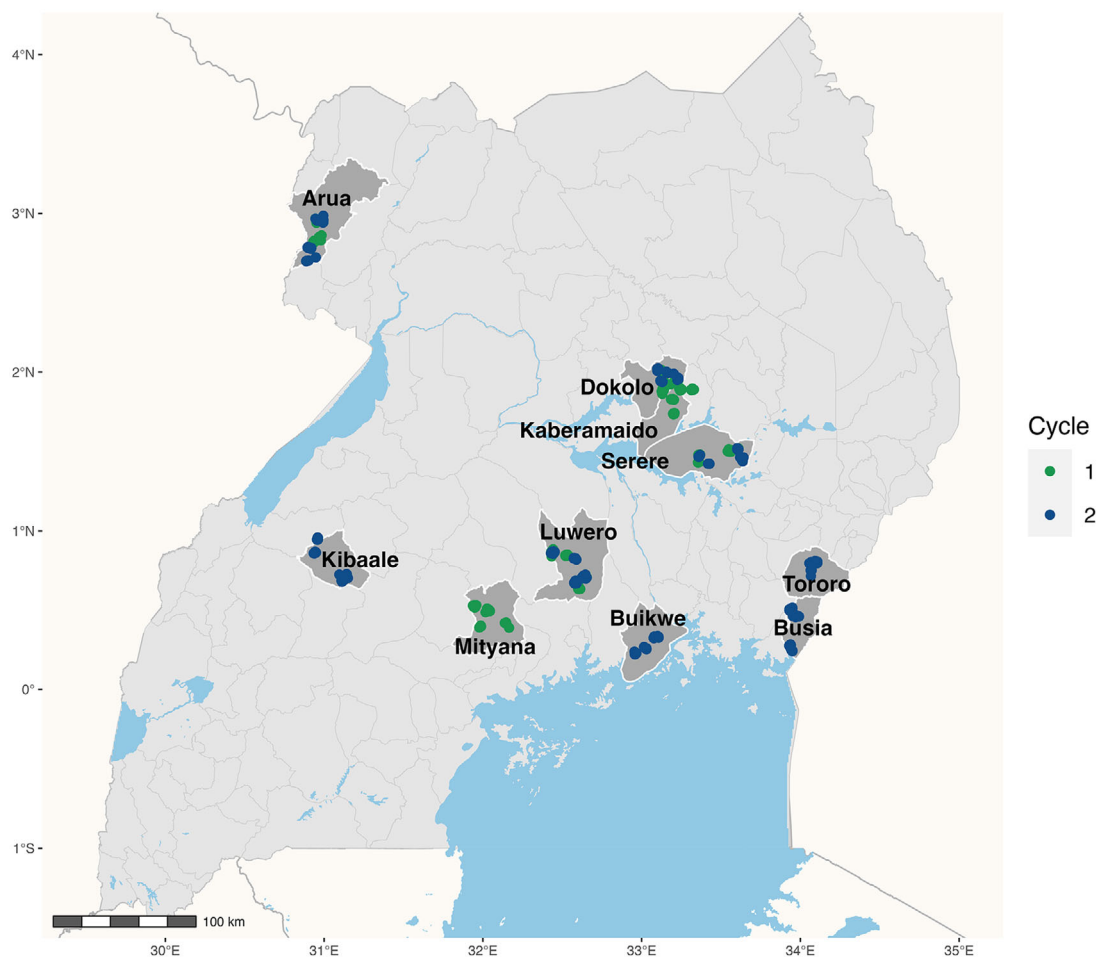


FIGURE 1 Location of cassava on-farm trikot trials across 10 districts in Uganda in two production cycles as follows: 1 = 2019–2020 and 2 = 2021–2022. Uganda administrative boundaries according to Ochola et al. (2021).

TABLE 2 Genetic material, their source, pedigree, and cycle of evaluation.

Elite cassava clone	Source	Pedigree ^a	Growing cycle
MM06/123	IITA	NA	2019–2020
MM16/0707	IITA	IITA-TMS-MM060128/IITA-TMS-MM060128	2019–2020
MM16/1627	IITA	IITA-TMS-MM060128/NA	2019–2020
UG120024	NaCRRRI	NASE14/UG11043	2019–2020
UG120124	NaCRRRI	NASE14/UG110066	2019–2020
UG120156	NaCRRRI	NA	2019–2020
UG120180	NaCRRRI	NA	2019–2020
UG120193	NaCRRRI	NA	2019–2020
UG120198	NaCRRRI	NA	2019–2020
UG130007	NaCRRRI	NA	2019–2020
UG130016	NaCRRRI	UG110041/NA	2019–2020
NAROCASS1 (check variety)	NaCRRRI	NA	2019–2020; 2021–2022
UG15F170P507	NaCRRRI	UG110234/NA	2021–2022
UG15F140P003	NaCRRRI	NA	2021–2022
UG15F302P513	NaCRRRI	UG130003/NA	2021–2022
UG15F265P001	NaCRRRI	UG120193/UG110228	2021–2022
UGC14170	NaCRRRI	UG110100/NA	2021–2022
UG15F177P502	NaCRRRI	UG110242/NA	2021–2022
UG15F106P002	NaCRRRI	UG120153/UG120036	2021–2022
UG110164	NaCRRRI	NA/NA	2021–2022
MM2018/0054	IITA	IITA-TMS-MM140233/NA	2021–2022

Abbreviations: IITA, International Institute of Tropical Agriculture; NaCRRRI, National Crops Resources Research Institute.

^aInformation is retrieved from <https://www.cassavabase.org/>. NA = unknown pedigree.

lead farmers from the farming groups. Initially, key informant interviews were conducted with district agricultural officers in order to select from each district two sub-counties with high cassava production and to identify one extension agent for each sub-county. Similarly, we conducted key informant interviews with extension agents to select two parishes per sub-county with farmers' groups. Subsequently, one farmer group which comprised at least 30 men and women (in total) was selected from each parish.

Subsequently, semi-structured questionnaires were used to interview men and women in each group to select participants to host tricot trials. Selection of participants was based on their willingness to voluntarily host and manage tricot trials and the importance of cassava to the household. The key variables were weighted to ensure the selection of a diverse group and the selection process catered for differences in gender and age groups among the farming community. We intentionally refer to either sex or gender throughout the text, with sex indicating the collected data variable and used in presenting disaggregated data, while we use gender when discussing the differences among men and women for gender analysis. In the first year, 10 men and 10 women were selected from each farmer group to host tricot trials, and in the second year, the number of participants was scaled up to 12 men and 12 women

per group. Overall, in two years, 294 men and 320 women were recruited to host tricot trials (Table 1).

2.4 | Establishment of on-farm trials and data collection

Men and women selected small plots of land measuring 9 m by 12 m in their gardens, and slashed and ploughed them in preparation for planting. Each farmer received a tricot package and was registered prior to planting using the ODK (open data kitmobile) application (Hartung et al., 2010), connected to the ClimMob platform. Routine training for extension agents and lead farmers prior to data collection provided in-depth explanations of the questions.

Farmer registration involved electronically filling in farmers' information including their names, sex, age, and location. Tricot trials were established using the incomplete block design at a spacing of 1 m gap between plants and 2 m between plots. The plots were demarcated with plastic labels inscribed with the letter corresponding to the assigned elite cassava clone (A, B, or C), and, thereafter, a field map was drawn in a book by the implementers (researchers). Farmers were briefed on the various attributes identified in cassava's

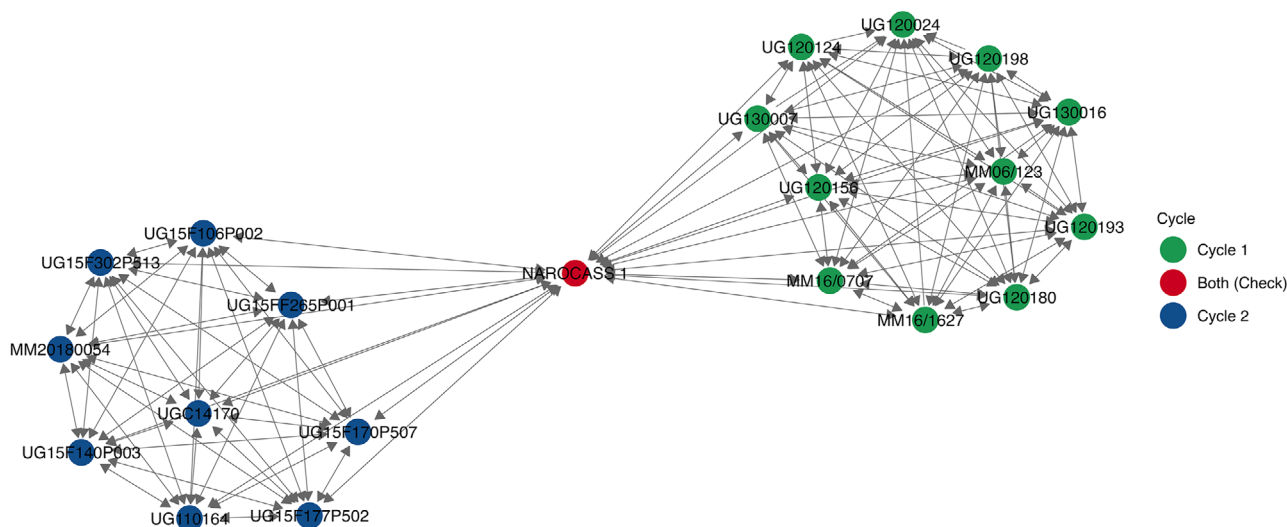


FIGURE 2 Network representation of the elite cassava clones tested in Uganda in each growing cycle. Arrows indicate direct paths of wins and losses between each pair of clones indicating that the clone co-occurs in at least one experimental block. In the analysis, clones with no direct path are connected using an artificial item, which is analogous to a Bayesian prior.

target product profile specific to certain crop stages that would be assessed to enable identification of genotypic performance during on-farm testing.

Data on agronomically related traits were collected at four crop stages (Table 3). Traits were assessed by farmers using rankings, where each farmer indicated the best (first in the ranking) and the worst (third in the ranking) performing clones for each trait. This way of asking for the ranking simplifies the questions. The second position in the ranking was then assigned to the clone not mentioned by farmers. Digitized data were collected from the tricots trials by the extension agents and lead farmers, who submitted it to the ClimMob platform, where it could be accessed by researchers at NaCRRI.

2.5 | On-farm evaluation of culinary-related traits of processed cassava roots

At 12 months after planting (MAP), the tricots approach was used to evaluate elite cassava clones for consumer preferences of the following two food products: (1) a boiled product and (2) a flour-based meal (thick paste) locally called *Kwon*, *atap(a)*, and *enyasa* for Northern, Eastern, and West Nile, respectively (Nanyonjo et al., 2021). The boiled cassava product was processed from fresh cassava roots, while *Kwon* was processed from cassava flour. These products were considered because they are the most common forms of consumption in Uganda (Kilimo Trust, 2012). Cassava roots were processed into the boiled product in all locations, but the flour-based

meal was processed in Serere, Arua, Tororo, Kaberamaido, and Busia.

Implementers backstopped the trial to support the facilitators. This ensured no mixing up clones during processing and/or evaluation for consumer preferences, mindful of standardizing the process during measurements. At each household, saucepans, knives, plates, 500-mL disposable cups, water, firewood, and stoves were assembled and labeled with letters A, B, and C as a precaution against mixing clones. For the boiled product, upon harvesting five plants, three marketable cassava roots from each variety were peeled, washed, sliced, and placed in labeled source pans which were filled with 750 mL of water.

Likewise, saucepans were simultaneously placed on lit firewood stoves to cook the cassava roots for 45 min. The evaluators then processed the sun-dried cassava flour and *Kwon* using the method in Nanyonjo et al. (2021). During evaluation of consumer preferences, one product was presented at a time on three plates labeled with letters A, B, and C corresponding to the respective harvested elite cassava clone. Hence, each labeled plate contained a product processed from cassava roots harvested from the corresponding elite cassava clone. Each participant was presented with three color-coded and labeled plates, each containing one product to evaluate. The participant was asked to rank the best and worst elite cassava clone depending on the trait being assessed (Table 3). After evaluating the product of one elite cassava clone, the participants rinsed their mouths with water before testing the product of another elite cassava clone.

TABLE 3 Trait name, evaluation time points, and trait description evaluated in the tricot (triadic comparison of technology options) trials. For each trait, tricot trial participants indicated which is the best and which is the worst, resulting in rankings of three.

Trait name	Evaluation time	Description
Vigor	3 MAP	How strongly or weakly plants in a plot are growing.
Susceptibility to pests	3 MAP	Presence or absence of insect pests or their larvae on the leaves.
Susceptibility to diseases	3 MAP	Presence or absence of mottled leaves or yellow streaks on the leaves.
General appearance	6 MAP	The general architecture of the plants.
Branching habit	6 MAP	How plants branch their stems or not.
Plant height	9 MAP	How tall or short the plants are.
Suitability soils	9 MAP	Candidate variety which is growing with or without vigor in the farmer's field.
Overall performance	9 MAP	In totality the best or worst performing clone.
Stem quality	12 MAP	Stem fitness for planting.
Fresh root shape	12 MAP	The shape of the fresh cassava roots.
Fresh root size	12 MAP	How big or small the roots are.
Fresh root yield	12 MAP	Cassava root yield from a plot.
Overall preferred fresh roots	12 MAP	Least or most preferred cassava clone considering appearance of fresh roots.
Overall performance harvest	12 MAP	Least or most preferred clone considering totality of agronomic performance for traits evaluated at harvest (root shape, root yield, root size, and stem quality).
Boiled root mealiness	12 MAP	Crumbly feeling in the mouth as one chewed boiled cassava roots.
Boiled root softness	12 MAP	Ease of biting and/or chewing boiled cassava.
Less fibrous boiled root	12 MAP	Absence of fibers as one chewed boiled cassava roots.
Preferred boiled food	12 MAP	Clone with or without preferred taste, cooked well, mealiness, and fibrousness.
Overall preferred from planting to boiled food	12 MAP	Least or most preferred cassava clone considering performance from germination up to processing boiled product.
Ease of drying	12 MAP	Candidate variety whose root chips dried fastest or slowest.
Ease of mixing flour paste	12 MAP	How easy or difficult it is to mix flour to form a paste.
Flour based meal color	12 MAP	The color of the flour-based meal.
Taste of flour meal	12 MAP	Taste of the flour-based meal in the mouth.
Texture of flour meal	12 MAP	Mouth feel of the flour-based meal.
Preferred flour-based meal	12 MAP	Clone with or without preferred color, stickiness, taste, and texture of the flour-based meal.
Overall performance from planting to flour meal	12 MAP	Least preferred or most preferred cassava clone considering performance from germination up to processing flour-based meal product.

Abbreviation: MAP, months after planting.

2.6 | Data analysis

We applied rank-aggregation to integrate the data from the two cycles in one single dataset (Brown et al., 2022). Due to unavoidable circumstances such as drought, hailstorms, and, in some few cases, poor farmer management practices, we lost a number of trials, reducing our initial sample size. We remained with 484 tricot trials (cycle 1, $n = 207$; cycle 2, $n = 277$), which were aggregated. The data were processed using the R packages *ClimMobTools* (de Sousa & van Etten, 2024) and *gosset* (de Sousa, Brown, et al., 2023). The data

were analyzed using the Plackett–Luce model (Luce, 1959; Plackett, 1975), implemented in the R package *PlackettLuce* (Turner et al., 2020), and extended with model-based recursive partitioning, which produces Plackett–Luce trees (Zeileis et al., 2008). The Plackett–Luce model with recursive partitioning has been applied in several studies analyzing data from tricot trials (Brown et al., 2022; van Etten, de Sousa, et al., 2019). Considering a set S with J elements, $S = \{i_1, i_2, \dots, i_j\}$, the probability that an element ij is selected from S is computed as $P(ij|S) = \frac{\alpha_{ij}}{\sum_{i \in S} \alpha_i}$, where $\alpha_i \geq 0$ is the worth of element i , representing how likely element i will be preferred

over the other items in S . To consider the effect that external factors may have on the probability of an item being preferred, the Plackett–Luce model is combined with recursive partitioning, allowing the use of model covariates. The recursive partitioning algorithm for the Plackett–Luce model involves four main steps, described by both Turner et al. (2020) and Zeileis et al. (2008) as follows:

1. Fit a Plackett–Luce model to the complete dataset;
2. For each covariate, assess for changes on the stability of worth parameters;
3. If a significant instability is detected, the dataset is split into two partitions by the covariate with the highest instability, according to a threshold specified to provide the highest improvement to the model fit;
4. Steps one to three are repeated until no more instabilities are detected or the resultant dataset partitions are smaller than a pre-specified size threshold.

The α parameter in the model specification sets the threshold referred to in step three, which defines the level of significance to allow a split (Zeileis et al., 2008). We used the default $\alpha = 0.05$ with a Bonferroni correction. For the minimum number of observations in each resulting partition, also known as nodes, we set the threshold to 10% of the total observations in the aggregated dataset. Plackett–Luce model worth estimates are computed by maximum likelihood, which requires a strongly connected network of wins and losses among evaluated varieties (Turner et al., 2020). In our study, the network of wins and losses is shown in Figure 2. When a network is not strongly connected, the *PlackettLuce* package implements the use of an artificial item to add pseudo-rankings, to guarantee that all the elements are connected, allowing computation of the model estimates (Turner et al., 2020). The number of wins and losses among each variety and the artificial one is indicated by the *npseudo* parameter in the Plackett–Luce model specification, with a default value of 0.5. That means that each pseudo-ranking is weighted by 0.5 and works like a Bayesian prior (Turner et al., 2020). Even with a strongly connected network, the use of pseudo-rankings is advisable in order to provide a shrinkage effect that reduces bias and variance (Turner et al., 2020). In our case, we used the default *npseudo* = 0.5.

2.6.1 | Assessing the influence of sociodemographic and geographic factors

To determine the sociodemographic and geographic factors influencing ranking of elite cassava clones, combined data of overall performance at harvest from both cycles were subjected to the Plackett–Luce tree model. The sociodemo-

graphic (sex and age) and geographic (district) variables were used as covariates in the Plackett–Luce tree model.

We further investigated the effect of climatic factors on the overall performance at harvest of the elite cassava clones. We fitted a Plackett–Luce tree model with climatic covariates on the overall agronomic performance of the varieties at harvest 12 MAP. We used a set of climatic variables and indices (Table 4) with putative influence on crop performance (Aguilar et al., 2005; Kehel et al., 2016). For each trial plot location, we used geographic coordinates to obtain climatic data corresponding to the period from planting to harvest. The climatic data were obtained from the AgERA5 database (Boogaard et al., 2020), using the R package *ag5Tools* (Brown, de Sousa, et al., 2023), and the climatic indices were computed with the R package *climatrends* (de Sousa, van Etten, et al., 2023).

2.6.2 | Stability assessment of Plackett–Luce tree models

We subjected the Plackett–Luce tree models to a stability assessment using the R package *stablelearner* (Philipp et al., 2016). We made an ensemble of 1000 Plackett–Luce trees, each one with a different dataset obtained by resampling without replacing 80% of the original aggregated dataset. This approach has been successfully applied to evaluate the stability of Plackett–Luce trees (Brown, de Bruin, et al., 2023). A stability assessment is required because of the well-known potential instability of tree-based models (Philipp et al., 2018; Strobl et al., 2009).

2.6.3 | Reliability assessment

Besides the probability of being ranked first, we were also interested in assessing the reliability of the elite cassava clones, that is, the probability of outperforming the check variety; NAROCASS 1 (Eskridge & Mumm, 1992). Using the worth values of the Plackett–Luce model on overall performance at harvest 12 MAP, we calculated the reliability of each elite cassava clone against the check variety (NAROCASS 1). Reliability was computed using the *gosset* package in R (de Sousa, Brown, et al., 2023).

2.6.4 | Performance of elite cassava clones considering all agronomic and quality traits

To assess the performance of varieties across all the evaluated traits, we fitted a Plackett–Luce model for each of the evaluated traits (Table 3) and then we calculated the reliability of

TABLE 4 Climatic variables and indices used as model covariates in the Plackett–Luce tree model, considering the period from planting to harvest.

Variable name	Description
max_24t (°C)	Maximum temperature during the 00- to 24-h period
max_dt (°C)	Maximum temperature during the 06- to 18-h period
mean_24t (°C)	Mean temperature during the 00- to 24-h period
mean_dt (°C)	Mean temperature during the 06- to 18-h period
mean_nt (°C)	Mean temperature during the 18- to 06-h period
min_24t (°C)	Minimum temperature during the 00- to 24-h period
min_nt (°C)	Minimum temperature during the 18- to 06-h period
Rainfall (mm)	Total daily rainfall (00–24 h)
rhum_06 (%)	Relative humidity at 06 h
rhum_09 (%)	Relative humidity at 09 h
rhum_12 (%)	Relative humidity at 12 h
rhum_15 (%)	Relative humidity at 15 h
rhum_18 (%)	Relative humidity at 18 h
Srf (J)	Solar radiation flux (00–24 h)
rainfall_total (mm)	Cumulative daily rainfall from planting to harvest
MLDS (days)	Maximum length of dry spell (precipitation <1 mm)
MLWS (days)	Maximum length of wet spell (precipitation ≥1 mm)
R10mm (days)	Number of days with rainfall ≥10 mm
R20mm (days)	Number of days with rainfall ≥20 mm
Rx1day (mm)	Maximum 1-day precipitation
Rx5day (mm)	Maximum 5-day precipitation
R95p (mm)	Total precipitation when rain >95th percentile
R99p (mm)	Total precipitation when rain >99th percentile
SDII (mm/days)	Total precipitation divided by the number of days with precipitation ≥1 mm
DTR (°C)	Mean difference between day and night temperature
SU (days)	Number of days with maximum temperature >30
WSDI (days)	Consecutive days with temperature >90th percentile
CSDI (days)	Consecutive days with temperature <10th percentile
T10p (°C)	The 10th percentile of night temperature
T90p (°C)	The 90th percentile of day temperature

the elite cassava clones for each evaluated trait. The reliability results were combined in a heatmap to make a comprehensive evaluation including both agronomic performance and food quality traits.

3 | RESULTS

3.1 | Key demographic variable influencing ranking of elite cassava clones for overall performance at harvest

The Plackett–Luce tree showed that location significantly ($p < 0.01$) influenced ranking of elite cassava clones (Figure 3). The locations largely from different agroecolog-

ical zones were segregated in two nodes specifically—node 2 composed of the following districts: Busia, Dokolo, Kabera-maido, Kibaale, Luwero, and Serere and node 3 comprising Arua, Buikwe, Mityana, and Tororo (Figure 3). In node 2, the top-performing elite cassava clones were UG130016, UG110164, and UG130007, with no difference compared to NAROCASS 1 (check variety) at $p < 0.05$ (Table S1). In node 3, the top-performing elite cassava clones were UG130007, UG120124, and UGC14170, with no difference with NAROCASS 1 (Table S2). In both nodes, the elite cassava clone UG120024 had the least ranking (Figure 3).

The stability assessment of the Plackett–Luce tree with sociodemographic and geographic variables is shown in Figure 4. The reduced data volume of the 80% random selections makes a split in only 530 out of the 1000 models

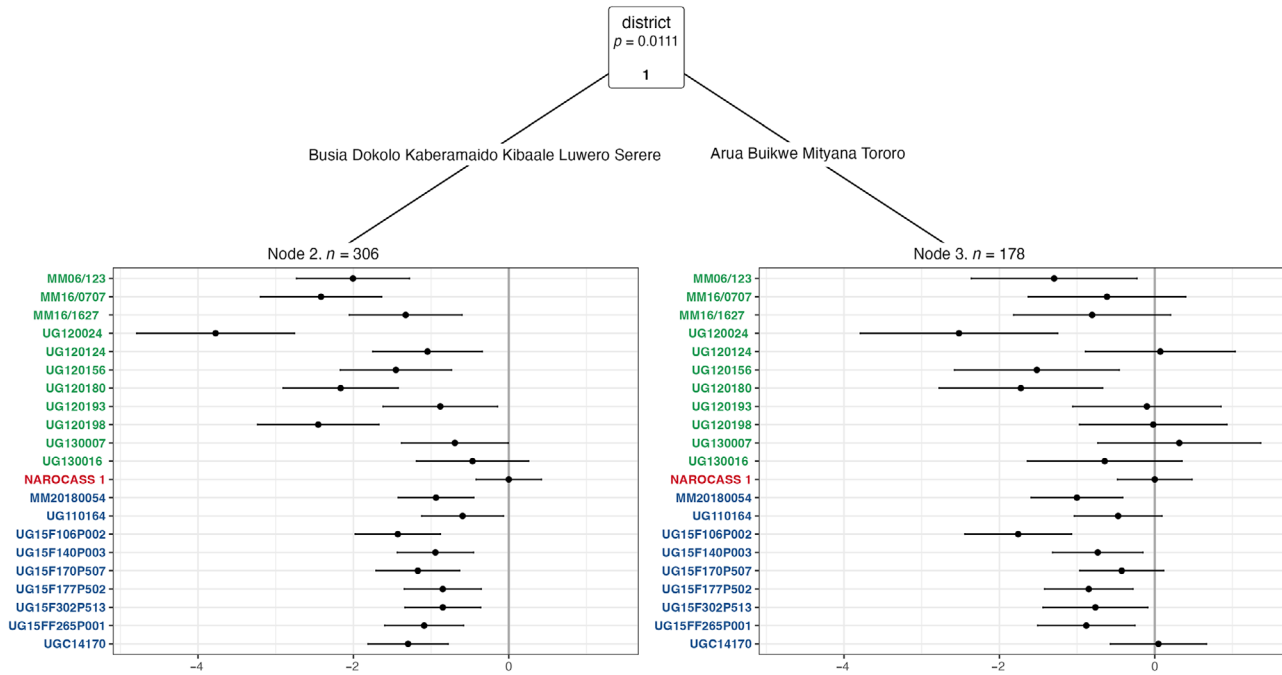


FIGURE 3 Plackett–Luce tree with district as covariate. Sex and age were tested but not selected as model covariates by the recursive partitioning algorithm. The x -axis represents the (log) worth estimates of each variety, with NAROCASS 1 set to zero as it serves as the reference. Horizontal bars represent quasi-standard errors (Firth & De Menezes, 2004). Color codes for the y axis are as follows: green, elite cassava clones evaluated in cycle 1; red, check variety; and blue, elite cassava clones evaluated in cycle 2.

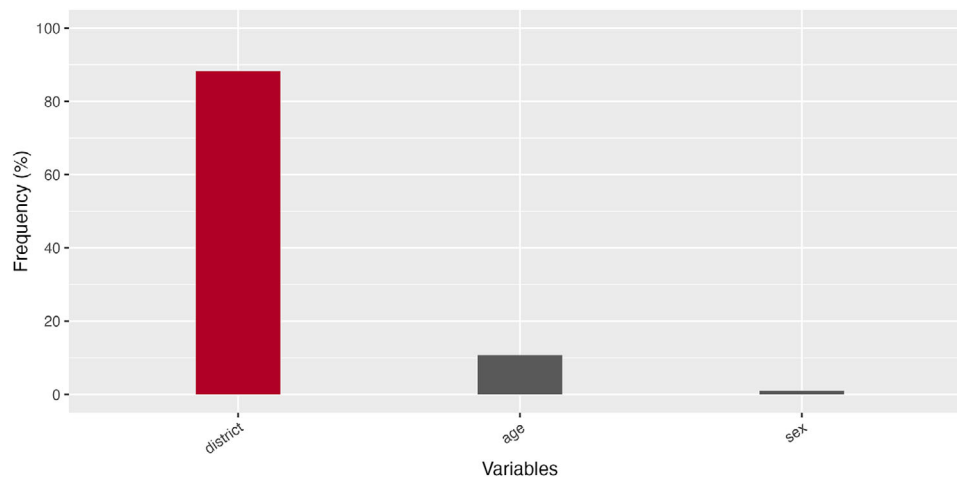


FIGURE 4 Relative frequencies of variables being selected for a split from 1000 runs of the Plackett–Luce tree model with 80% of data using resampling without replacement from the aggregated dataset (only runs making a split are counted). Variable district is highlighted in red to denote it was selected in the original Plackett–Luce tree.

generated. This is exacerbated by the fragile connectivity between the datasets of cycles one and two, which relies on one common check variety (Figure 2). Therefore, to fairly assess the stability of variable selection, we selected the models with at least one split and displayed the relative frequency

that different variables were selected (Figure 4). Out of the total number of times in which the algorithm made a split, district was selected in almost 90% of the times. This supports the selection of variable district as the most important factor compared to age and sex.

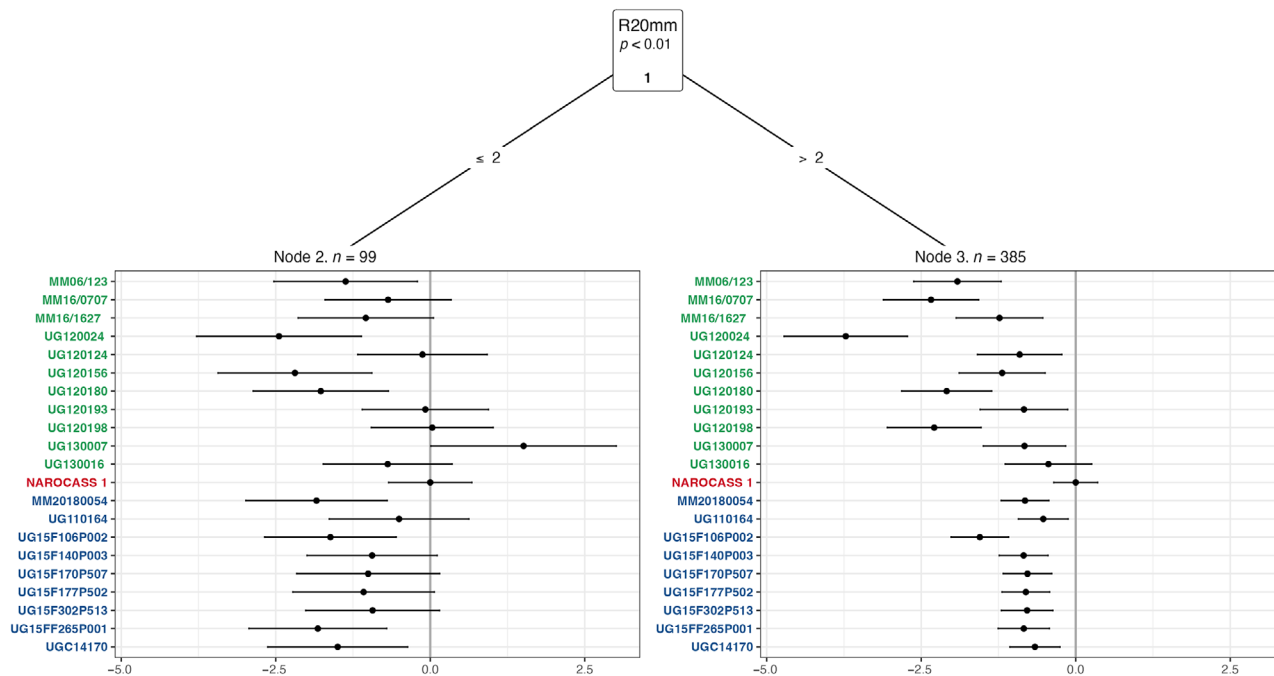


FIGURE 5 Plackett–Luce tree split by number of days with rainfall ≥ 20 mm out of all the climatic variables (Table 4) as model covariates. The x-axis represents the (log) worth estimates of each variety, with NAROCASS 1 set to zero as it serves as the reference. Horizontal bars represent quasi-standard errors (Firth & De Menezes, 2004). Color codes for the y axis are as follows: green, elite cassava clones evaluated in cycle 1; red, check variety; and blue, elite cassava clones evaluated in cycle 2.

3.2 | Climate variables influencing ranking of elite cassava clones for overall performance at harvest

The Plackett–Luce tree model with climatic covariates splits the dataset into two, represented by nodes 2 and 3 (Figure 5). In node 2, the locations received more than 20 mm of precipitation for ≤ 2 days, while in node 3, the locations received more than 20 mm for more than 2 days. Therefore, node 2 represents relatively dry environments and node 3 relatively wet environments. In the dry environments (node 2), elite cassava clone UG130007 was superior to the check variety NAROCASS 1, yet in the wet environments (node 3), the check variety was superior to all the elite cassava clones (Figure 3). As in the first Plackett–Luce tree (Figure 3), elite cassava clone UG120024 had the lowest ranking in both nodes.

The stability assessment of the Plackett–Luce tree model with climate covariates show that variable R20mm (number of days with rain > 20 mm) was selected as the splitting variable in almost 55% of the of the times in which the algorithm made a split (Figure 6). As in the case of stability assessment for the model with sociodemographic and geographic variables, the relative frequencies of splits out of the 1000 Plackett–Luce tree models are low. This is mainly caused by the reduced data volume of the 80% random selections and the fragile link of the two datasets from cycles one and two, which heavily

depends on the common check variety used in the two cycles (Figure 2).

3.3 | Probability of the elite cassava clones to outperform the check variety based on the climatic covariates

Reliability and worth estimates for node 2 from the Plackett–Luce tree model with climatic covariates (Table 5) showed that elite cassava clones UG130007 and UG120198 have the highest probability to outperform the check variety NAROCASS 1 in environments of relatively low precipitation (node 2; Figure 5). Furthermore, none of the elite cassava clones outperformed the check variety in the relatively wet environments (node 3; Figure 5), but elite cassava clone UG130016 did not significantly differ from the check variety ($p < 0.1$) in performance (Table 6).

3.4 | Performance of elite cassava clones in comparison to the check variety for agronomic and quality traits

In general, elite cassava clones had relatively high reliability (probability to outperform the check) for some agronomic related traits evaluated between 3 MAP and 9 MAP

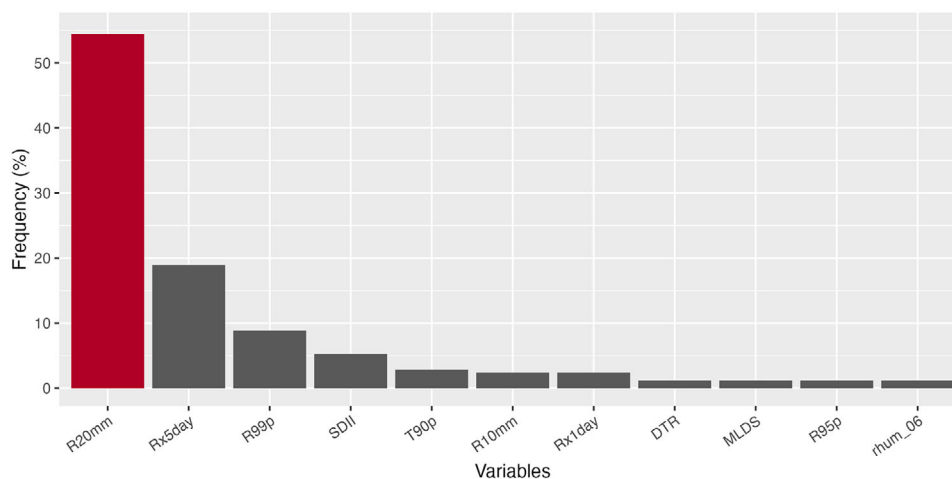


FIGURE 6 Relative frequencies of climatic variables being selected for a split from 1000 runs of the Plackett–Luce tree model with 80% of data using resampling without replacement from the aggregated dataset (only runs making a split are counted). Variable R20mm is highlighted in red to denote it was selected in the original Plackett–Luce tree. Only variables selected at least once are shown. See Table 4 for variable description.

TABLE 5 Reliability of elite cassava clones and worth estimates for node 2 of the Plackett–Luce tree with climatic covariates.

Elite cassava clones	Reliability	Reliability SE	Worth	Z value	Pr(> z)
UG130007	0.819	0.141	0.343	1.851	0.064
UG120198	0.508	0.124	0.078	0.056	0.955
NAROCASS 1	0.5	0.085	0.000	NA	NA
UG120193	0.480	0.126	0.070	−0.137	0.891
UG120124	0.469	0.128	0.067	−0.207	0.836
UG110164	0.377	0.123	0.046	−0.752	0.452
MM16/0707	0.336	0.105	0.038	−1.112	0.266
UG130016	0.334	0.106	0.038	−1.108	0.268
UG15F302P513	0.282	0.098	0.030	−1.373	0.17
UG15F140P003	0.281	0.095	0.030	−1.438	0.151
UG15F170P507	0.268	0.099	0.028	−1.414	0.157
MM16/1627	0.261	0.093	0.027	−1.626	0.104
UG15F177P502	0.254	0.094	0.026	−1.509	0.131
MM06/123	0.203	0.079	0.019	−2.037	0.042
UGC14170	0.183	0.071	0.017	−2.139	0.032
UG15F106P002	0.166	0.062	0.015	−2.410	0.016
UG120180	0.145	0.057	0.013	−2.704	0.007
UG15FF265P001	0.140	0.055	0.012	−2.655	0.008
MM20180054	0.137	0.056	0.012	−2.602	0.009
UG120156	0.101	0.045	0.008	−3.048	0.002
UG120024	0.080	0.038	0.007	−3.262	0.001

Abbreviation: NA, not available.

(Figure 7). Accordingly, elite cassava clones UG110164, UG15F140P003, and MM16/1627 had significantly high reliability ($p < 0.05$) for vigor (0.71, 0.67, and 0.66) (Figure 7; Table S3). Elite cassava clones MM16/1627, UG110164, and MM20180054 had high reliability for less susceptibility to

diseases (0.74, 0.68, and 0.65), respectively. Additionally, elite cassava clones UG15FF265P001, UG15F140P003, and UG15F302P513 had significantly high reliability for height (0.75, 0.75, and 0.72), respectively. However, the check variety was better than the elite cassava clones for yield-related

TABLE 6 Reliability of elite cassava clones and worth estimates for node 3 of the Plackett–Luce tree with climatic covariates.

Elite cassava clones	Reliability	Reliability SE	Worth	Z value	Pr(> z)
NAROCASS 1	0.5	0.045	0	NA	NA
UG130016	0.391	0.081	0.081	−1.085	0.278
UG110164	0.372	0.047	0.074	−1.96	0.05
UGC14170	0.341	0.045	0.065	−2.421	0.015
UG15F170P507	0.314	0.041	0.057	−2.929	0.003
UG15F302P513	0.313	0.044	0.057	−2.854	0.004
UG15F177P502	0.309	0.04	0.056	−3.088	0.002
MM20180054	0.306	0.04	0.055	−3.098	0.002
UG130007	0.304	0.067	0.055	−2.121	0.034
UG120193	0.302	0.07	0.054	−1.997	0.046
UG15FF265P001	0.301	0.043	0.054	−3.073	0.002
UG15F140P003	0.301	0.041	0.054	−3.174	0.002
UG120124	0.288	0.066	0.051	−2.246	0.025
UG120156	0.233	0.057	0.038	−2.898	0.004
MM16/1627	0.226	0.056	0.036	−3.009	0.003
UG15F106P002	0.175	0.032	0.027	−5.318	0.000
MM06/123	0.129	0.035	0.018	−4.575	0.000
UG120180	0.11	0.032	0.016	−4.861	0.000
UG120198	0.092	0.028	0.013	−5.145	0.000
MM16/0707	0.088	0.027	0.012	−5.235	0.000
UG120024	0.024	0.009	0.003	−6.612	0.000

Abbreviation: NA, not available.

traits evaluated at 12 MAP, specifically, fresh root yield, size, and shape.

Nonetheless, elite cassava clones had significantly high reliability for some quality traits related to processing and food products, which were evaluated at 12 MAP (Figure 7). For the boiled product, elite cassava clones UG110164, UGC14170, and UG15F302P513 had significantly high reliability (0.73, 0.71, and 0.70) for mealiness. Moreover, the elite cassava clone UG110164 had significantly high reliability for softness (0.69). Meanwhile, both UG110164 and UG120193 had significantly high reliability (0.68) for less fibrousness. Indeed, UG110164 and UGC14170 had significantly high reliability (0.66 and 0.64) for the preferred boiled food product. It suffices to note that UG120198 and UG120156 had the significantly high reliability of 0.78 and 0.76, respectively, for ease of drying.

It is notable that none of elite cassava clones had significantly high reliability for quality traits related to the flour-based meal.

4 | DISCUSSION

Results from the study showed that location (district) significantly influenced ranking of elite cassava clones based on the

overall performance at harvest. Importantly, ranking of elite cassava clones for overall performance at harvest was based on totality of agronomic performance for traits evaluated at harvest, namely, fresh root yield, shape, size, and stem quality (Table 3). Consequently, location had a higher influence on ranking of elite cassava clones for overall performance at harvest than sex or age. Similar results were documented by Oryemo et al. (2021), who found that adoption of improved cassava varieties was not influenced by farmers' age. Irigaba et al. (2021), in Uganda, and Teeken et al. (2018), in Nigeria, also found that differences in cassava trait preferences between men and women depended on location. Gender has been shown to be related to differential crop trait preferences across a range of crops (Polar et al., 2021; Weltzien et al., 2019), but the differences are too complex to be captured when applying homogenous and binary models (McDougall et al., 2022). This may explain why gender was not emerging as an explaining ranking of varieties.

The study found that the number of days with precipitation >20 mm was a climatic factor which significantly influenced the ranking of elite cassava clones. We hypothesize that UG130007 is drought tolerant, and hence can perform well in relatively dry conditions such as those represented by node 2 of the Plackett–Luce tree (Figure 5). On the other hand, UG130016 adapts better to relatively wet conditions,

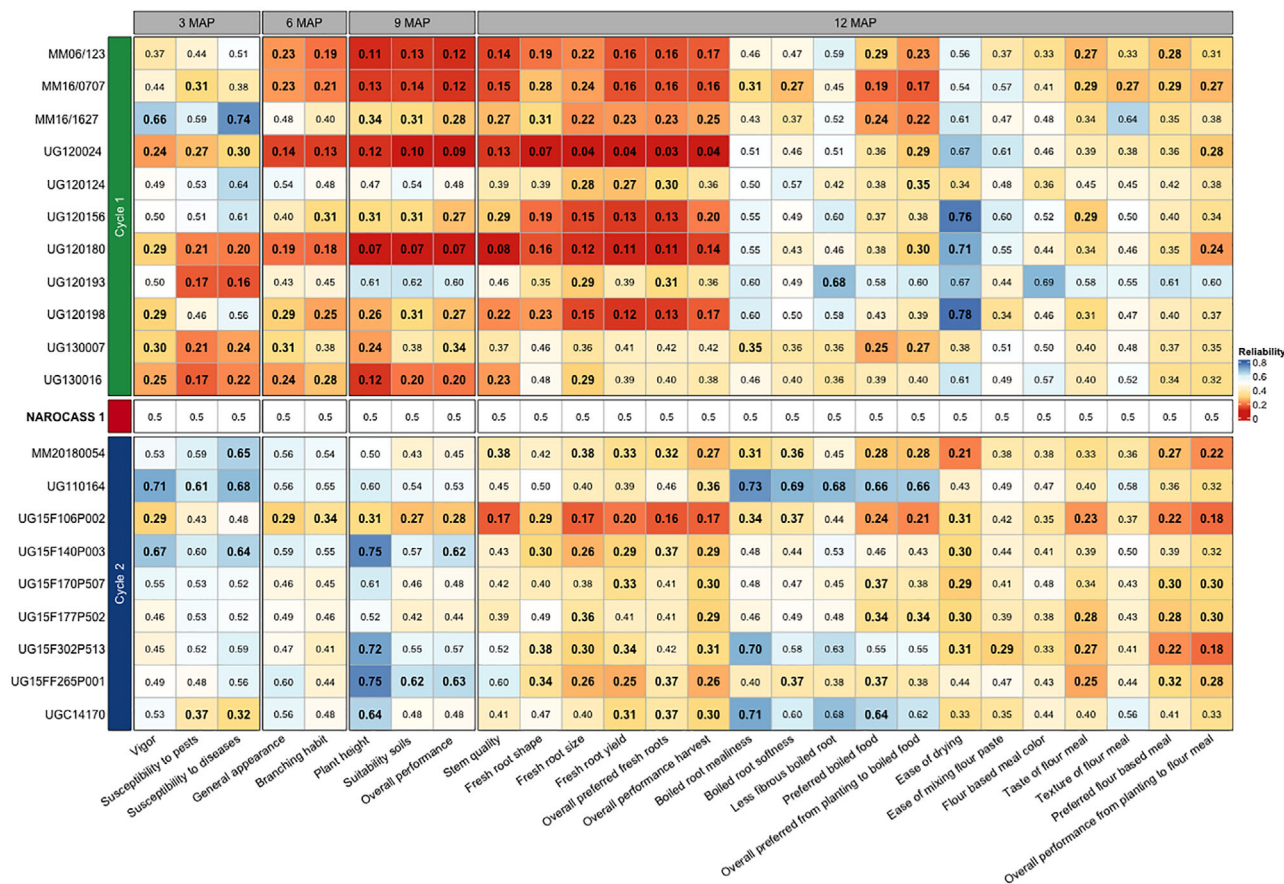


FIGURE 7 Heatmap of reliability estimates produced by fitting a Plackett–Luce model with aggregated data from all the trials for each trait (x-axis) (Table 3) and elite cassava clones (y-axis). The check variety NAROCASS 1 is used as a reference. Elite cassava clones with reliability values above 0.5 are better than the check variety; elite cassava clones reliability values below 0.5 are worse than the check variety. Reliability estimates in bold indicate that the elite cassava clone is significantly different ($p < 0.05$) than the check variety for the trait in the corresponding column. MAP, months after planting.

as the ones represented in node 3 (Figure 5). This seems to be confirmed by the reliability results, which showed that UG130007 was superior to the check variety NAROCASS 1 in locations that received less precipitation. Therefore, this study presents the elite cassava clone UG130007 as an elite cassava clone that can be used as a source of genes for drought tolerance in future crosses. Additionally, genome-wide association studies are needed to map quantitative trait loci for drought tolerance in populations developed from the crosses made with UG130007. It is known that cassava is a drought-tolerant crop (Muiruri et al., 2021). However, Orek et al. (2020) observed that there is genotypic variation in drought tolerance in cassava. Additionally, locations in node 3 (Figure 3) comprised Mityana and Buikwe from the central region of Uganda where it has been common to receive high rainfall (Nsubuga et al., 2014). It is worth noting that recent research shows a shift from this norm in central Uganda because rains have decreased (Ssentongo et al., 2018).

In our study, a heat map shows the reliability of the elite cassava clones, representing the probability of each clone to outperform the check variety for each evaluated trait. Some elite cassava clones possessed higher probabilities to outperform the check variety for some agronomic and quality traits, which showed progress in cassava breeding. For example, MM16/1627, UG110164, and MM20180054 had higher reliability for tolerance to disease. These elite cassava clones can be potential surrogate varieties to NAROCASS 1, the check variety which, at the moment, tolerates major cassava diseases (Ano et al., 2021; Mukiibi et al., 2019) to curb challenges of disease susceptibility. Additionally, we postulate that UG120156 and UG120198, which had high reliability for ease of drying, could have high dry matter and this could be attributed to selection for high dry matter as a key trait in cassava breeding over time (Manze et al., 2021). However, this needs to be confirmed with further research, mindful that these elite cassava clones could be potential varieties for the starch industry. Recent research has found a direct

relationship between dry matter content and starch content (Odedeyi et al., 2022).

Notwithstanding, all the evaluated elite cassava clones had an inferior reliability for yield-related traits evaluated at 12 MAP, for example, root shape, yield, size, overall performance at harvest, and preferred fresh roots. Similarly, the assessment of cassava breeding in Uganda done by Manze et al. (2021) showed very low genetic gain for yield. This exhibits a major challenge to cassava breeding to find elite cassava clones with higher on-farm yield than the check variety.

The cassava breeding program has devoted efforts to integrate food-product quality traits (Kawuki et al., 2011). Moreover, scientists under the RTBFoods project (<https://rtbfoods.cirad.fr/>) committed efforts to understand end-user quality traits for purposes of their integration during crop improvement (Dufour et al., 2021). In this study, we found that elite cassava clones had mostly significantly high reliability for quality traits related to the boiled food product, namely, mealiness, softness, and less fibrousness. The elite cassava clones, UG110164 and UGC14170, which had significantly high reliability for quality traits, can be put forward as candidates for variety release targeting the boiled food product.

We suggest that UG110164 can be presented to farmers as an alternative to the landraces they persistently grow despite their disease and yield penalties (Ribeiro et al., 2012). It is commonplace for end-users to process and consume landraces because they possess their preferred traits (Chiwona-Karlton et al., 2015; Nanyonjo et al., 2021). Accordingly, presenting alternatives with their trait preferences could improve adoption of improved varieties.

While the use of the same check variety (NAROCASS 1) in the two evaluation cycles allowed the integration and analysis of the data, it also presented a limitation for applying the Plackett–Luce tree model, especially to assess the stability of Plackett–Luce trees (Figures 4 and 6). Also, using a single check variety makes the interpretation of the trial rely a lot on the environmental response of this variety. Although maximizing the use of resources is desirable, we suggest keeping some level of consistency in including check varieties for on-farm testing over different seasons to allow a more robust statistical analysis and model fit. For future studies aiming to expand our current findings, using the same check variety NAROCASS 1 is recommended, especially if the main goal is to compare against the same reference. However, this is not mandatory as long as other clones included in this study are also evaluated in future studies, in order to keep the network connectivity described in Section 2.6.

5 | CONCLUSION

Our study has demonstrated how the tricot approach was implemented to conduct PVS evaluation of elite cassava clones in Uganda. Three key findings were evident: (1) Combining the tricot approach with rank aggregation enabled merging trial data from two cycles, each one with a different set of elite cassava clones. This makes more efficient use of time and resources compared to analyzing each cycle individually. (2) The use of sociodemographic and climatic data as model covariates enabled identification of number of days with rainfall >20 mm, which significantly influenced agronomic performance of elite cassava clones. (3) The assessment combining agronomic and food quality traits provided a comprehensive and reliable way of identifying promising elite cassava clones such as UG110164, UGC14170, and UG120193, which can be put forward as candidate varieties for release targeting food products. Therefore, our study demonstrates the important contribution that end-users can make to crop improvement and provides insights to the cassava breeding program in Uganda, which can be used to support decision-making for variety release. Since the study has shown that data from tricot trials can be aggregated, we recommend integration of data from new studies to update our current findings. Moreover, there is a need to further investigate the interaction between gender and location.

AUTHOR CONTRIBUTIONS

Ann Ritah Nanyonjo: Conceptualization; investigation; validation; writing—original draft; writing—review and editing. **Stephen Angudubo:** Conceptualization; investigation; validation; writing—review and editing. **Paula Iragaba:** Conceptualization; investigation; validation; writing—review and editing. **David Brown:** Data curation; formal analysis; methodology; software; validation; visualization; writing—review and editing. **Ephraim Nuwamanya:** Investigation; writing—review and editing. **Williams Esuma:** Supervision; writing—review and editing. **Alfred Ozimati:** Investigation; writing—review and editing. **Enoch Wembabazi:** Investigation; writing—review and editing. **Michael Kanaabi:** Investigation; writing—review and editing. **Nicholas Muhumuza:** Investigation; writing—review and editing. **Irene Baiyiyana:** Writing—review and editing. **Jacob van Etten:** Conceptualization; methodology; software; writing—review and editing. **Kauê de Sousa:** Data curation; formal analysis; methodology; software; writing—review and editing. **Hale Tufan:** Conceptualization; funding acquisition; project administration; supervision; validation; writing—review and editing. **Robert Sezi Kawuki:** Conceptualization; funding

acquisition; project administration; supervision; validation; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT


The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The code and data used for this research are available at https://github.com/EQUAL-Lab/NextGen_Cassava_tricot_Uganda. We used R and RStudio for all the statistical analysis (Posit Team, 2023; R Core Team, 2023). Data analysis with the Plackett–Luce model was done in R using packages *PlackettLuce* and *gosset* (de Sousa, Brown, et al., 2023; Turner et al., 2020). Visualization was performed using the R packages *ggplot2*, *sf*, *ggparty*, *patchwork*, and *ComplexHeatmap* (Borkovec & Madin, 2019; Gu, 2022; Pebesma, 2018; Wickham, 2016).

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REFERENCES

- Aguilar, E., Peterson, T. C., Obando, P. R., Frutos, R., Retana, J. A., Solera, M., Soley, J., García, I. G., Araujo, R. M., Santos, A. R., Valle, V. E., Brunet, M., Aguilar, L., Álvarez, L., Bautista, M., Castañón, C., Herrera, L., Ruano, E., Sinay, J. J., ... Mayorga, R. (2005). Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. *Journal of Geophysical Research: Atmospheres*, 110(D23). <https://doi.org/10.1029/2005jd006119>
- Alamu, O., Teeken, B., Ayetigbo, O., Adesokan, M., Kayondo, I., Chijioko, U., Madu, T., Okoye, B., Abolore, B., Njoku, D., Rabbi, I., Egesi, C., Ndjouenkeu, R., Bouniol, A., De Sousa, K., Dufour, D., & Maziya-Dixon, B. (2023). Establishing the linkage between eba's instrumental and sensory descriptive profiles and their correlation with consumer preferences: Implications for cassava breeding. *Journal of the Science of Food and Agriculture*, 104(8), 4573–4585. <https://doi.org/10.1002/jsfa.12518>
- Ano, C. U., Ochwo-Ssemakula, M., Ibanda, A., Ozimati, A., Gibson, P., Onyeka, J., Njoku, D., Egesi, C., & S Kawuki, R. (2021). Cassava Brown streak disease response and association with agronomic traits in elite Nigerian cassava cultivars. *Frontiers in Plant Science*, 12, 720532. <https://www.frontiersin.org/articles/10.3389/fpls.2021.720532>
- Boogaard, H., Schubert, J., De Wit, A., Lazebnik, J., Hutjes, R., & Van der Grijn, G. (2020). *Agrometeorological indicators from 1979 to present derived from reanalysis*. Copernicus Climate Change Service, Climate Data Store. <https://doi.org/10.24381/cds.6c68c9bb>
- Borkovec, M., & Madin, N. (2019). Ggparty: “ggplot” Visualizations for the “partykit” (Package 1.0.0) [Computer software]. CRAN. <https://CRAN.R-project.org/package=ggparty>
- Brown, D., de Bruin, S., de Sousa, K., Abadie, C., Carpentier, S., Machida, L., & van Etten, J. (2023). Rank-based data synthesis of heterogeneous trials to identify the effects of climatic factors on the reaction of Musa genotypes to black leaf streak disease. *Agronomy Journal*, 115(6), 2990–3009. <https://doi.org/10.1002/agj2.21436>
- Brown, D., de Bruin, S., de Sousa, K., Aguilar, A., Barrios, M., Gómez, M., Hernandez, J. C., Chaves, N., Madriz, B., Machida, L., Mejía, P., Mercado, L., Pavón, M., Rosas, J. C., Steinke, J., Suchini, J. G., Zelaya, V., & van Etten, J. (2022). Rank-based data synthesis of common bean on-farm trials across four Central American countries. *Crop Science*, 62(6), 2246–2266. <https://doi.org/10.1002/csc2.20817>
- Brown, D., de Sousa, K., & van Etten, J. (2023). ag5Tools: An R package for downloading and extracting agrometeorological data from the AgERA5 database. *SoftwareX*, 21, 101267. <https://doi.org/10.1016/j.softx.2022.101267>
- Bua, A., Acola, G., Adupa, R. L., Otim-Nape, G. W., Baguma, Y. K., Sserunkuma, D., Manyong, V., & Coulibaly, O. (2007). The economic impact of investments in cassava research in Uganda. In P. Anandajayasekeram, M. Rukuni, S. Babu, F. Liebenberg, & C. L. Keswani (Eds.), *Impact of science on African agriculture and food security* (pp. 147–151). CABI. <https://doi.org/10.1079/9781845932671.0147>
- Chiwona-Karlton, L., Nyirenda, D., Mwansa, C. N., Kongor, J. E., Brimer, L., Haggblade, S., & Afoakwa, E. O. (2015). Farmer preference, utilization, and biochemical composition of improved cassava (*Manihot esculenta* Crantz) varieties in southeastern Africa. *Economic Botany*, 69(1), 42–56. <https://doi.org/10.1007/s12231-015-9298-7>
- de Sousa, K., Brown, D., Steinke, J., & van Etten, J. (2023). *gosset*: An R package for analysis and synthesis of ranking data in agri-

- cultural experimentation. *SoftwareX*, 22, 101402. <https://doi.org/10.1016/j.softx.2023.101402>
- de Sousa, K., & van Etten, J. (2024). ClimMobTools: API Client for the “ClimMob” Platform (Version 1.2) [Computer software]. CRAN. <https://cran.r-project.org/web/packages/ClimMobTools/index.html>
- de Sousa, K., van Etten, J., Manners, R., Abidin, E., Abdulmalik, R. O., Abolore, B., Acheremu, K., Angudubo, S., Aguilar, A., Arnaud, E., Babu, A., Barrios, M., Benavente, G., Boukar, O., Cairns, J. E., Carey, E., Daudi, H., Dawud, M., Edughaen, G., ... Zaman-Allah, M. (2024). The tricot approach: An agile framework for decentralized on-farm testing supported by citizen science. A retrospective. *Agronomy for Sustainable Development*, 44(1), Article 8. <https://doi.org/10.1007/s13593-023-00937-1>
- de Sousa, K., Van Etten, J., Neby, M., & Solberg, S. Ø. (2023). Climate variability indices for ecological and crop models in R: The climatrends package. *Journal of Open Source Software*, 8(85), 4405. <https://doi.org/10.21105/joss.04405>
- de Sousa, K., van Etten, J., Poland, J., Fadda, C., Jannink, J.-L., Kidane, Y. G., Lakew, B. F., Mengistu, D. K., Pè, M. E., Solberg, S. Ø., & Dell'Acqua, M. (2021). Data-driven decentralized breeding increases prediction accuracy in a challenging crop production environment. *Communications Biology*, 4(1), Article 944. <https://doi.org/10.1038/s42003-021-02463-w>
- Dufour, D., Hershey, C., Hamaker, B. R., & Lorenzen, J. (2021). Integrating end-user preferences into breeding programmes for roots, tubers and bananas. *International Journal of Food Science & Technology*, 56(3), 1071–1075. <https://doi.org/10.1111/ijfs.14911>
- El-Sharkawy, M. A. (2004). Cassava biology and physiology. *Plant Molecular Biology*, 56(4), 481–501. <https://doi.org/10.1007/s11103-005-2270-7>
- Eskridge, K. M., & Mumm, R. F. (1992). Choosing plant cultivars based on the probability of outperforming a check. *Theoretical and Applied Genetics*, 84(3), 494–500. <https://doi.org/10.1007/bf00229512>
- Firth, D., & De Menezes, R. X. (2004). Quasi-variances. *Biometrika*, 91(1), 65–80. <https://doi.org/10.1093/biomet/91.1.65>
- Gu, Z. (2022). Complex heatmap visualization. *iMeta*, 1(3), e43. <https://doi.org/10.1002/imt.2.43>
- Hartung, C., Lerer, A., Anokwa, Y., Tseng, C., Brunette, W., & Borriello, G. (2010). Open data kit: Tools to build information services for developing regions. In *ICTD '10: Proceedings of the 4th ACM/IEEE International Conference on Information and Communication Technologies and Development* (pp. 1–12). ACM. <https://doi.org/10.1145/2369220.2369236>
- Howeler, R. H., Lutaladio, N., & Thomas, G. (2013). *Save and grow: Cassava: A guide to sustainable production intensification*. Food and Agriculture Organization of the United Nations.
- Iragaba, P., Hamba, S., Nuwamanya, E., Kanaabi, M., Nanyonjo, R. A., Mpmire, D., Muhumuza, N., Khakasa, E., Tufan, H. A., & Kawuki, R. S. (2021). Identification of cassava quality attributes preferred by Ugandan users along the food chain. *International Journal of Food Science & Technology*, 56(3), 1184–1192. <https://doi.org/10.1111/ijfs.14878>
- Kawuki, R. S., Kaweesi, T., Esuma, W., Pariyo, A., Kayondo, I. S., Ozimati, A., Kyaligonza, V., Abaca, A., Orone, J., Tumuhimbise, R., Nuwamanya, E., Abidrabo, P., Amuge, T., Ogwok, E., Okao, G., Wagaba, H., Adiga, G., Alicai, T., Omongo, C., ... Baguma, Y. (2016). Eleven years of breeding efforts to combat cassava brown streak disease. *Breeding Science*, 66(4), 560–571. <https://doi.org/10.1270/jsbbs.16005>
- Kawuki, R. S., Pariyo, A., Amuge, T., Nuwamanya, E., Ssemakula, G., Tumwesigye, S., Bua, A., Baguma, Y., Omongo, C., & Alicai, T. (2011). A breeding scheme for local adoption of cassava (*Manihot esculenta* Crantz). *Journal of Plant Breeding and Crop Science*, 3(7), 120–130.
- Kehel, Z., Crossa, J., & Reynolds, M. (2016). Identifying climate patterns during the crop-growing cycle from 30 years of CIMMYT elite spring wheat international yield trials. In A. Bari, A. B. Damania, M. Mackay, & S. Dayananandan (Eds.), *Applied mathematics and omics to assess crop genetic resources for climate change adaptive traits* (pp. 151–174). CRC Press. <https://doi.org/10.1201/9781315369006>
- Kilimo Trust. (2012). *Development of Inclusive Markets in Agriculture and Trade (DIMAT): The nature and markets of honey value chains in Uganda*. United Nations Development Programme.
- Luce, R. D. (1959). *Individual choice behavior: A theoretical analysis*. Dover Publications. <https://doi.org/10.1037/14396-000>
- Manze, F., Rubaihayo, P., Ozimati, A., Gibson, P., Esuma, W., Bua, A., Alicai, T., Omongo, C., & Kawuki, R. S. (2021). Genetic gains for yield and virus disease resistance of cassava varieties developed over the last eight decades in Uganda. *Frontiers in Plant Science*, 12, 651992. <https://www.frontiersin.org/articles/10.3389/fpls.2021.651992>
- McDougall, C., Kariuki, J., Lenjiso, B. M., Marimo, P., Mehar, M., Murphy, S., Teeken, B., Akester, M. J., Benzie, J. A. H., Galiè, A., Kulakow, P., Mekkwaw, W., Nkengla-Asi, L., Ojango, J. M. K., Tumuhimbise, R., Uwimana, B., & Orr, A. (2022). Understanding gendered trait preferences: Implications for client-responsive breeding programs. *PLOS Sustainability and Transformation*, 1(8), e0000025. <https://doi.org/10.1371/journal.pstr.0000025>
- Moyo, M., Ssali, R., Namanda, S., Nakitto, M., Dery, E. K., Akansake, D., Adjebeng-Danquah, J., van Etten, J., de Sousa, K., Lindqvist-Kreuze, H., Carey, E., & Muzhingi, T. (2021). Consumer preference testing of boiled sweetpotato using crowdsourced citizen science in Ghana and Uganda. *Frontiers in Sustainable Food Systems*, 5, Article 620363. <https://doi.org/10.3389/fsufs.2021.620363>
- Muiruri, S. K., Ntui, V. O., Tripathi, L., & Tripathi, J. N. (2021). Mechanisms and approaches towards enhanced drought tolerance in cassava (*Manihot esculenta*). *Current Plant Biology*, 28, 100227. <https://doi.org/10.1016/j.cpb.2021.100227>
- Mukiibi, D. R., Alicai, T., Kawuki, R., Okao-Okuja, G., Tairo, F., Sseruwagi, P., Ndunguru, J., & Ateka, E. M. (2019). Resistance of advanced cassava breeding clones to infection by major viruses in Uganda. *Crop Protection*, 115, 104–112. <https://doi.org/10.1016/j.cropro.2018.09.015>
- Nanyonjo, A. R., Kawuki, R. S., Kyazze, F., Esuma, W., Wembabazi, E., Dufour, D., Nuwamanya, E., & Tufan, H. (2021). Assessment of end user traits and physicochemical qualities of cassava flour: A case of Zombo district, Uganda. *International Journal of Food Science & Technology*, 56(3), 1289–1297. <https://doi.org/10.1111/ijfs.14940>
- Nassar, N. M. A., & Ortiz, R. (2007). Cassava improvement: Challenges and impacts. *The Journal of Agricultural Science*, 145(2), 163–171. <https://doi.org/10.1017/S0021859606006575>
- Nsubuga, F. W. N., Botai, O. J., Olwoch, J. M., deW Rautenbach, C. J., Bevis, Y., & Adetunji, A. O. (2014). The nature of rainfall in the main drainage sub-basins of Uganda. *Hydrological Sciences Journal*, 59(2), 278–299. <https://doi.org/10.1080/02626667.2013.804188>
- Ochola, D., Boekelo, B., van de Ven, G., Taulya, G., Kubiriba, J., van Asten, P., & Giller, K. E. (2021). *Accompanying data and R scripts*:

- Mapping the spatial distribution and geographic shift of East African highland banana (Musa sp.) cropping systems in Uganda* (Version 2) [Data set]. 4TU.ResearchData. <https://doi.org/10.4121/16908469.V2>
- Odeyeyi, T., Rabbi, I., Poole, C., & Darwazeh, I. (2022). Estimation of starch content in cassava based on coefficient of reflection measurement. *Frontiers in Food Science and Technology*, 2, 878023. <https://www.frontiersin.org/articles/10.3389/frfst.2022.878023>
- Olaosebikan, O., Bello, A., de Sousa, K., Ndjouenkeu, R., Adesokan, M., Alamu, E., Agbona, A., Van Etten, J., Kégah, F. N., Dufour, D., Bouniol, A., & Teeken, B. (2023). Drivers of consumer acceptability of cassava gari-eba food products across cultural and environmental settings using the triadic comparison of technologies approach (tricot). *Journal of the Science of Food and Agriculture*, 104(8), 4770–4781. <https://doi.org/10.1002/jsfa.12867>
- Orek, C., Gruissem, W., Ferguson, M., & Vanderschuren, H. (2020). Morpho-physiological and molecular evaluation of drought tolerance in cassava (*Manihot esculenta* Crantz). *Field Crops Research*, 255, 107861. <https://doi.org/10.1016/j.fcr.2020.107861>
- Oryemo, B., Mbatudde, M., Zziwa, S., Nabatanzi, L., Talengera, D., Davis, B., Najjuma, V., & Nafula, M. (2021). Adoption of improved cassava varieties among small scale farmers in Apac district. *International Journal of Applied Science and Engineering Review*, 2(5), 38–53. <https://doi.org/10.52267/IJASER.2021.2503>
- Ozimati, A. A., Esuma, W., Manze, F., Iragaba, P., Kanaabi, M., Ano, C. U., Egesi, C., & Kawuki, R. S. (2022). Utility of Ugandan genomic selection cassava breeding populations for prediction of cassava viral disease resistance and yield in West African clones. *Frontiers in Plant Science*, 13, 1018156. <https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2022.1018156>
- Pebesma, E. (2018). Simple features for R: Standardized support for spatial vector data. *The R Journal*, 10(1), 439–446. <https://doi.org/10.32614/RJ-2018-009>
- Philipp, M., Rusch, T., Hornik, K., & Strobl, C. (2018). Measuring the stability of results from supervised statistical learning. *Journal of Computational and Graphical Statistics*, 27(4), 685–700. <https://doi.org/10.1080/10618600.2018.1473779>
- Philipp, M., Zeileis, A., & Strobl, C. (2016). *A toolkit for stability assessment of tree-based learners* (Working papers in economics and statistics No. 2016-11). University of Innsbruck. <http://hdl.handle.net/10419/146128>
- Plackett, R. L. (1975). The analysis of permutations. *Journal of the Royal Statistical Society. Series C (Applied Statistics)*, 24(2), 193–202. <https://doi.org/10.2307/2346567>
- Polar, V., Mohan, R. R., McDougall, C., Teeken, B., Mulema, A. A., Marimo, P., & Yila, J. O. (2021). *Examining choice to advance gender equality in breeding research*. International Food Policy Research Institute. https://doi.org/10.2499/9780896293915_02
- Posit Team. (2023). RStudio: Integrated Development for R [Computer software]. Posit Software, PBC. <http://www.posit.co/>
- Quirós, C., de Sousa, K., Steinke, J., Madriz, B., Laporte, M.-A., Arnaud, E., Manners, R., Ortiz-Crespo, B., Müller, A., & van Etten, J. (2024). ClimMob: Software to support experimental citizen science in agriculture. *Computers and Electronics in Agriculture*, 217, 108539. <https://doi.org/10.1016/j.compag.2023.108539>
- R Core Team. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. <https://www.R-project.org/>
- Ribeiro, P. F., Akromah, R., & Manu-Aduening, J. (2012). Using marker assisted selection to hasten screening of cassava cultivars developed through introgression of cassava mosaic disease (CMD) resistance into cassava landraces in Ghana. *Journal of Agricultural Science and Technology*, B, 2(1B), 74–80. <https://search.proquest.com/openview/d960f3b735f4effcbdc56c8242178e4/1.pdf?pq-origsite=gscholar&cbl=2029907>
- Rutsaert, P., Donovan, J. A., Mawia, H., de Sousa, K., & Etten, J. V. (2022). *Future market segments for hybrid maize in East Africa*. <https://cgspace.cgiar.org/handle/10568/128238>
- Sánchez, T., Salcedo, E., Ceballos, H., Dufour, D., Mafla, G., Morante, N., Calle, F., Pérez, J. C., Debouck, D., Jaramillo, G., & Moreno, I. X. (2009). Screening of starch quality traits in cassava (*Manihot esculenta* Crantz). *Starch—Stärke*, 61(1), 12–19. <https://doi.org/10.1002/star.200800058>
- Snapp, S. (2002). Quantifying farmer evaluation of technologies: The mother and baby trial design. Quantitative analysis of data from participatory methods in plant breeding. In M. R. Bellon & J. Reeves (Eds.), *Quantitative analysis of data from participatory methods in plant breeding* (pp. 9–17). CIMMYT.
- Ssentongo, P., Muwanguzi, A. J. B., Eden, U., Sauer, T., Bwanga, G., Katerrega, G., Aribo, L., Ojara, M., Mugerwa, W. K., & Schiff, S. J. (2018). Changes in Ugandan climate rainfall at the village and forest level. *Scientific Reports*, 8(1), Article 3551. <https://doi.org/10.1038/s41598-018-21427-5>
- Steinke, J., & van Etten, J. (2016). *Farmer experimentation for climate adaptation with triadic comparisons of technologies (tricot): A methodological guide*. <https://ccafs.cgiar.org/resources/publications/farmer-experimentation-climate-adaptation-triadic-comparisons>
- Strobl, C., Malley, J., & Tutz, G. (2009). An introduction to recursive partitioning: Rationale, application and characteristics of classification and regression trees, bagging and random forests. *Psychological Methods*, 14(4), 323–348. <https://doi.org/10.1037/a0016973>
- Teeken, B., Olaosebikan, O., Haleegoah, J., Oladejo, E., Madu, T., Bello, A., Parkes, E., Egesi, C., Kulakow, P., Kirscht, H., & Tufan, H. A. (2018). Cassava trait preferences of men and women farmers in Nigeria: Implications for breeding. *Economic Botany*, 72(3), 263–277. <https://doi.org/10.1007/s12231-018-9421-7>
- Turner, H. L., van Etten, J., Firth, D., & Kosmidis, I. (2020). Modelling rankings in R: The PlackettLuce package. *Computational Statistics*, 35, 1027–1057. <https://doi.org/10.1007/s00180-020-00959-3>
- UBOS. (2018). *Uganda agricultural survey*. https://www.ubos.org/wp-content/uploads/publications/06_2020AAS_2018_Report_Final_050620.pdf
- UBOS. (2019). *Uganda agricultural survey*. https://www.ubos.org/wp-content/uploads/publications/04_2022AAS2019_Report.pdf
- van Etten, J., Abidin, E., Arnaud, D., Brown, E., Carey, E., Laporte, M.-A., López-Noriega, I., Madriz, B., Manners, R., Ortiz-Crespo, B., Quirós, C., de Sousa, K., Teeken, B., Tufan, H. A., Ulzen, J., & Valle-Soto, J. (2020). *The tricot citizen science approach applied to on-farm variety evaluation: Methodological progress and perspectives* (RTB working paper No. 2021-2). CGIAR Research Program on Roots, Tubers and Bananas (RTB). <https://doi.org/10.4160/23096586RTBWP20212>
- van Etten, J., Beza, E., Calderer, L., van Duijvendijk, K., Fadda, C., Fantahun, B., Kidane, Y. G., van de Gevel, J., Gupta, A., Mengistu, D. K., Kiambi, D. A. N., Mathur, P. N., Mercado, L., Mitra, S., Mollel, M. J., Rosas, J. C., Steinke, J., Suchini, J. G., & Zimmerer, K. S. (2019). First experiences with a novel farmer citizen science approach: Crowdsourcing participatory variety selection through on-farm triadic comparisons of technologies (tricot).

- Experimental Agriculture*, 55(S1), 275–296. <https://doi.org/10.1017/S0014479716000739>
- van Etten, J., de Sousa, K., Aguilar, A., Barrios, M., Coto, A., Dell'Acqua, M., Fadda, C., Gebrehawaryat, Y., van de Gevel, J., Gupta, A., Kiros, A. Y., Madriz, B., Mathur, P., Mengistu, D. K., Mercado, L., Nurhisen Mohammed, J., Paliwal, A., Pè, M. E., Quirós, C. F., ... Steinke, J. (2019). Crop variety management for climate adaptation supported by citizen science. *Proceedings of the National Academy of Sciences*, 116(10), 4194–4199. <https://doi.org/10.1073/pnas.1813720116>
- Weltzien, E., Rattunde, F., Christinck, A., Isaacs, K., & Ashby, J. (2019). Gender and farmer preferences for varietal traits. In I. Goldman (Ed.), *Plant breeding reviews* (pp. 243–278). John Wiley & Sons. <https://doi.org/10.1002/9781119616801.ch7>
- Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. Springer-Verlag. <https://ggplot2.tidyverse.org>
- Witcombe, J. R., Joshi, A., Joshi, K. D., & Sthapit, B. R. (1996). Farmer participatory crop improvement. I. Varietal selection and breeding methods and their impact on biodiversity. *Experimental Agriculture*, 32(4), 445–460. <https://doi.org/10.1017/S0014479700001526>

- Zeileis, A., Hothorn, T., & Hornik, K. (2008). Model-based recursive partitioning. *Journal of Computational and Graphical Statistics*, 17(2), 492–514. <https://doi.org/10.1198/106186008x319331>

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