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Breeding dryland legumes for diverse needs: Using multi-location trials and participatory variety selection to develop farmer-preferred groundnut (*Arachis hypogaea*) and pigeon pea (*Cajanus cajan*) varieties

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Abstract

Agriculture in Sub-Saharan Africa is primarily smallholder-based, employing up to 60% of the workforce and accounting for 14%–23% of GDP. The smallholders grow crops for domestic and off-farm markets, necessitating crop variety attributes for which trait mismatches may limit adoption. Indeed, improved variety adoption is varied and limited, especially for self-pollinated crops, in part due to the mismatch in characteristics of commercialised varieties. The international research community leads breeding of varieties for under-invested crops, especially legumes. These varieties are often resilient and productive, but the dynamisms in target agri-food systems may limit their relevance. Gaining a better understanding of the trait profiles that crop value chain actors consider will increase their adoption. This study combined multi-location trials and participatory variety selection (PVS) of pigeon pea and groundnut across different environments to evaluate the efficacy of both processes in the breeding of desired varieties. The present study shows improvement in the new materials regarding performance and preference by farmers. Additionally, PVS showed that men prioritised productivity and market-enhancing traits, whereas women ranked food security traits highest.

KEYWORDS
gender disparities, groundnut, participatory breeding, pigeon pea, PVS, trait prioritisation

1 | INTRODUCTION

Agricultural production in most of Sub-Saharan Africa (SSA) is done under smallholder-based production systems that employ more than 60% of the workforce and accounts for between 14% and 23% of GDP (Goedde et al., 2019; OECD/FAO, 2016). Given this central role in the economy, smallholder production systems are critical for feeding and growing Africa's economies. Smallholder production systems vary in size ranging from 0.5 to 2 ha (Eastwood et al., 2010; Gollin, 2014) but are diverse, involving several crops and livestock enterprises. Enterprise diversification in these systems secures harvests and livelihoods against uncertainties common in under-resourced agriculture (Gollin, 2014; Makate et al., 2016; McGuire & Sperling, 2013; Okori et al., 2022; Peng et al., 2020). Most farmers, including smallholders, see new agricultural technologies as a means of unlocking productivity for their subsistence (Makate et al., 2016; Piesse & Thirtle, 2010). Although many improved plant varieties with the ability to increase productivity have been commercialised, their adoption has been limited and varied, especially among smallholder farmers (Muzari et al., 2012; Simtowe et al., 2019; Tsusaka et al., 2016). Simtowe et al. (2019) and Porteous (2020) have attributed such relatively lower rates of technology adoption, especially by smallholder farmers in SSA, to among others, the poor match between traits present in the new varieties and the farming requirements, dysfunctional input and output markets, and low purchasing power by farming communities. Inexpensive agricultural technologies that carry low-risk premiums can be easily adopted by smallholder farmers (Kakumanu et al., 2016; Wiggins et al., 2010).

Plant breeders have been aware of the variety–farmer requirement mismatch challenge and have responded by implementing inclusive breeding approaches to identify farmer-preferred traits and varieties as part of the solution (Ceccarelli et al., 2009; Louwaars, 2018). Participatory variety selection is a popular framework for undertaking such inclusive breeding, which has recently been expanded to include users of crop products within respective value chains (Bishaw & van Gastel, 2009; Ceccarelli & Grando, 2020). Indeed, crop breeding programme operations are currently underpinned by demand-led breeding, in which variety of product profiles based on market needs guide variety development and deployment. Despite these improvements, there are still challenges, as crop breeding in many developing economies depends on materials from international research. National research programmes in most cases only conduct final adaptation and commercialisation tests. Such materials may therefore not have the requisite farming and end-use traits, limiting adoption and enhancing disadoption. Depending on the crop and region of Africa, it has been estimated that up to 80% of crop harvest is consumed and or sold to local peri-urban and urban communities, signifying their role as a key psychographic market segment (Gollin, 2014). Such a large domestic demand by farm-households and peri- and urban populations increases the portfolio of required traits in improved crop varieties. Furthermore, demand for nearly uniform crop produce, especially for food processors, requires that breeders develop varieties with similar attributes. In view of the two market requirements, domestic consumption and non-agricultural markets (processing and trade markets), breeders must take up the challenge of developing varieties that meet these market needs. In many cases, plant breeding programmes combine as many 'favourable traits' as possible into a genotype and or a few genotypes to maximise their presence (Louwaars, 2018). These materials are typically developed based on key adaptability traits such as yield and resilience to biotic and abiotic as the basic traits. Farmers are thus presented with candidate materials that have a priori determined traits by researches from which to select their preferences. This process could be improved by engaging farmers in the selection of candidate parental material for their agro-ecological and food system needs from a diverse pool of genotypes but is compounded by the logistics of doing so (Ceccarelli, 2009).

ICRISAT's centrally bred crops (groundnut, pigeon pea, chickpea, sorghum and millets), are commonly shared with national breeding programmes that receive test kits comprising five-to-ten candidate lines or more, depending on the crop species for national performance trialling. However, the limited diversity of varieties adopted may be an indicator of their non-preference by farmers and consumers, because they do not have one or few traits of their interest. For example, in Malawi, impact assessments of ICRISAT's groundnut breeding activities, showed predominance of two varieties *CG7* and *Nsinjiro* against a backdrop of five released varieties, with an old variety *Chalimbana* still popular (Tsusaka et al., 2016). Similarly, whereas five new pigeon pea varieties had been released in Malawi, the landrace *Mthawajuni* was still popular (Simtowe et al., 2010). Gaining a deeper understanding of requisite traits by crop value chain actors can enhance their adoption and utilisation. The study examined the effectiveness of participatory variety selection (PVS) across multi-locations to breed pigeon pea (*Cajanus Cajan* [L.] Huth) and groundnut (*Arachis hypogaea L*) for smallholder cereal-legume-based agri-food systems in Malawi, Zambia and Tanzania. The smallholder farmers represented different niches of their respective agri-food systems and were the proxy to other market segments, particularly the food and food processing segment. Acceptability and performance of the improved lines by farmers, whose breeding had been informed by earlier PVS showed progress with the best-rated materials carrying desirable traits. The results also show gender influences on preferred traits, signifying the role of women in the production of these crops. The implications of these findings for breeding of market-required traits are discussed.

2 | MATERIALS AND METHODS

2.1 | Description of study areas

2.1.1 | Malawi

On-station experiments were conducted at Chitedze Research Station, which is located in the mid-altitude agro-ecology, to identify candidate materials for adaptability and commercialisation in East and Southern Africa by private and public sector agencies. Groundnut was bred at ICRISAT-Malawi, whereas pigeon pea was bred at ICRISAT-Kenya. On-farm trials were conducted in all three agroecologies, that is, low altitude (200–700 m above sea level); mid-altitude (650–1300 m above sea level) and high altitude (>1300 m above sea level) (Monyo et al., 2012; Okori et al., 2022), in four districts (Supplementary Table 1).

2.1.2 | Tanzania

On-station trials were conducted at Tanzania Agricultural Research Institute-Hombolo in the Dodoma region (Supplementary Table 1). On-farm trials were conducted in the districts of Kongwa, Kiteto and Iringa, which represent three agro-ecologies (Supplementary Table 1). Kongwa is one of the seven districts in the Dodoma region and has typical semi-arid conditions. Kiteto district is located in the Manyara region and has sub-humid to semi-arid weather conditions. The amount of rainfall received in the Kongwa and Kiteto districts between 2013 and 2016, the study period, averaged 202.4 mm per annum. Further testing was done in the Iringa district, (found in the Iringa region), which lies at an altitude of 1550 m above sea level and receives up to 750 mm of rain fall in good years.

2.1.3 | Zambia

On-station trials were conducted at Chiawa in Kafue district, Golden Valley Agricultural Trust—Chisamba and Mount Makulu at Chilanga in Lusaka Province; Mambwe in Masumba district and Msekera in Chipata district of Eastern Province as well as Misamfu in Kasama district, Northern Province (Supplementary Table 1). The research stations are located within the three major agro-ecologies of Zambia, namely, regions I, II, and III agro-ecologies (Table 1). On-farm trials were conducted only in the eastern province, being the major legume-producing region of the country. The trials were conducted in the districts of Chipata, Msekera, Lundazi, Katete and Petauke (Supplementary Table 1).

2.2 | Genetic materials

For each crop, genotypes improved mostly for production traits such as grain yield and in some cases market preferred traits were used (Supplementary Table 2). Three types of materials were used for the PVS. The first type of materials were those whose breeding had been informed by previous PVS as was the case with groundnut, short duration and medium pigeon pea. The second type of materials included varieties commercialised in the same country, but introduced into a new agro-ecology where they had not been grown before, as was the case for pigeon pea in Tanzania. The third type of materials comprised varieties commercialised in other countries of the region but not available in the test country, as was the case with medium-duration pigeon pea in Zambia. In general, the control commercial checks in some cases varied because they were not released in all the study countries. Similarly, test genotypes in some cases varied across the study countries due to differences in production and market requirements that influence the type of varieties commercialised. In Zambia, in order to fast track the variety release of groundnut and pigeon pea after nearly a decade, elite materials tested in Malawi's medium altitude agro-ecology that has similar agro-ecological characteristics as eastern Zambia's Agroecological zone (AEZ) II were evaluated on-farm in Chipata, Petauke and Lundazi. The materials had been developed based on PVS on groundnut conducted by ICRISAT over the years that had documented the market-preferred traits.

TABLE 1 Performance of eight medium-duration Virginia groundnut lines at three research stations in Malawi during the 2012–2013 cropping season.

	Low altitude agro-ecology		Mid-altitude agro-ecology
	Grain yield (kg/ha)		Chitedze
Genotypes	Chitala	Ngabu	(kg/ha)
ICGV-SM 01708	1450	1341	1430
ICGV-SM 01724	1345	1363	1555
ICGV-SM 01728	1360	1310	1225
ICGV-SM 01731	1950	1450	2545
ICGV-SM 08501	1844	1999	2355
ICGV-SM 08503	1521	1364	1350
ICGV-SM 90704 ([a]CM 1)	1294	1981	1850
Chalimbana 2005 ([a]CM 2)	895	880	1400
***p* Value**	.003	.083	.004
[b]L.S.D (*p* ≤ .05)	350.1	713.1	564.3
[c]CV %	10.4	21.2	14.3

[a]Commercial check.
[b]Fisher's protected least significant difference test.
[c]Coefficient of variation.

2.2.1 | Groundnut

The genotypes were evaluated for adaptability with experiments arrayed in a randomised complete block design. The improved genotypes tested were considered based on their maturity period, that is, medium-duration Virginia genotypes and short-duration Spanish and Valencia genotypes (Supplementary Table 2). Virginia genotypes are the major commercial varieties of groundnut grown in Eastern and Southern Africa followed by the Spanish and Valencia genotypes. Inclusion of Spanish and Valencia genotypes was done to cope with changes in the targeted cropping systems, where groundnut is planted after the main staples, thus missing the first rains. Missing the first rains exposes crops to shorter growing seasons and may lead to yield loss. Commercial varieties (Supplementary Table 2) were included as controls against which both performance and preference assessments were done. The improved materials were resistant to major endemic diseases of groundnut in most agro-ecologies of East and Southern Africa namely the groundnut rosette virus disease (GRD), early leaf spot (*Cercospora arachidicola* Hori, Teliomorph: [*Mycosphaerella arachidis*], Deighton) and groundnut rust (*Puccinia arachidis* Speg).

In Malawi, Virginia and Spanish elite materials were evaluated on-station and on-farm (Supplementary Table 2). The Virginia commercial checks included ICGV-SM 90704, commercialised in 2000 and very tolerant to the destructive groundnut rosette disease. Chalimbana 2005 the second Virginia commercial check was commercialised in 2005 and has large seed (bold kernels). The Spanish commercial checks were JL 24 (Kakoma) and ICGV SM 99568 (Chitala), commercialised in 2000 and 2005, respectively.

In Tanzania, one Virginia test line and five Spanish test lines were tested on-station at Hombolo and on-farm in five villages of Moleti, Laikala, Mlali and Chitego in Kongwa and Njoro and Kiperesa in Kiteto district (Supplementary Table 2). The commercial check was ICGMS 33 that commercialised in 2002. The Spanish variety ICGV SM 99568 commercialised in Malawi, Zimbabwe and Mozambique was used as a comparator commercialisation in all the study countries. It was first commercialised in Malawi in 2005 and subsequently in other countries. It is an early maturing material that is preferred by farmers in east and southern Africa for earliness, especially in drought-prone environments.

In Zambia, the final test lines included two Virginia genotypes, two Spanish genotypes and one Valencia genotype (Supplementary Table 2). The Virginia commercial check ICGV SM-83708 (MGV 4) was commercialised in 1990 and was then the most popular variety, whereas the Spanish commercial check was JL 24, commercialised in 1999. It was also the check for Valencia material since they fall in the same maturity group, and no Valencia material had been commercialised in the country in the recent past. No major groundnut variety releases had occurred since then.

2.2.2 | Pigeon pea

Test materials belonging to three maturity groups (Silim et al., 2006) based on their phenology, that is, medium duration (takes 120–160 days to flower and 170–190 days to reach physiological maturity) and short duration (takes 90–100 days to flower and 130–150 days to reach physiological maturity) and long duration (takes >160 days to flower and 240 days to reach physiological maturity) were used in the study (Supplementary Table 2). These materials were evaluated in response to changes in pigeon pea production systems, that increasingly, prefer varieties that mature in less than 6 months. The older pigeon pea varieties, commercialised in the target countries, are long-duration materials used as commercial checks in the study and are therefore prone to late-season drought, an increasingly frequent phenomenon. In this study, the long-duration pigeon pea variety ICEAP 00040 was used as a commercial check in all the target countries. The medium-duration commercial checks varied being the focus of pigeon pea breeding programme to replace the long duration that cannot perform well in the dynamic weather conditions characterised by drought. The most recent releases in the respective countries were used as commercial checks. In Malawi, ICEAP 00557 was the commercial check first commercialised in 2009. It was also the commercial check in Tanzania and was commercialised in 2015. In Zambia, the medium-duration commercial check was ICEAP-00554 the most popular variety commercialised in 2016. Short-duration materials have limited commercialisation in the target countries but are suitable for the production of pigeon pea vegetable, an important product among urban and rural pigeon pea consumers. As such, the seed yield for the short duration is also important since the green seed is the one used as a vegetable. In general, all the improved materials had cream-coloured kernels, the market-preferred trait, and are resistant to fusarium wilt (*Fusarium udum* Butler), a devastating challenge to its production. They are also tolerant to leaf spots (*Mycovellosiella cajani* (Henn.) Rangel ex Trotter (synonym *Cercospora cajani* Henn). The land race *Mthawajuni* is multi-coloured kernels (cream and red/brown speckled), and is tolerant to the pod borer (*Helicoverpa armigera*), the most important pest of the crop in east and southern Africa (Hillocks et al., 2010).

2.3 | Treatment structure: Number and choice of treatments

2.3.1 | Researcher managed trials

The trials were conducted both on-station and on-farm. Initially, large adaptability trials involving a minimum of 20 entries, that comprised materials belonging to the respective maturity groups were evaluated on-station in Malawi at Chitedze Research Station (data not shown). The breeding of these candidate lines had been informed by PVS in previous breeding cycles of both pigeon pea and groundnut. The large experiments were established following an alpha lattice experimental design with two replications. These evaluations were used to identify up to seven lines for commercialisation by especially public breeding programmes, the main route for release in east and southern Africa, especially for crops that are underinvested by private seed companies. The different candidate materials were selected for each of the three countries guided by the specifications of a popular market segment.

The most popular commercial varieties and or land races were used checks. These materials were evaluated both on-station and on-farm at experimental sites managed by researchers, to confirm their adaptability in each country as described below for each crop.

2.3.2 | Groundnut

The evaluations of the selected test lines were conducted in Malawi, Zambia, and Tanzania using the same protocol. Briefly, experiments were established following a randomised complete block design, in 10-m-long, six-row plots spaced at 60 cm between rows and 10 cm between each planting station. The net plot area consisted of the four central rows, excluding 0.5 m from each end, with a total area of 12 m^2. Recommended groundnut agronomy was used to ensure a clean and productive crop (Nigam, 2015; Okori et al., 2019). In Tanzania, the experiments were conducted for 3 years between 2013–2014 and 2015–2016 cropping seasons, and from 2012–2013, 2013–2014 and 2014–2015 in Malawi and Zambia. These trials included all the materials included in the farmer-managed trials. The researcher designed and managed trials were the reference farmer training site considered as the mother plot in the mother–baby on-farm experimentation approach (Snapp, 2002). A group of farmers (45–50), hosted a mother trial, which also acted as a learning centre for other farmers. The mother trial is designed and managed by the researcher and has all the genotypes in the study, whereas the baby trial has a subset of the test genotypes and is managed by the farmer.

2.3.3 | Pigeon pea

The evaluations were conducted in Malawi, Tanzania and Zambia. These evaluations were conducted between the 2017–2018, 2018–2019 and 2019–2020 cropping seasons, to support the commercialisation of the new medium and short duration materials in Malawi, whereas in Tanzania and Zambia, they were conducted from 2014–2015, 2016–2017, 2017–2018 and 2019–2020 cropping seasons.

Test materials were planted in 10-row plots per entry, that was 10 m long, 0.9 m between rows and 0.9 m between planting stations. After germination, each planting station was thinned to two plants. Both on-farm and on-station trials included selected entries from adaptability trials conducted in the 2016–2017 cropping season. A setup similar to the one described for groundnut was used to establish on-farm evaluations, with up to 50 farmers hosting a trial at the test sites.

2.3.4 | On-farm evaluation

These trials were conducted to enable farmers to select genotypes that are well adapted to their agro-ecological and cropping system needs that capture market-preferred traits. The mother-baby technology evaluation approach was used (Okori et al., 2022; Snapp, 2002). The mother trials were researcher-managed as described above but established within farming communities, whereas the baby trials were farmer-managed. The baby trials were used to promote the candidate genotypes and their improved agronomy. They also supported the identification of traits of interest by farmers. The baby trials had two farmer-selected improved genotypes (a subset of materials included in researcher-managed trials), and a commercial check or a land race. Baby trials were hosted by a maximum of three farmers and were located within a maximum radius of 5 km from the mother trial in each village. The crops were respectively established in six-row plots as described for the researcher-managed trials. Crop management to maturity was supported by an agricultural extension worker, trained lead farmers, and ICRISAT staff, who monitored the trials and provided advice as required. This technical team recorded comments regarding variety performance and trait preferences during the crop-growing cycle.

Participatory variety evaluations. PVS were conducted during field days organised at the researcher-managed field trial sites. Field days took place at flowering or physiological maturity. Prior to the PVS of varieties, farmers were guided on the objective of the exercise by the researchers, and a focus group discussion was subsequently held to identify and prioritise key traits including those generated during the baby trials, to be used in the selection process. The focus group discussions were used to collect information on the major role/s of the target crops in their agri-food systems/community and key production adaptation requirements for their agro-ecologies. In both crops, characteristics associated with crop production (input traits), and those associated with market/utilisation (output traits) were identified and prioritised through open voting for a trait of preference. Voting was used to capture a variety of ratings of illiterate farmers who were the vast majority. During the voting, participants were divided by gender to capture peculiar traits that underpin gender responses to the adoption and utilisation of the focus crops. The traits were subsequently ranked based on the total number of votes received. Up to six ranked traits were subsequently used for PVS, with farmers allowed to use any of them for variety selection. Usually, farmers used any four important traits from the prioritised trait list. A total of 1247 (510 women and 737 men) farmers were involved in the participatory variety evaluation in Malawi; 1757 (587 women and 1170 men) farmers in Zambia and 736 (452 women and 384 men) farmers in Tanzania.

2.4 | Data collection

2.4.1 | Groundnut

Data from researcher-managed trials were collected on the initial plant stand (counts per plot), final plant stand (counts per plot), early leaf spot (severity rating using a scale of 1–9), groundnut rosette disease (incidence per plot) and days to 75% flowering. The net plot from which data were collected included the two middle rows out of the four rows with 20 plants per row. Data were collected on 30 plants on-station and 36 plants on-farm. All assessments were done as described by Nigam (2015) and Okori et al. (2019). At harvest, data were collected on haulm yield, pod yield and kernel yield and 100 g seed weight. Grain yield data per plot was converted to kg/ha using the following formula (Yield in grams × 10,000/(Net plot area × 1000 for kg)). Additional output traits data such as ease of shelling, taste of fresh grain, and seed size (bold or small seeded) were collected during PVS. These output traits were rated using a qualitative scale of 1 to 5, where 1 is the lowest score, which is equal to the highest preference, and 5 is the highest score, which is equal to the least desirability. Each participant who could write was provided with a score sheet to record their rating during the PVS. Where the majority of PVS participants could not read or write, a voting system was used. In such cases, farmers indicated their preferred traits and subsequently used them to select (vote) for the best genotypes by standing next to test line. The test line that had the largest number of votes was selected as the most preferred genotype. Participants also provided their overall rating for each candidate genotype. For each trait, the mean score of participant evaluations was obtained and used in the matrix ranking of genotypes based on the selection criteria ratings.

2.4.2 | Pigeon pea

Adaptability assessments (pest and disease tolerance and grain yield) were performed as described by Silim et al. (2006). Briefly, data were collected during the crop growth cycle from two-row plots (on-station) and three-row plots (on-farm), that constituted the net plot, excluding plants located 0.5 m from the end of each row. Data was collected from 10 plants on-station and 15 plants on-farm largely due to better management of on-station trials. Data were collected on the initial plant stand, days to 50% flowering, harvest stand count, leaf spot (scores using 1–9), Fusarium wilt incidence (proportion of infected plants per net plot) and pod damage rated using a 1–5 scale where 1 = highly resistant with limited pod damage and 5 = damage to nearly all developing pods evidenced by shrivelled pods and or several entries and exit pest-holes on pods). At harvest, data were collected on dried pod weight (kg per net plot that consisted of two rows and three with about 10 to 15 plants on-station and on-farm, respectively), 100 seed weight (g) and grain yield (kg per net plot number). Grain yield data per plot was converted to kg/ha as described for groundnut. In cases, were the crop was not physiologically mature, especially during PVS, the potential yield was assessed using plant aspect with respect to podding using a 1–5 scale, where 1 = good podding and 5 = poor podding. The traits used included pod size, grain size (bold or small seeded) and the number of branches per plant. PVS was conducted as described for groundnut for the two farmer types, that is, those who can read and write and those who cannot do so.

2.5 | Data analysis

2.5.1 | Researcher managed trials

Quantitative data were subjected to analysis of variance (ANOVA) using GenStat, 22nd edition (https://vsni.co.uk/software/genstat), to assess varietal differences and interaction effects of various factors on variety performance. Tests for homogeneity of error variance across locations were done (Steel et al., 1997). For parameters with homogeneous error variances, combined data analysis was performed, and for parameters with heterogeneous error variances, ANOVA was performed separately for each location. Fixed effects included varieties and test locations, whereas replications were treated as random effects. Where significant differences among variables were found, means were compared using Fisher's protected least significant difference (LSD) at a 5% level of probability or using the standard error of the difference of means (SED). As appropriate, the Finlay and Wilkinson modified joint regression analysis was performed to confirm genotype sensitivity to environments (locations and cropping years).

2.5.2 | On-farm variety evaluations

Only data assembled from on-farm researcher-managed trials were analysed using ANOVA, and their means were compared as described for researcher-managed trials. PVS data were pooled for multi-year assessments and rankings of the varieties were derived based on mean scores. Pigeon pea is a crop whose multiple roles in east and southern Africa, dryland agri-food systems are variable and are therefore suitable for studying changes in demand characteristics of producers and other value chain actors. In this paper we investigated the role of pigeon pea on food security and income, being a cash crop, and on trait prioritisation by farming communities. The production agro-ecology was treated as the main block, whereas test varieties and their role in the value chains (as food or cash crop or both) were treated as factors. ANOVA was implemented in GenStat. PVS ratings of traits associated with the role of the crop as a food and or cash crop were collected for both groundnut and pigeon pea and used to infer their impacts on trait prioritisation for different uses of either crop product.

3 | RESULTS

3.1 | Researcher managed trials

3.1.1 | Performance of groundnut test lines

In Malawi, significant ($p \leq .05$) differences in the yield of improved medium-duration materials were observed in Chitedze and Chitala research stations (Table 1). Grain yield of test materials was higher in the mid-altitude compared to that in the low altitude of Malawi. ICGV-SM 01731 was the best-performing material at Chitedze, located in the mid-altitude AEZ, with a grain yield of 2545 kg/ha. It was also the best material at Chitala, located at a low altitude with a grain yield of 1950 kg/ha. The difference in grain yield between the best medium duration material ICGV-SM 01731 and the two commercial checks at Chitala was 1055 and 656 kg, respectively.

The grain yield for Spanish materials was lower than for Virginia materials (Supplementary Table 3). There were significant ($p \leq .05$)

differences in grain yield among the genotypes at the Ngabu research station (Supplementary Table 3). At Chitedze, ICGV-SM 99551 was the best performer, producing 249 kg/ha above the commercial check. While at Ngabu, another low-altitude AEZ and highly stressed environment, ICGV-SM 99551 was still the best material, producing 575 kg/ha more than the commercial check. At Chitala, ICGV-SM 99567, was the best-performing material, with a grain yield advantage of 273 kg/ha over the commercial check.

In Tanzania, over two cropping seasons (2013–2014 and 2014–2015), that had relatively better rains, ICGV-SM 02724 the only Virginia entry produced 421 kg/ha above the best Spanish line ICGV-SM 05650 and 1080 kg/ha above the commercial check (Table 2). The best Spanish entry ICGV-SM 05650 out yielded the commercial check by a factor of 1.6 (659 kg/ha). The earliest maturing line ICGV-SM 99568 had stable grain yield during the 2013–2014 and 2014–2015 cropping seasons, with yields above one ton per hectare. The grain yield difference between the best and least performing Spanish entries was 659 kg in 2013–2014, the best year, and 71 kg in 2015–2016, the most constrained year, an indication of genotype by environment interaction effect (Table 2).

In Zambia, during the 2013–2014 cropping season, grain yields were lowest in AEZ 1 and highest in AEZ 2, which also received relatively more rainfall. Over the study period, performance in AEZ 1 was higher during the 2014–2015 cropping season, and fairly stable in AEZ 2, especially at Msekera research station (Table 3). Grain yield of the least-performing material, ICGV-SM 01728 was 302 kg/ha at Masumba (AEZ 1) and was over four-fold higher at Msekera (AEZ 2), producing 1323 kg/ha (Table 3). Genotype performance at other AEZ II sites (Kasama and Mansa) that receive relatively more rainfall was varied and in some cases higher than the grain yield of the same materials planted in other locations within the same AEZ. During the second study cropping season (2014–2015), The materials consistently performed better at Msekera, compared to Masumba. Msekera, therefore, was the most optimal testing site that supported expression of full genetic potential of the candidate materials. The commercial check MGV4 was highly adapted, performing better than some of the new test materials (Table 3).

Significant differences ($p \le .05$) in grain yield were observed in trials conducted at Masumba (AEZ 1) in 2013–2014 and at Kabwe (AEZ 2) in 2014–2015 among the Spanish genotypes studied (Supplementary Table 4). Performance of the materials at other AEZs was not significantly different ($p \le .05$) over the two study years. However, within each agro-ecology, differences in performance were observed, the Kabwe site having the lowest grain yield across the two study cropping seasons. Grain yield was markedly higher during the 2014–2015 cropping season, with grain yields increasing by 471.7 kg to 601.8 kg/ha for the least productive materials ICGV-SM 00530 and ICGV-SM 08513, respectively, across the two cropping seasons (Supplementary Table 4). Overall, the highest grain yield was obtained in AEZ 2 and AEZ 3 test sites the best performance occurring at Msekera (Supplementary Table 4). Msekera research station is found in the eastern province, a major groundnut producer region of Zambia.

3.1.2 | Performance of pigeon pea test lines

Malawi

There were significant differences ($p \le .05$) in yield among the pigeon pea genotypes evaluated to replace the long-duration pigeon pea material with medium duration material during the 2008–2009 cropping season (Supplementary Table 5). Three out of five new medium-duration materials out-performed the popular land race *Mthawajuni* (Supplementary Table 5), with yield differences between ICEAP 00557 the best performer and *Mthawajuni* of 287 kg/ha. The medium-duration lines ICEAP 00557 and ICEAP 01514/15 where subsequently recommended for commercialisation and have since been grown in Malawi. During the 2018–2019 cropping season, eight new medium (3) and short (5) duration materials were evaluated to

TABLE 2 Grain yield performance of medium and short duration groundnut genotypes on-station at TARI-Hombolo over three cropping seasons.

		Grain yield (kg/ha)		
		Cropping seasons		
Genotypes	Botanical group	2013–2014	2014–2015	2015–2016
ICGV-SM 01513	Spanish	1166	1191	762
ICGV-SM 02724	Virginia	2025	1840	1185
ICGV-SM 03519	Spanish	1316	1256	852
ICGV-SM 05650	Spanish	1604	1435	870
ICGV-SM 99568	Spanish	1155	1074	799
Pendo ([a]CM)	Spanish	945	858	–
***p* Value**		<.001	<.001	<.001
[b]L.S.D ($p \le .05$)		449	274	355
[c]CV %		14	9	18

[a]Commercial check.
[b]Fisher's protected least significant difference test.
[c]Coefficient of variation.

TABLE 3 Grain yield performance of five Virginia genotypes on-station across three agro-ecologies of Zambia during the 2013–2014 and 2014–2015 cropping seasons.

	2013/2014 season					2014/2015 season		
	Agro-ecological zone (AEZ)					Agro-ecological zone (AEZ)		
	1 Masumba	2 Msekera	2 Kabwe	3 Kasama	3 Mansa	1 Masumba	2 Msekera	3 Kabwe
Genotypes	Grain yield (kg/ha)					Grain yield (kg/ha)		
ICGV-SM 01728	302	1323	1302	1418	813	1097	1416	818
ICGV-SM 06729	475	1700	1694	699	1321	992	1329	676
ICGV-SM 07599	341	1344	2137	1121	780	1124	1389	1120
ICGV-SM 08503	322	1410	1164	1108	733	1213	1709	528
MGV 4 ([a]CM)	381	1031	1446	1544	711	1012	1610	525
p Value	.174	.132	.067	.595	.091	.841	.848	<.001
[b]L.S.D ($p \leq .05$)	153.4	497.9	685.5	1313.2	485.3	478.1	911.3	95.8
[c]CV %	23.2	20.1	24.3	55.8	30.2	24.2	32.5	7.2

[a]Commercial check.
[b]Fisher's protected least significant difference test.
[c]Coefficient of variation.

TABLE 4 Performance of new medium duration pigeon pea genotypes across three research stations of Malawi during the 2018–2019 and 2019–2020 cropping seasons.

	2018–2019 cropping season					2019–2020 cropping season		
Genotypes	Chitala	Chitedze	Makoka	Mean	Genotypes Chitedze	Makoka	Chitala	Mean
ICEAP 01150/1	1600.0	1733.3	1866.7	1000.0	2400.0	2300.0	2180.0	2224.21
ICEAP 00979/1	1466.7	1413.3	1400.0	1733.3	1997.1	1905.0	1545.8	1815.97
ICEAP 01147/1	1666.7	893.3	933.3	1164.4	1711.9	1876.5	1996.0	1861.46
[b]ICEAP 00557 ([a]CM)	933.3	1000.0	1066.7	1426.7	2150.4	1855.9	2666.3	2293.33
[c]*Mthawajuni*	800.0	800.0	533.3	711.1	1954.1	2100.2	2100.2	2051.49
p Value					.006			.086
[d]SED					533.5			345.5
[e]CV %					45.2			30.5

[a]Commercial check.
[b]Medium-duration commercial check variety.
[c]Local highly adapted land race that is tolerant to pod borer damage.
[d]Standard error of the difference of means across sites.
[e]Coefficient of variation.

increase the variety of options for farming communities. Significant ($p < .01$) differences in yield were observed among the lines tested.

Ten years later, trials conducted to replace the older varieties identified three new medium-duration materials ICEAPs 01150/1, 01147/1 and 00979/1, as the best performers (Table 4). These new materials had grain yield of up to 1800 kg/ha at Chitedze with mean severity ratings for pod borer damage of 1.06 for ICEAP 01150/1, 1.48 for ICEAP 01147/1 and 1.69 for ICEAP 00979/1, compared to 1.75 for ICEAP 00557 the commercial check and 2.5 for Mthawajuni the land race. During the 2019–2020 cropping season, significant differences ($p \leq .05$) in the performance of the same medium duration test genotypes were observed with ICEAP 00979/1 and ICEAP 01150/1 being the best performers. Grain yield at Chitala, Chitedze and Makoka were 1648.2, 1555.6 and 1704 kg/ha, respectively. In the subsequent cropping seasons, performance was comparable but with higher grain yield during the 2019–2020 cropping season (Table 4). The Finlay and Wilkinson modified joint regression analysis showed that the new test lines ICEAP 00979/1 (−.0698) and ICEAP 01150/1 (.2133), along with the land race Mthawanjuni (.1592), were least sensitive compared to the commercial check ICEAP 00557 (1.3153) that was most sensitive.

In the earlier testing, Makoka and Mulanje (in the high-altitude agro-ecology) were the best test environments for short-duration pigeon pea. The best performance was at Makoka research station, during the 2017–2018 cropping season, where ICPL 87091, ICEAP 01106/1 and ICEAP 01284 produced grain yields of 1665, 1355.2

and 1323.9 kg/ha, respectively. The yield difference compared to the commercial check ICEAP 01514/15 was 351, 141 and 109 kg/ha, respectively.

The 2018–2019 cropping season performance followed a similar trend (Table 5). ICEAP 87091 was the best genotype at Chitala producing 2866.7 kg/ha of grain. At Chitedze, ICEAP 00612 was the best performer producing 2666.7 kg/ha of grain, and at Makoka, ICEAP 01106/1 was the best genotype, producing 2733.3 kg/ha of grain. During the 2019–2020 cropping season, ICEAP 87091 was again the best genotype at Chitala, producing 2166.7 kg of grain. At Chitedze, ICEAP 01284 was the best performer, producing 1927.3 kg/ha of grain and at Makoka ICPL 87091 was the best test line, producing 1767.6 kg/ha of grain. Across the two study years, with the exception of ICEAP 00612 performance at Chitedze, the three test lines ICPL 87091, ICEAP 01106/1 and ICEAP 01284 were the best performers, with yield differences of up to 632.8 kg during the 2018–2019 cropping season and 469 kg in 2019–2020 cropping season at Makoka (Table 5). The Finlay and Wilkinson modified joint regression analysis showed that ICEAP 00612 was the least sensitive (.5136), whereas ICPL 87091 was the most sensitive (1.3215). The test line ICEAP 01101/2 was the second least sensitive genotype with a value of .6940.

Tanzania

Significant differences ($p \le .05$) in the performance of candidate pigeon pea varieties in the semi-arid districts of Kongwa and Kiteto were observed during initial evaluation studies (Table 6). In the first cropping season, all test lines outperformed the commercial check. The best entry out yielded the landrace by factors of 5 and 2 in the Kiteto and Kongwa districts, respectively. The least adapted test material out yielded the land race by a factor of 2 in both districts. Across the three study years, medium-duration materials, (ICEAP 00554 and ICEAP 00557), performed better than the long-duration variety ICEAP 00040, especially in the 2019–2020 cropping season. For example, in Iringa, they performed better by 433 and 425 kg/ha for ICEAP 00554 and ICEAP 00557, respectively (Table 6). The Finlay

TABLE 5 Performance of new short duration pigeonpea genotypes across three research stations of Malawi during the 2018–2019 and 2019–2020 cropping seasons.

	2018–2019 cropping season				2019–2020 cropping season			
Genotypes	**Chitala**	**Chitedze**	**Makoka**	**Mean**	**Chitala**	**Chitedze**	**Makoka**	**Mean**
ICEAP 00612	2333.3	2666.7	2373.3	2457.78	1166.1	1134.2	1222.2	1174.15
ICEAP 01101/2	1666.7	2133.3	2133.3	1977.78	1360.0	1000.9	1028.2	1129.7
ICEAP 01106/1	2533.3	2266.7	2733.3	2511.11	1066.5	1254.6	1824.1	1381.71
ICEAP 01284	2533.3	2533.3	1666.7	2244.44	1666.6	1927.3	1420.3	1671.4
ICPL 87091	2866.7	2266.7	2266.7	2466.67	2166.7	1564.4	1767.6	1832.14
[b]**ICEAP 01514/15 ([a]CM)**	1954.2	2120.5	2100.5	2058.42	1999.2	1705.4	1355.6	1686.7
***p* Value**				.054				.056
[c]**SED**				185.6				432.1
[d]**CV %**				15.5				20.5

[a]Commercial check.
[b]Medium-duration commercial check variety.
[c]Standard error of the difference of means across sites.
[d]Coefficient of variation.

TABLE 6 Performance of three pigeon pea varieties in semi-arid regions of Central Tanzania over three cropping seasons.

	Kiteto			Kongwa		Iringa	
	2016–2017	**2017–2018**	**2019–2020**	**2016–2017**	**2017–2018**	**2017–2018**	**2019–2020**
Genotypes	**Grain yield in kg/ha**						
ICEAP 00040	471	1024	1935	705	747	567	1765
ICEAP 00554	483	663	2870	1350	665	1000	1896
ICEAP 00557	458	511	2185	1388	790	992	1930
***p* Value**	.94	.076	.589	.225	.712	.428	.901
[b]**LSD ($p \le .05$)**	1334.4	451.6	2736.2	955.7	317.4	1044.1	871.4
[c]**CV %**	65.9	51	36.9	53.8	41.6	38.5	28.7

[a]Kilograms per hectare.
[b]Fisher's Protected least significant difference test.
[c]Coefficient of variation.

and Wilkinson modified joint regression analysis showed that the new candidate medium-duration material, ICEAP 00932, was the most stable line, with a sensitivity value of 1.0152, followed by ICEAP 00557 (1.0464) with the long-duration material ICEAP 00040 most sensitive (1.4877).

3.1.3 | Participatory variety selection (PVS)

The scope and importance of traits identified varied across countries, although varied, had several commonalities, largely due to cereal-based and legume-based food systems of the region. In groundnut, the common productivity-enhancing traits (input traits), were early maturity and resistance to groundnut rosette disease and early leaf spot disease. Traits associated with yield and utilisation of the crop (output traits), included grain yield, taste of fresh kernels, seed size (bold seeded or small), and ease of shelling. For pigeon pea, the input traits were early maturity, resistance to pod borers, other insect pests and disease especially Cercospora leaf spot. The output traits included the number of branches and grain yield potential assessed using the number of pods per plant, pod size, seed size and number of seeds per pod. The detailed results of the PVS are discussed below.

3.1.4 | Participatory variety selection of groundnut

Malawi

Performance on-farm was lower than on-station, even within the same altitude. Non-significant differences ($p \geq .05$) in grain yield were found across the two cropping seasons, the exception being at Mzimba, during the 2011–2012 cropping season. The improved lines ICGV-SM 01724 and ICGV-SM 08501 were the best performers with yield differences of 508 and 426 kg/ha in Mchinji and Mzimba when compared to the commercial check, Chalimbana 2005 and 283 and 503 kg/ha for the commercial check ICGV-SM 90704 during 2011–2012 cropping season. During the 2012–2013 cropping season, the same lines were the best performers. In Mchinji (mid-altitude)), ICGV-SM 08501 produced 326 kg/ha of grain above the commercial check Chalimbana 2005 but was lower than ICGV-SM 90704 the second commercial check. At Mzimba, ICGV-SM 01724 consistently outperformed both commercial checks with yield differences of 764 and 375 kg/ha for Chalimbana 2005 and ICGV-SM 90704, respectively. In general, the commercial check ICGV-SM 90704 performed better than Chalimbana 2005, because its tolerant to groundnut rosette disease, an endemic and biggest threat to groundnut production in Africa.

The common traits provided by smallholder farmers and used in the PVS included; yielding ability (number of well-filled pods), disease resistance especially to groundnut rosette disease, tolerance to drought, kernel taste (milky, sweet and oil taste), crop maturity duration, ease of shelling, kernel colour (red or tan), kernel size (bold or small seed), fresh seed dormancy, growth habit (bunch or runner), cooking quality, number of seeds per pod (two or more), seed weight (100 g weight) and oil content. These traits were ranked by farmers and the top eight traits were subsequently used for PVS (Table 7). Yielding ability was the most important trait for men but was ranked second by women. Women considered traits associated with labour (ease of shelling) and food security (yielding ability, taste and early maturity) as the most important traits. Conversely, men ranked traits associated with productivity improvement such as yielding ability, early maturity, disease resistance and drought tolerance as the most important traits. Many of the candidate materials had a better ranking than the commercial check Chalimbana 2005, with the ICGV-SM 01708 ranked best because of its high yield ability, drought tolerance, ease of shelling and seed size (Table 8).

Tanzania

In the semi-arid agro-ecologies of central Tanzania, specifically in Kongwa and Kiteto districts, drought tolerance was a major trait of consideration by male and female farmers (Table 9). Men however

TABLE 7 Prioritisation of selection criteria for participatory variety selection (PVS) of groundnut, disaggregated by gender, conducted in three districts of Malawi for the period 2012–2013, 2013–2014 and 2014–2015 cropping seasons.

	PVS by men		PVS by women		
Traits	[a]Number of votes	Rank	Trait	[a]Number of votes	Rank
Yielding ability	134	1	Shelling	90	1
Maturity	112	2	Yielding ability	77	2
Disease resistance	108	3	Taste	71	3
Drought tolerance	101	4	Maturity	60	4
Pod filling	80	5	Drought tolerance	51	5
Taste	68	6	Disease resistance	50	6
Shelling	53	7	Seed size	45	7
Seed size	41	8	Pod filling	39	8
Kernel colour	40	9	Kernel colour	27	9

Note: $n = 510$ for women and $n = 737$ for men.
[a]The total number of farmers who selected a particular variety as the best choice during the study period.

TABLE 8 Participatory variety selection (PVS) of new medium duration groundnut varieties by smallholder farmers three in districts of Malawi during the 2013–2014 and 2014–2015 cropping seasons.

Genotypes	[b]Mean scores	Rank	[c]Selection traits
ICGV-SM 01708	1.9	1	1, 2, 4, 5
ICGV-SM 90704 ([a]CM)	2	2	1, 2, 3, 4
ICGV-SM 01728	2	2	1, 2, 3, 5
ICGV-SM 01731	2	2	2, 3, 4, 5
ICGV-SM 08503	2.2	3	1, 2, 3, 4
Chalimbana 2005 ([a]CM)	2.3	4	1, 4, 5, 6
ICGV-SM 01724	2.4	5	1, 2, 3, 4
ICGV-SM 08501	2.4	5	1, 2, 4, 6

[a]Commercial check.
[b]Mean scores from three PVS ratings. Ratings were performed using a 1–5 qualitative scale, where 1 = Preferable and 5 = Least preferable.
[c]Traits used for selection: 1 = Yielding ability based on podding, 2 = Disease resistance especially to groundnut rosette, 3 = Drought tolerant, 4 = Taste, 5 = Ease of shelling and 6 = Seed size.

TABLE 9 Participatory variety selection (PVS) of new groundnut varieties by smallholder farmers, disaggregated by gender in the Kongwa and Kiteto districts of Central Tanzania for the period 2013–2014, 2014–2015 and 2015–2016 cropping seasons.

	Selection of traits by men			Selection of traits by women		
Genotypes	[a]Number of votes	Rank	[c]Selection traits	[a]Number of votes	[b]Rank	[c]Selection traits
ICGV-SM 02724	89	2	1, 3	78	3	3, 1, 5
ICVG-SM 03519	77	3	2	83	2	2, 4, 6
ICGV-SM 05650	95	1	2, 1	92	1	1, 6, 2
ICGV-SM 01513	38	6	2	72	6	6, 2
ICGV-SM 99568	44	4	2, 1	72	5	1
Local check	41	5	2	75	4	2, 6

Note: $n = 452$ for women and $n = 384$ for men.
[a]The total number of farmers who selected a particular variety as the best choice during the study period.
[b]The most preferred varieties were ranked with 1 being the best and 6 being the least.
[c]Traits used for selection: 1 = Yielding ability based on podding, 2 = Drought tolerant, 3 = Seed size, 4 = Early maturing, 5 = Seed colour, 6 = Taste, 7 = Ease of shelling and 8 = Disease resistance to groundnut rosette disease.

prioritised yielding ability, drought tolerance and seed size to select their preferred materials. Women, on the other hand, used production and food security-related traits such as yielding ability, kernel taste, drought tolerant, early maturity, seed size and seed colour to rank their best varieties. This trend was also observed in Malawi. Interestingly, though the ranking of traits between men and women varied, both genders selected ICGV-SMs 05650, 02724 and 03519 as the top three preferred materials (Table 9).

Zambia

Priority traits used by men and women during the PVS were varied, with women including food security traits among their selection criteria (Table 10a). Women ranked yielding ability highest, but considered seed colour (a proxy indicator for oil content, since they have associated kernels of red colour with a high oil content as present in the MGV 4, a variety which has >40% oil content), kernel taste and early maturity as the top four rated variety quality traits. The men ranked production-related traits highest, with yielding ability and seed size receiving a similar number of votes (Table 10b).

3.1.5 | Participatory variety selection of pigeon pea

Malawi

In the 2008–2009 cropping season, ICRISAT introduced medium duration pigeon pea material, during which, farmers ranked ICEAP 00557 because of its high-yielding ability and good grain qualities. It received a similar ranking for other yield attributes also present in the land race *Mthawajuni*. The second-ranked medium-duration material ICEAP 01514/15, also commercialised in the same period as ICEAP 00557, was ranked third due to yield qualities and relative early maturity.

Under the current investigation, conducted 10 years after the commercialisation of ICEAP 00557, one new test line ICEAP001150/1, consistently outperformed it across the study period (Table 11a). All the improved materials were ranked by farmers as better than the popular land race *Mthawajuni* (Table 11b). Ten years earlier (2008–2009), only ICEAP 00557 (PVS score 2.8) and ICEAP 01514/15 (PVS score 2.9), received scores similar to *Mthawajuni*. The PVS conducted a decade later (2017–2018 and 2018–2019) show improvement in farmer rating of tolerance to pod borers (*Helicoverpa*

Genotypes	[b]Mean score (women)	[c]Rank by women	[d]Selection traits
ICGV-SM 03517	1.65	1	1, 3, 4, 5
ICGV-SM 08513	2.4	2	1, 3, 4, 5
ICGV-SM 05534	2.6	3	1, 3, 4, 5
JL 24 ([a]CM)	5.8	4	1, 2, 3, 4
	[b]Mean score (men)	[c]Rank by men	[d]Selection traits
ICGV-SM 08503	2.1	1	1, 2, 4, 5
ICGV-SM 06729	2.3	2	1, 3, 4, 5
ICGV-SM-83708 ([a]CM)	9.6	3	1, 2, 3, 4

[a]Commercial check.
[b]Mean scores from two PVS ratings. The ratings were performed using a 1–5 qualitative scale, where 1 = preferable and 5 = least preferable.
[c]Ranking was done in order of preference with women paying more attention to food and nutrition security traits, whereas men focused on yield and seed size.
[d]Traits used for selection: 1 = Yielding ability based on podding, 2 = Drought tolerant, 3 = Seed size, 4 = Early maturing, 5 = Taste, 6 = Ease of shelling and 7 = Disease resistance to groundnut rosette disease.

TABLE 10a Participatory variety selection (PVS) of new groundnut varieties by smallholder farmers, disaggregated by gender in five districts of eastern Zambia during the 2013–2014 and 2014–2015 cropping seasons.

TABLE 10b Prioritisation of traits for participatory variety selection (PVS) of groundnut conducted in four districts of eastern Zambia during the 2013–2014 and 2014–2015 cropping seasons.

Trait prioritisation by women			Trait prioritisation by men		
Traits	[a]Number of votes	Rank	Trait	Number of votes	Rank
Yielding ability	178	1	Yielding ability	388	1
Colour	89	2	Seed size	338	2
Taste	84	3	Pod filling	104	3
Early maturity	77	4	Drought tolerance	102	4
Ease of shelling	60	5	Early maturity	78	5
Seed size	41	6	Ease of shelling	56	6
Drought tolerance	27	7	Disease resistance	42	7
Disease resistance	19	8	Taste	38	8
Pod filling	12	9	Bunchy growth habit	24	9

Note: $n = 587$ for women and $n = 1170$ for men.
[a]The total number of farmers who selected a particular variety as the best choice during the study period.

armigera), among new materials. Indeed, the new materials, ICEAP001150/1 and ICEAP00979/1, received mean ratings of less than 2 (Table 11a). The short duration in general had a better preference rating by farmers compared to the commercial check ICEAP 01514/15 (Supplementary Table 6). Only two lines, ICPL 87091 and ICEAP 01106/1 had higher grain yield than the commercial check.

The direct role of the pigeon pea as a food or income security crop in the agri-food systems was not significant. However, the interaction between the role of the improved varieties in the agri-food systems by test varieties was significant ($p < .010$), given the varied use of pigeon pea for food, feed and fuel. The improved variety ICEAP 00557 has been highly rated for its role in agri-food systems by strengthening food security and income (Supplementary Table 7). It was followed by *Mthawajuni*, which flowered earlier and therefore guarantees the early supply of protein. The variety ICEAP 01514/15, similarly, was ranked high as a good income crop, compared to all the other varieties.

Tanzania

Grain yield on-farm was higher in Kiteto than in Kongwa district. During the 2014–2015 cropping season, the long-duration variety ICEAP 00040 produced 2532.2 kg/ha at Kiteto. The new medium duration material ICEAP 00932 was the second-best material followed by ICEAP 00557 (Table 12a). Farmers however ranked ICEAP 00557 as a better variety than ICEAP 00040 because of early maturity and tolerance to drought, receiving more than four times the number of votes compared to all (Table 12b). ICEAP 00932 was ranked second best because of its yielding ability, drought tolerance and earliness.

Zambia

Pigeon pea is a relatively new crop in the country and therefore materials commercialised earlier elsewhere are actually relatively new in Zambia. The best performers on-farm were ICEAP 01514 and ICEAP 00557, which produced 2189 and 2117 kg/ha, respectively, of grain. In fact, both varieties received a high score for the yield parameters

TABLE 11a Participatory variety selection (PVS) of new medium duration pigeon pea varieties by smallholder farmers in Malawi during the 2017–2018 and 2018–2019 cropping seasons.

	Production trait ratings by farmers				
Genotypes	Pod borer damage	Cercospora leaf spot	Number of pods/plant	[b]Mean score	Ranking
ICEAP 001150/1	1.96	1.7	2.02	1.74	1
ICEAP 00557 ([a]CM)	2.15	2.27	2.65	1.8	2
ICEAP 00979/1	1.92	2.7	2.55	2.08	3
ICEAP 01147/1	2.36	2.61	2.83	3.59	4
Mthawajuni ([c]LR)	1.5	1.5	4.01	4.48	5

[a]Commercial check.
[b]Mean scores from five PVS ratings conducted districts of Malawi; Central region -Lilongwe, Mchinj; Northern region districts—Nkhotakota, Karonga and Mzimba North.
[c]Highly adapted land race tolerant to pod borer damage.
[d]Standard error of the difference of means.
[e]Coefficient of variation.

TABLE 11b Participatory variety selection (PVS) of new medium duration pigeon pea varieties by smallholder farmers by gender in Malawi during the 2017–2018 and 2018–2019 cropping seasons.

	PVS rating by men			PVS rating by women		
Genotypes	[b]Vote	[c]Reasons	Ranking	Vote	Reasons	Ranking
ICEAP 001150/1	30	1, 2, 4	1	40	1, 2, 3, 4, 5	1
ICEAP 00557 ([a]CM)	34	1, 2, 3	3	38	1, 2, 3, 5	2
ICEAP 00979/1	33	1, 2, 3, 4	4	31	1, 2, 3, 4	4
ICEAP 01147/1	21	1, 2	2	25	1, 2, 3, 5	3
Mthawajuni ([d]LR)	30	1, 2, 3	5	15	1, 2	5

[a]Commercial check.
[b]The total number of farmers who selected a particular variety as the best choice during the study period.
[c]Selection criteria used by farmers to identify their preferred varieties. 1 = Pod number, a proxy indicator for grain yield; 2 = Seed size; 3 = Earliness based on overall grain maturity during PVS; 4 = Pest damage and disease resistance; 5 = Cooking time and taste.
[d]Highly adapted land race tolerant to pod borer damage.

TABLE 12a Participatory variety selection (PVS) of new pigeon pea varieties by smallholder farmers in two districts of semi-arid Central Tanzania during the 2014–2015 cropping season.

	Trait ranking and votes accorded by farmers					
Genotypes	Grain yield	Drought tolerant	Seed size	Earliness	Total votes	Rank
ICEAP 00932[a]	66	52	38	58	214	2
ICEAP 00040[b]	40	20	79	12	151	5
ICEAP 00557[a]	72	59	45	57	233	1
ICEAP 00576–1	32	28	26	47	133	5
ICEAP 00554	60	53	40	53	206	3
ICEAP 00936	37	55	32	53	177	4

[a]Highly ranked by women due to early maturity thereby acting as a source of food security in lean periods thus overall win.
[b]Long duration and high yielding thus preferred highly by men but low by women due to long maturation date.

(podding ability and seed size) and early maturity, which are crucial traits for food security (Table 13a). It had the highest grain yield, flowered earliest and had the least damage by pod pests. The second-best rated material, ICEAP 00557, while maturing later than *Mthawajuni*, was selected due to good yield attributes (seed size and podding). The ranking of these new materials differed by gender, with men preferring ICEAP 01514, because of high yielding ability and tolerance to pod damage, a critical driver of pigeon pea grain yield. Male farmers ranked ICEAP 00557 as their second choice. Women ranked *Mthawajuni* first because of high yielding ability and earliness, a key trait for

TABLE 12b Participatory variety selection (PVS) of new pigeon pea varieties by smallholder farmers by gender in semi-arid central during the 2014–2015 cropping season.

	PVS rating by men			PVS rating by women		
Genotypes	[a]Vote	[b]Reasons	Ranking	Vote	Reasons	Ranking
ICEAP 00932[c]	31	1, 2, 3, 4	2	28	1, 2, 3, 4	2
ICEAP 00040[d]	32	1, 2	5	19	1, 2, 3	6
ICEAP 00557[c]	36	1, 2, 3, 4	1	39	1, 2, 3, 4	1
ICEAP 00576–1	23	1, 2	5	25	1, 2	3
ICEAP 00554	15	1, 2	3	20	1, 2	5
ICEAP 00936	24	1, 2	4	21	1, 2	4

[a]The total number of farmers who selected a particular variety as the best choice during the study period.
[b]Selection criteria used by farmers to identify their preferred varieties. 1 = Podding, a proxy indicator for grain yield; 2 = Seed size; 3 = Earliness based on overall grain maturity during PVS; 4 = drought tolerant.
[c]The best ranked varieties by farmers due to drought tolerance and early maturity.
[d]Long duration variety was not highly ranked since it takes long to mature, therefore not able to withstand prolonged water stress.

TABLE 13a Participatory variety selection (PVS) rating of new medium duration pigeon pea varieties by smallholder farmers in the Chipata, Lundazi and Katete districts of eastern Zambia during the 2017–2018 cropping season.

	[b]Preference scores				
Genotypes	[c]Podding	Seed size	Earliness	Mean score	Rank
ICEAP 00557	2.4	2.2	2.2	2.2	1
ICEAP 01514	2.6	2	2	2.2	2
ICEAP 01485/3	3	2.4	2.2	2.5	3
ICEAP 00554 ([a]CM)	3.4	3.2	2.4	3	4

[a]Commercial check.
[b]Mean scores from nine PVS ratings conducted in the Chipata, Lundazi and Katete districts of eastern Zambia. The ratings were performed using a 1–5 qualitative scale, where 1 = preferable and 5 = least preferable.
[c]The PVS was conducted 4 weeks after flowering when the grain filling is at maximum.
[d]Fisher's protected least significant difference test.
[e]Coefficient of variation.

food security (Table 13b). The commercial check was ranked lowest by both men and women because of susceptibility to pests and relatively late maturity.

4 | DISCUSSION

Smallholder farmers in developing countries are producers and consumers of agricultural produce for domestic and off-farm markets. Their specificities for certain qualities in a crop variety are thus an indicator of domestic to off-market agricultural produce market needs. The aim of this paper was to assess the effectiveness of participatory variety selection (PVS) across multi-locations in the development of demanded groundnut and pigeon pea. Both legumes often occupy the same agro-ecologies and are used as food and income (cash) crops. They are also key components of the dryland cereal-legume agri-food systems of Malawi, Zambia and Tanzania. This study investigated farmers' preferences for new materials presented to them following improvements based on previous PVS. Three types of materials were used for the PVS. The first type of materials were those whose breeding had been informed by previous PVS as was the case with groundnut, short duration and medium pigeon pea. The second type of materials included varieties commercialised in the same country but introduced into a new agro-ecology where they had not been grown before, as was the case in Tanzania, whereas the third type of materials comprised varieties commercialised in other countries of the region but not available in the test country of the present study, as was the case with medium-duration pigeon pea in Zambia.

Across all material categories, there was evidence of improvement in the performance of the elite materials compared to the existing commercial check and or land laces. In the first category of materials, starting with groundnut, both on-farm and on-station multi-year trials showed significant differences ($p < .05$) between the older commercial materials and the new test material. Grain yields were highest among mid-duration materials belonging to the Virginia botanical group, compared to the short duration belonging to the Spanish botanical group. The grain yield across all countries was highest in the most optimal agro-ecologies of each country. In Malawi, the most optimal agro-ecology was the mid-altitude AEZ, where a grain yield of 2545 kg/ha was obtained for the best material. The same material was the best material even in the constrained low-land agro-ecology

TABLE 13b Participatory variety selection (PVS) of new medium duration pigeon pea varieties by smallholder farmers in the Chipata, Lundazi and Katete districts of eastern Zambia during the 2017–2018 cropping season.

Genotypes	PVS rating by men			PVS rating by women		
	[b]Vote	[c]Reasons	Ranking	Vote	Reasons	Ranking
ICEAP 01514	35	1, 2, 4	1	22	1, 2, 4	4
ICEAP 00557	36	1, 2	2	38	1, 2, 3	2
[d]**Mthawajuni**	33	1, 2, 3, 4	3	36	1, 2, 3, 4	1
ICEAP 01485/3	21	1, 2	4	25	1, 2	3
[b]**ICEAP 00554 ([a]CM)**	15	1, 2	5	20	1, 2	5

[a]Commercial check.
[b]The total number of farmers who selected a particular variety as the best choice during the study period.
[c]Selection criteria used by farmers to identify their preferred varieties. 1 = Podding, a proxy indicator for grain yield, 2 = Seed size; 3 = Earliness based on overall grain maturity during PVS; 4. Pest damage and pod filling.
[d]Highly ranked local landrace by women as a food security variety because of yielding ability, earliness and tolerant to pests.

with a grain yield of 1950 kg/ha at Chitala and lower by 500 kg at 1450 kg/ha in Ngabu. In Tanzania, ICGV-SM 02724, the only Virginia entry produced 421 kg of grain above the best Spanish line ICGV-SM 05650, a similar trend observed in Malawi. The reaction of short-duration material was varied, in Malawi, with significant differences only found in the most stressed environment (Ngabu), where the test material ICGV-SM 99551 produced 1650 kg/ha, 575 kg more than the commercial check. Ngabu is found at the bottom of the rift valley in Malawi and frequently experiences end-of-season drought that may have affected material performance. In Zambia, the effects of the environment on genotype performance were evident, with materials performing better in AEZ II and AEZ III. Material performance in Masumba, (AEZ 1), was the lowest and is similar to results for Ngabu in Malawi. Across all three countries and environments, performance among the final selected materials for advanced yield trials, was mostly non-significant ($p > .05$), signifying the rigour of initial screens conducted to identify material for regional trials by ICRISAT's groundnut breeding programme in Malawi. Materials shared for regional advanced trials are usually the top 10 best entries from the multi-environment testing in Malawi. They must among others have over 15% yield advantage over the most recent commercial check. The improved material in this study in most cases exceeded the 10% higher yield threshold than the local or commercial check (Nigam, 2015) required to enhance genetic gain on-farm. The checks used in this study had been commercialised in earlier breeding cycles. Their higher yield gains are indicative of the progress made in the breeding that is mainly underpinned by resistance to groundnut rosette and leaf spot diseases. Groundnut rosette is the most destructive disease that can completely destroy the crop, whereas leaf spots affect the grain-filling stage by reducing the photosynthetic surface area of the crop. Using the grain yield, these studies show that the groundnut testing sites used by ICRISAT in Malawi are suitable for the identification of elite material for advanced yield trials that will lead to the commercialisation of the crop in East and Southern Africa's (ESA) dryland agro-ecologies. Climate change, an ever-present phenomenon, that is changing traditionally defined agro-ecologies by creating new zones and overlaps between existing ones (Muluneh, 2021), requires precise breeding that is undertaken for the target population of environment (TPES) for groundnut. In previous studies (Okori et al., 2019), using grain yield data, the presence of three mega-environments for groundnut evaluations in ESA, two of which match the low and mid-altitude agro-ecologies of Malawi, and a third overlapping environment were found. Complete characterisation of the three-testing environment (low, mid- and high altitude agro-ecologies) and other AEZs of ESA into the TPES for groundnut, requires the inclusion of ecological information in the analysis. The characterisation of TPEs will support the accurate prediction of future material performance (Basford et al., 2002), an essential issue for climate change adaptation breeding, as has been demonstrated for cereals including maize, a major staple for ESA (Ciampitti et al., 2020; Setimela et al., 2017; Windhausen et al., 2012). When done, this will support the enhancement of genetic gains on-farm, as it will identify potential technology spill-over and or overlapping agro-ecologies as well as support shuttle-breeding between breeding programmes speeding up breeding cycles both within Malawi and the ESA.

Contemporary plant breeding practices require that users of breeding products are involved in the process. In this study, multi-year participatory variety selection on groundnut and pigeon pea across different agro-ecologies and environments was used to assess responsiveness to demand by the breeding process. Legumes have been described as women's crops (Joe-Nkamuke et al., 2019; Me-Nsope & Larkins, 2016) and are critical for nutrient supply and replenishment respectively for humans and cropping systems. The PVS process investigated and evaluated progress towards gender disaggregated demand on these legumes among others. The PVS results confirm gender differences in trait prioritisation in both crops. In general, men preferred traits associated with increased grain productivity. In groundnut, in Malawi, men prioritised grain yield and its components (seed size and number of pods) and disease resistance a yield influencing factor accounting for up to 61.7% of qualities of interest, whereas in Tanzania, men similarly prioritised yielding ability, drought tolerance, and seed size accounting for 79.4% of critical traits driving selection of good groundnut. In Zambia, yielding ability, seed coat colour, taste, early maturity and ease of shelling accounted for 79% of the trait's that men consider important in groundnut. Clearly, men prioritised these traits as they affected the overall tonnage available for sale given that groundnut is a major income-generating crop in ESA. Women prioritised traits that enhance productivity, reduce drudgery and food insecurity. In Malawi, the women-preferred traits were ease of shelling, yielding ability, taste, maturity and drought tolerance, accounting for 58.4% of the preferred qualities. In Tanzania, women prioritised yielding ability, kernel taste, drought tolerant, early maturity, seed size and seed colour accounting for 69.5% of preferred traits, whereas in Zambia, the priority traits included yielding ability seed coat colour, kernel taste and early maturity, accounting for 79.7% of the critical traits in groundnut. These traits are all associated with women's role in groundnut production and their gender roles in the households in Malawi and ESA (Joe-Nkamuke et al., 2019; Mugisha et al., 2019). The application of these priority traits during the multi-year evaluations shows that a combination of both input and output traits drives the decision making by farmers. Productivity, external and household consumption patterns are the key factors that inform farmer selection of a good groundnut variety. This is consistent with the fact that groundnut is both a food and income crop for smallholder households in ESA drylands agro-ecologies (Mugisha et al., 2019; Nigam, 2015; Okori et al., 2022). Thus, the focus of the homestead in production will help in reconciling the choice of variety for adoption. These multi-year and multi-national studies demonstrate the common traits favoured by farmers in the region's diverse cereal and legume-based cropping systems, which also underpin agri-food systems. For groundnut, the must-have traits in the focus that may also apply to the wider region include grain yield (yielding ability—number of well-filled pods prior to maturity), resistance to groundnut rosette disease and leaf spots, tolerance to drought, ease of shelling, crop maturity duration and kernel size (bold seeds are preferred to small seeds). The good-to-have traits include kernel taste (milky, sweet and oily taste), number of seeds per pod, kernel colour red or tan, pod filling, fresh seed dormancy, growth habit (bunch as opposed to runner), 100 g seed weight and oil content. Given the changing roles and use of groundnut in the agri-food systems of ESA, breeding programmes must from time-to-time review and blend emerging must-have traits with agri-food system contextual good-to-have traits, as they develop new groundnut varieties (Kimani, 2017).

The pigeon pea PVS followed a similar trend to groundnut with the most improved materials outperforming the commercial checks across all the countries. In Malawi and Zambia, where improved medium- and short-duration pigeon pea were introduced as replacements for a landrace and commercial check, gender preferences based on input and output traits where evident. During the first introductions of medium duration pigeon pea in Malawi in 2008, *Mthawajuni* a mid-duration land race was ranked second best, notwithstanding its lower grain yield than the new improved introductions. *Mthwawajuni* is tolerant to pod pests, the most important threat to pigeon pea production (Hillocks et al., 2010). The PVS conducted in the present study, 10 years later, show better scores for the new medium-duration materials than the land race, an indication that earlier PVS efforts informed the new variety design. In Zambia, men prioritised ICEAP 01514 as the best material based on yield traits (podding and seed size) and tolerance to pod damage, with these traits accounting for 74.6% of the selection criteria. Conversely, women selected *Mthawajuni* a land race in Malawi, but an introduction to Zambia, as the best material in spite of its relatively lower yield due to its tolerance to pest damage and pod filling. *Mthawajuni* also matures earlier than all the improved materials. Early maturity allows farmers to access a fresh protein supply during lean periods when they are short of common bean, a popular and common source of proteins. Most legumes are annually harvested in April, whereas *Mthawajuni* is ready to be consumed in July to August, thus bridging the protein gap in traditional cereal-based diets (Saxena et al., 2010). Collectively, the yield attributes and tolerance to pests accounted for 63.9% of the selection trait drivers. In Tanzania, whereas the long-duration material ICEAP 00040 was the best performer, and preferred by men, women preferred the medium-duration materials, that is, ICEAP 000557 and ICEAP 00932, because they matured earlier. These medium-duration materials mature 50 days before the long-duration variety, and for dryland communities, this is a new source of food security. Clearly, gender influences, like in the case of groundnut, had an impact on the prioritisation of pigeon pea. The PVS conducted on short-duration pigeon pea followed a similar trend with grain yield and tolerance to pod pests as key factors affecting the prioritisation of the test materials. The top-ranked material was ICEAP 01161/1 and the second was ICEAP 01106/1. These materials have since been submitted for commercialisation in the country. Overall, pigeon pea pigeon pea, the must-have-traits for ESA agro-ecologies as informed by the market include resistance to grain yield (key attributes include podding, seed size and number of seeds per plant), tolerance to pod pests, early maturity and resistance to diseases especially fusarium wilt and cercospora leaf spot. The good-to-have traits include biomass production for fuel wood, fodder and nutrient recycling.

We further examined the role pigeon pea plays in the agri-food systems of Malawi by investigating its impact as (a) a major source of food and income, (b) a minor food crop and (c) minor food and major income crop. The interaction between the role of improved pigeon pea in the agri-food systems as food or cash crop was significant ($P \leq 010$), showing its significance as a source of food, feed and fuel. The results show that ICEAP 00557 was the best-rated material as a food and income security source, and the second best-rated medium-duration material was ICEAP 01514/15. *Mthawajuni* the land race was poorly rated as a source of income. *Mthawajuni* has variegated grains, a non-desirable feature for dehulling, which reduces the yield of processed grains as further dehulling cycles are required and lead to losses.

5 | CONCLUSIONS

The present study demonstrates improvement in the acceptance of new materials regarding their performance and preference by agricultural communities providing evidence that when users of crop varieties are engaged in the crop improvement process, there is a high likelihood for technology relevance. Given the dynamism of agri-food systems, conducting multiple PVS and variety evaluations is critical, especially when agri-food systems cover multiple AEZs, to inform trait prioritisation for new variety profiles (Govaerts et al., 2021; Thompson & Scoones, 2009). The present study involves two crops that are essential legumes of the same agri-food system especially in ESA, and provides a basis for comparison of key drivers of their adoption by the same agricultural communities. The studies further partition farmer-preferred traits by gender, and importantly, show that grain yield is the most important trait, whereas critical across both genders must be accompanied by other critical agri-food system needs and aspirations of the farming and consuming population. The higher productivity-leaning focus on male-preferred crop traits, compared to women's broadened focus on productivity, household and production needs underscores the need for inclusion in crop improvement processes. Thus, conducting PVS regularly will place farmers at the centre of demand-led and inclusive plant breeding, and enable the breeding programme to learn from the farming community's rich indigenous knowledge (Ceccarelli & Grando, 2007, 2020). The critical processes of multi-location trials that are coupled with PVS are sometimes compromised and may have significantly led to limited adoption and or disadoption of improved crop varieties (Coromaldi et al., 2015; Uduji & Okolo-Obasim, 2018). Finally, for both crops, completing the characterisation of the TPEs will improve targeted breeding, especially as agro-ecologies transition and change under climate change.

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AUTHOR CONTRIBUTIONS

Patrick Okori and James Mwololo were involved in designing of experiments, data curation and analysis; interpretation of results and development of the manuscript. Wills Munthali, Oswin Madzonga, Harvey Charlie and Swai Elirehema were involved in the execution of field experiments, data collection and synthesis, data analysis and manuscript review. Nadigatla Ganga Rao was involved in the designing of the pigeon pea experiments, Jumbo Bright was involved in the implementation of the field experiments, whereas Moses Siambi and Mateete Bekunda secured the funding and reviewed the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no competing interest that would be impacted by publishing this paper.

DATA AVAILABILITY STATEMENT

Data are available in article supplementary material.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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