Taye Tadesse, Andrew Borrell, Mekonnen Sime

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Executive summary

Sorghum is a climate resilient crop as compared to many other cereals and produces high biomass per unit volume of water. It is thus considered as a potential crop to address the growing food and feed demand in the semi-arid tropics, where drought is a recurrent phenomenon. Although sorghum production and productivity has shown an increasing trend in Ethiopia, the trend was not commensurate with the population growth. The low accessibility of improved sorghum production technologies, poor value chain and climate change related production constraints are the major contributors for the gap. Hence, it is critical to create access for improved technologies, as well as linkage along the value chain actors. The project aimed to enhance the use of improved climate-resilient sorghum production technologies to overcome the risk of drought stress, reduce post-harvest loss through use of improved technologies, reduce drudgery, enhance sorghum utilization and create market linkage for surplus produce.

Demonstration of climate resilient improved sorghum varieties along production package was conducted to showcase the technologies and create demands. The improved sorghum varieties showed an overall superior grain yield performance ranging from 2.7 to 4.8 tons/ha. The average productivity of the improved varieties was 3.9 tons/ha, which was 44% higher than the conventional practices. The performance of the improved technologies varies depending on the extent of drought and adaptation of the improved varieties to the specific environmental conditions. For instance the mean performance in Arsi zone was 3.4 t/ha and in East Hararghe zone 4 t/ha with the yield advantage of 21% and 43%, respectively. Seven early maturing improved varieties, including the recently released high yielding and high biomass producing variety called “Argity” which was targeted by the project, were demonstrated in the project target areas. The demonstration was conducted in a total of 323 sites of which 292 were on farmer’s field and 19% of the farms owned by women farmers. The remaining demonstrations were conducted on farmer training centers. The number of women farmers’ participation was lower than the target due to shortage of women headed households having land. Development agents, experts and selected farmers were trained on the improved production package to ensure extending the technologies and good practices to other farmers. In total 247 development agents and experts of whom 53 of them were women were attended the training.

The seed of the preferred varieties were multiplied through the formal and informal seed systems. The on-farm demonstration revealed that the variety Melkam had wider acceptance than the variety Argity for the reason that Melkam is early flowering and escapes the terminal stress. However, the variety Argity was found better in both grain yield and biomass production in good season and areas having extended rainfall. Hence, based on the demand from the growers and seed producers, different classes of seed were multiplied and delivered to seed growers and farmers. The project targeted to multiply 400 kg breeder and 10 tons of pre-basic seed classes. For the variety Melkam, Argity and Girana-1 a total of 697 kg and 15.3 tons breeder and pre basic seed classes, respectively, which were more than by half from the target were multiplied.

In addition, 208 Tonnes of certified and quality declared seed (QDS) were produced through the formal seed system and community seed growing schemes. The performance was 83% of the project target. The project had a shortage in delivering the target on the QDS and certified seed because of security reasons that impeded access to some of the project target areas.

The seed multiplied through the formal and informal seed systems was extended to farmers through large scale demonstration (LSD), small seed packs and farmer-to-farmer seed exchange. Hence, in total 8523 farmers, of which 16% of them were women households owning farmland, directly accessed the improved varieties through LSD and small seed pack distribution. In addition, it is estimated that more than 12,000 farmers accessed seeds of the improved varieties through the local seed exchange. Overall, more than 19,000 ha of land were covered through the on-farm demonstrations and promotion of early maturing sorghum varieties adapted to drought stress environments and preferred by growers with the potential of expanding to other small holder farmers. The variety Melkam is already taken up by the seed formal seed system for its wide demand, however, support is still needed to sustain availability of the improved early maturing varieties which have an important specific niche. A recent report indicated that 32% of sorghum growing farmers are using improved sorghum varieties (Etaferahu *et al.*, 2020). These efforts will increase the chance of technology accessibility and the use of improved varieties thereby increasing the productivity of sorghum.

Sorghum threshing is the most challenging job for farmers and is especially arduous for women and children. Different threshers were tested for the first time for threshing efficiency and quality of service. Based on the feedback from farmers, redesigning and fabrication of three threshers was conducted. Demonstration of the threshers was undertaken in the project target areas to create demand and establish a system to make them accessible to users. In total demonstrations and training on threshers were undertaken with 2,155 beneficiaries of which 571 of them or 27% were female farmers. The cost of threshing using the on-service bases was in the range of 800 to 900 birr/ha, which is about 0.6 % of the total revenue per hectare of land. It would also reduce the time required for threshing a hectare of sorghum land to thresh from a whole day using traditional means to two hours. Hence, besides reducing the loss of grain during threshing manually and using animals, farmers have time to do additional farm activities, specifically, the women burden on the on-farm activities reduced and enabled children to go to school.

Farmers do not generally benefit as much from their harvest as they are forced to sell their grain immediately after harvesting when grain price is low (i.e with the range of 17 to 20 birr/kg). In the past four years demonstration and training on how to use the PICS bags and metal silos were conducted for a total of 4412 farmers (48 % of them women), development agents and experts. In total 5500 PICS bags and 8 metal silos were distributed to 2781 farmers involved in sorghum production technologies and the cluster formed for larger scale demonstration. As the quality of seed is maintained by keeping the seed in the PICS bags, farmers were able to sell their grain with the range of 29 to 34 birr/kg after six months of storage with an average profit of 1,179 birr/100 kg. In addition to the quality benefit of keeping the grain in the PICs bags, farmers are using the additional income to purchase farm inputs, food items and access other services.

Injera is one of the staple foods in Ethiopia and is made mainly from teff. Sorghum is preferred next to it for *injera* making. However, more than 72% of the grain produced is consumed locally. The project aimed to trigger the *injera* value chain in the towns and the rural community with improved *injera* making techniques and poultry feed as a pulling factor for farmers to use improved technologies and increase productivity. The use of de-hulled sorghum grain with 50:50 mixed with tef produced best quality *injera*, and a recipe mix with up to 40% sorghum grain was developed and promoted to users. The project supported establishment of five groups to make *injera* with a total of 84 members of whom 77 were women and provided training in using the optimized *injera* making protocol. A pilot study was conducted through providing dehulled sorghum grain to selected business groups. The reduced cost for *injera* and consumer acceptance encouraged them to use the dehulled sorghum grain in their business. However, accessibility of the dehulling machine and linkage with the sorghum producers needs further work for wider impact. The efforts, generally, gave the lesson that a business model to enable greater access needs to be developed to ensure sustainable impact along the sorghum value chain.

As an option for a sorghum market outlet, a sorghum-based recipe was tested for the developing poultry feed industry in Ethiopia. The results showed there was no significant variation between the birds fed with the conventional (maize-based feed formulation) and sorghum-based diets. Partial budget analysis results in this study showed a better net benefit when the variety Degalit Yellow was mixed at all levels than with Melkam with 30-40% mix. From the results revealed by most parameters of egg production and egg qualities considered, it was concluded that the varieties Degalit and Melkam were best for egg production.

As part of the development of climate resilient improved varieties and management practices, studies were conducted on root architecture (RA) and the transpiration efficiency (TE) as key traits for drought adaptation of sorghum. The two traits are critical in determining water use and biomass production in water limited environments. In total, 1187 sorghum breeding lines in Ethiopia and 727 unique genotypes in Australia were phenotyped for root angle and different root architecture traits. The mean root angle ranged from 9 to 31 indicating the wider variability in the targeted populations and moderate to high heritability ranging from 0.5 to 0.8. The result also showed that narrow root angle contributed positively to increased grain yield performance under drought stress environment. The phenotyping and marker data generated on the targeted population are useful resources to develop tools for future crop improvement.

The research problem

Sorghum in Ethiopia is primarily grown for food while the plant biomass is also equally important as a source of feed and fuel. The crop is predominantly grown in the dry lowlands where climate change is creating a higher frequency of drought and crop failures, exposing farmers to food shortages and loss of livestock due to feed shortage. If downstream industries which use sorghum are to be developed, it will be essential to increase smallholder farmers' capacity to produce, store and market surpluses. Drought has major impacts on smallholder farmers' capacity to consistently generate grain surpluses which are necessary for the creation of sustainable downstream industries.

The traditional varieties grown have high biomass and are late maturing which takes more than six months. These varieties are generally planted after the first rains in April of the typical bi-modal rainfall pattern. In recent years, this first rain has become unreliable and the extent of the dry period between the two rains has increased. As a result, the traditional varieties fail more often. Despite having higher reliability and a higher yield, the short-season varieties which have been bred to be planted on the second rainfall event have been poorly accepted by farmers due to their low biomass production. The increasing climate change effect, specifically, limited water availability is one of the major limitations for sorghum productivity. The project considered addressing adaptation of sorghum in drought stress environments focusing on the root architecture (RA) and transpiration efficiency (TE) and developed tools for future breeding. The project also contributed to knowledge from a scientific, developmental and policy perspective.

Most of the grain produced is consumed locally and farmers do not primarily target the market in producing sorghum, which does not encourage farmers to use the improved production technologies. The situation is exacerbated by limited availability of threshing and storage technologies which result in 30 to 40% post-harvest loss (FAO, 2017) and the threshing task is laborious. Technological intervention is highly needed to reduce the post-harvest loss, grain quality deterioration and enable the storing of surplus grain for year-round food availability and to better the livelihoods of the farming community.

The major staple food in Ethiopia is *injera,* a fermented flat bread. While teff is preferred for *injera* making, most *injera* is made from a mixture of sorghum and teff flour due to the soaring price of teff and the increasing difficulty of producing sufficient teff to meet the increasing demand. Lack of an optimized protocol for sorghum-teff mix for *injera* making and lack of sorghum dehulling technologies to remove the seed cover are limitations for wider use of sorghum in the *injera* value chain. The growing chicken feed industry in Ethiopia is suffering from feed-shortage. This could be considered as a good market outlet for sorghum growing farmers in the dry lowlands of Ethiopia.

Progress towards milestones

1. Phenotyping of sorghum genotypes for root architecture traits

This study aimed at understanding root architecture variability, its effect to adaptation to drought stress and to develop tools for future breeding. In 2019 and 2020 a total of 1047 sorghum genotypes advanced from the breeding pipeline were phenotyped for Root architecture traits. The genotypes were also evaluated for their performance in three sites (Miesso, Sheraro, and Kobo) representing the dry lowland areas. The result showed the presence of genetic variability for root-angle traits among the tested genotypes ranging from 8.0^0 to 30.1^0, with an average root angle of 19.05^0. However, the root angles for the improved and newly released sorghum varieties ranged from 14.04 to 19.5^0 degrees, indicating that the improved varieties showed narrow root angle, which implies that there is a higher risk susceptibility to severe drought stress. UQ also assessed 2000 root chambers and evaluated 725 unique sorghum genotypes for root architecture traits. The root angles ranged from 9-31^o across experiments, with a mean root angle of 17^o; and heritability was moderate to high, ranging from 0.5 to 0.8. The result generally indicated there is a possibility of improved sorghum genotypes through targeted breeding to narrow root angle and deep root system.

In addition, a total of 56 stay green introgressed lines were evaluated for root architecture traits and significant variation was obtained ($p < 0.001$) for leaf length, root vigor, and root fresh and dry weights. The stay green traits of sorghum genotypes also demonstrated a significant and negative association ($r = -0.83$) between grain yield and root angle traits. This finding suggested that narrow root angle traits contribute to the higher grain yield performance in water limited environments. In addition, genotypes exhibiting narrow root angle and high grain yield performance (ETSC300388 and ETSC300368) were identified to be used in the breeding program.

2. Phenotyping sorghum genotypes for transpiration efficiency (TE)

This activity was initiated to understand genetic variation for TE and develop tools for future use in sorghum breeding. UQ assessed a total 2800 pots and evaluated 1108 unique sorghum genotypes. The result showed that transpiration efficiency ranged from 5.2-8.2 g/kg across experiments, and heritability was moderate, ranging from 0.4 to 0.5. As this study was the first of its kind in Ethiopia, a manual loaded lysimeter facility was established with the support of the project having a capacity of phenotyping up to 300 genotypes per trial. Trial was delayed in Ethiopia due to the storm damage of the newly constructed lysimeter and delay in setting up the facility at Melkassa. A total of 375 advanced sorghum genotypes from the local breeding were phenotyped for TE at Melkassa. The TE for shoot ranged from 5.8 to 7.6 g/kg. Genotype SC56-14E exhibited the lowest TE (5.79) and R08512-35 the highest (7.59). For an equivalent amount of water used (e.g. 8000 ml), plants with higher TE produced more biomass (e.g. 70 g) than those with lower TE (e.g. 40 g). The significant genotypic variation in TE suggests that there is scope (i.e. sufficient natural variation) to select for this trait in breeding programs. The mean TE shoot was 6.38 and broad-sense heritability was 0.49 indicating selection from the targeted population could be possible for genetic improvement. The delay of lysimetry construction, travel restrictions due to COVID affected the implementation of activities on TE. In addition, alignment of the data generated in Ethiopia and Australia was not conducted due to the delay in generating the data. In general, the study in TE exhibited the potential to improved sorghum for better water use efficiency which can perform well in water limited environments.

3. Genomic analysis for root architecture and TE

The project supported development of Nested Association Mapping populations (NAM) derived from 15 selected lines based on the genetic distance and specific merits to be used as mapping population and line development. A total of 2074 recombinant inbred lines (RIL) were developed for future use of which 32 of the lines were selected and tested in the advanced variety trials. A total of 1500 sorghum genotypes phenotyped for RA and TE and selected RIL from the NAM populations outsourced to DArT in Canberra, Australia for genotyping. Due to the delays in root architecture and TE phenotyping in both Australia and Ethiopia, this activity has not been completed. Association mapping using the phenotyping and genotyping data and marker validation work will continue depending on the availability of funds from different sources. The data set will be publicly available after the results are confirmed and published.

4. Optimization of agronomic practices and demonstration to farmers

Two activities focusing on identification of cost-effective sorghum management practices for the newly released sorghum variety (Argity) and demonstration of the best and farmers management practices to enhance adoption of agronomic practices were conducted in the project target areas. The fertilizer response trial demonstrated that there was no significant difference for plant population between the varieties and no response was obtained for high level of phosphorous fertilizer application. A trial was conducted in 2021 at two sites to estimate the rate of N and P level for the two varieties (Argity vs Melkam). The result showed that the two varieties had no significant difference in grain yield performance. The yield increases due to nitrogen application ranged from 764 to 1871 kg ha^{-1} corresponding to an increase of 43 to 106%. There was no form of statistical response curve found for P fertilizer application, but it generally showed an increased yield up to 10 kg P ha^{-1} but it was inconsistent across the N rates and the varieties. On farm validation of 46% N and 10% P will be implemented in the project target areas for wider promotion. Based on the validation response and farmers feedback the rate will be integrated with the package and promoted to be used with the improved varieties.

In addition, long term scenario analysis was made using APSIM model for different application rates of nitrogen fertilizer. The result showed that moderate N application (23 kg N ha^{-1}) improves both the long-term average and the minimum yearly guaranteed yield without increasing inter-annual variability compared to no N fertilizer application. Although it does imply a lower average yield than that of the recommended 46 kg N ha^{-1}, the application of 23 kg N ha^{-1} appears more appropriate for small-holder subsistence farmers to guarantee higher minimum yield in season that have low precipitation, thereby reducing their vulnerability.

5. Seed multiplication and support to the formal and informal seed system

Access for early generation (breeder and pre basic) seed multiplication is a major bottleneck for the seed system to multiply and deliver certified and quality declared seed (QDS) to growers. The project aimed to support multiplication of early generation seed (EGS), technical support and supervision to multiply certified and/or QDS seed through the formal and informal seed system to avail the seed for the extension activities. The aim was to produce 400 kg breeder seed for demanded varieties with the project support. In total of 697 kg breeder seed multiplied the preferred varieties of Melkam, Argiti and Girana-1. In addition, 15,340 kg pre-basic seed of the same varieties were produced in four seasons of the project. This indicated that the project milestones achieved more than the project target to address the demand of the varieties. In addition, 208 tons certified/QDS seed was produced, which was 92% of the target, for the on-farm demonstration and dissemination of the varieties. The community-based seed multiplication scheme has been the major contributor of the seed produced, while the Amhara and Oromia regional seed enterprises were also engaged in the multiplication of the highly demanded Melkam variety. The project trained technicians on quality seed production and supervision and technical support for the community in producing quality seed, certification and established linkage with unions to sell the seed. From 2023 seed is being produced through the community with 80 tons of the Melkam variety seed already procured and ready for sale through unions in Amhara region.

6. Technology demonstration and capacity building to beneficiaries

In the past three years demonstrations of the released varieties and management practices were conducted on farmers' fields and on farmers' training stations. During the project period out of the project target of 360 demonstrations, a total of 323 were implemented in seven districts of the project target regions through the federal and regional research centers. This indicated that 90% of the project target was achieved. The security problem in the project targeted areas and restriction to travel and contact with people due to Covid-19 had an impact on the demonstration plan. Based on the feedback from the demonstration activities the varieties demanded were scaled up through small seed packs with a size of 2 kg per pack and large-scale demonstration. This activity has created accessibility of the improved varieties for wider uptake and increased the visibility of the technologies in the targeted areas. In the large-scale demonstrations, 2,806ha of land was covered by 8,523 participating farmers of whom 1308 were women, which accounted for 15% of the total beneficiaries. In addition, seed of the preferred varieties were also distributed through the formal extension system through the bureau of Agriculture, and it is estimated that more than 12000 farmers accessed the improved varieties in the project intervention areas. The technology promotion activities were accompanied by distribution of promotion materials (brochures and leaflets) of the improved technologies. Field days were also organized with the participation of neighboring farmers, regional and federal level professionals and other relevant stakeholders for wider impact. In total 5,579 of which 1,151 were female farmers and other stakeholders participated in the field days organized to demonstrate the technologies and to help expand to other areas. During the events, feedback was collected from farmers and the efforts have created interest for the earliness of the varieties due to their performance. Specifically, involvement of women farmers in the events boosted confidence to influence decisions at the household level on technology selection and land allocation.

7. Demonstration of thresher and postharvest storage technologies

At the initial stage of the project, three different types of mechanical threshers used for other crops were evaluated on farmers' fields for threshing efficiency and convenience to farmers. Based on the feedback and limitation, modification was made on the selected thresher which increased its efficiency from 1.15 to 1.63 t h-1. In the project period a total of 2,155 of whom 571 of them were female farmers accounting for 27% of the beneficiaries were involved in the demonstrations on how to use the threshing machines. In 2021, two custom hire service providers were formed and provided threshing services to growers in two districts in Oromia region, Gololcha and Fedis. As a result, a number of farmers accessed the thresher service through a custom hire arrangement. To ensure more reliable supply and maintenance service, six workshop technicians were trained for local fabrication of the thresher. Three sorghum threshers were manufactured by the trainees, which have been used for demonstration and have been handed over to Fedis research center in Oromia and Sirinka Research center in Amhara regional states.

The project also aimed to demonstrate and distribute grain storage solutions to farmers. In 2019, a total of 507 male and 487 female beneficiary farmers were selected from nine villages. In each village, selected farmers, along with development agents and experts were trained on the use of hermetic grain storage technology (PICs bag and household metal silo) before distribution. The training focused on demonstrating how to check for air tightness before use, how to fill grains, seal and place them in the storage room. In the consecutive years training of farmers continued for additional farmers using trained development agents as trainers. Overall, a total of 3000 farmers, 32 development agents and 15 experts have been trained since 2019. The participation of women in the training was about 49%, which is more than the 30% project target. Furthermore, nine researchers from the regional research centers were also trained to monitor their usage at the regional level. During the project period along with training, a total of 5500 PICS bags were distributed to 2781 smallholder farmers. In addition, seven artisans selected from nearby major towns in the project intervention areas were trained in local fabrication of the household metal silo. The assessment made on the benefit of using the storage technologies indicated that the grain quality of sorghum could be maintained for up to six months or more and with an economic benefit on average that was 58% higher in income over the traditional storage practice.

Dehulling, which is removing the seed coat from the grain, is an arduous task for women. The project targeted to introduce and test user friendly and locally accessible dehuller to the project targeted areas and establish business models to link with the *injera* making groups in the urban areas. However, because of Covid-19 and absence of local suppliers to import the equipment, the Engineering team at EIAR fabricated an electric dehuller through reverse engineering and this is being established in the central town of Adama to provide dehulling services at a reasonable price. The prototype was tested to optimize the operating conditions for minimum losses and higher dehulling efficiency. The repeated test results showed that close to 94% maximum dehulling efficiency was obtained at lower grain inlet opening using the variety Melkam. This implies that managing the seed entering through the inlet is important to reduce breakage and improve the quality of the dehulled grain.

8. Sorghum utilization for *injera* and poultry feed as a market outlet

Sorghum has a poor value chain in Ethiopia and the lion's share of the grain is consumed at the household level. This has led to the poor adoption of improved sorghum production technologies and lower sorghum productivity. The project supported developing and delivering an optimized *injera* making protocol, capacitating *injera* making business groups to use sorghum as an ingredient in the *injera* value chain and establishing linkage with sorghum growers. The Protocol was optimized for using sorghum for injera and bread making. It was reported that mixing a 50:50 proportion of sorghum with teff can make an acceptable quality *injera* and reduce the cost by 20% compared to the *injera* made only with teff. However, the quality of bread is reduced if the amount of sorghum mixed with teff is exceeded by 20% in volume. For poultry feeds, the sorghum-based recipe for broilers and egg layers chicken was tested against the known maize-based chicken for product quality and return on investment. The study revealed that a recipe consisting of 30 to 40% sorghum would produce the best egg quality and comparable number of eggs. Both studies have shown the potential of sorghum in the food and feed value chain and could be a potential market outlet for sorghum growing farmers.

Hands on training was given to women groups engaged in the *injera* making business and at the household level. In total 84 members (77 female and 7 male individuals) from Harar, Babile, Adama, Golocha and Shenenkolu attended the practical training and obtained dehulled grain to pilot test the quality of *injera* in their business. The sorghum-based chicken feed was also demonstrated to 10 women farmers in Western Hararghe supported with 10 layers each and sorghum based scavenging feed supplement for their scavenging chicken, maize based feed was also used as a reference. The outcome of the demonstration showed that the sorghum-based recipe can be scaled up through engaging different actors in areas where sorghum is the major crop.

Synthesis of research results and development outcomes

1. Develop improved drought-adapted sorghum varieties and management packages as a tool to increase small-holder productivity

1.1. Breeding drought adapted varieties and breeding tool development for root architecture (RA) and transpiration efficiency (TE)

1.1.1. Phenotyping of sorghum genotypes for root architecture (RSA) traits

Root architecture traits reported to contribute to extracting water specifically genotypes with narrow root angle could have an advantage to grow deep and extract water under drought stress environments (Vijaya et al., 2011). Incorporation of root angle as a selection criterion in sorghum breeding programs requires a rapid and cost-effective screening method with repeatable results.

This requires screening with small soil-filled chambers to allow plants to grow for a few weeks. Since sorghum produces only one seminal root and the major root system forms from the nodal root axes, nodal root angle in sorghum influences vertical and horizontal root distribution in the soil profile and is thus relevant to drought adaptation.

Root architecture phenotyping was conducted with the view to exploring genetic variability and developing tools for future improvement to drought adaptation. In Ethiopia a total of 1929 sorghum genotypes (673 in 2019 and 376 genotypes in 2020) were evaluated in three sites (Miesso, Kobo, and Sheraro) for grain yield performance and drought adaptation traits. These genotypes were also phenotyped for root architecture traits. In addition, 56 stay green were introgressed with their recurrent parents and evaluated under field and controlled environments (Annex 1). A total of four phenotyping trials for a total of 725 unique sorghum genotypes were also conducted in Australia (Annex 9 and 10).

The result showed the presence of genetic variability for nodal root-angle traits among the tested genotypes ranging from 8.0^0 to 30.1^0, with an average root angle of 19.05^0. However, the root angles for the improved and newly released sorghum varieties ranged from 14.04 to 19.5^0 degrees, indicating that varieties showed wider nodal root angle and the risk of susceptibility of the released varieties to severe drought stress is found to be higher (Figure 1). This finding suggests that narrow root angle traits of sorghum genotypes lead to enhanced grain yield in drought-prone conditions. Also, the negative association shown between root angle and grain yield supported the use of the stay-green trait to choose sorghum genotypes with narrow root angle (Annex 1). The genetic variability in Australia sorghum genotypes for nodal RA also ranged from 9-31°. It is likely that most of the RA variation was captured for Ethiopia since representative sorghum lines from all over Ethiopia (agro-ecological zones, different altitudes, and sorghum production areas) were assessed (Menamo et al., 2023). However, sorghum breeding populations in Ethiopia and Australia need to be further evaluated.

Similar to this, stay green introgressed traits of sorghum genotypes were phenotyped, and high significant differences ($p < 0.001$) for leaf length, root vigor, and root fresh and dry weights were detected. The stay green traits of sorghum genotypes also demonstrated a significant and negative association ($r = -0.828$) between grain yield and root angle traits, indicating that narrow root angle contributed to better performance of the genotypes under drought stress environments (Figure 2). The negative association between root angle and grain yield for stay-green traits also suggests the possibility to use the stay-green trait to choose sorghum genotypes with narrow root angles.

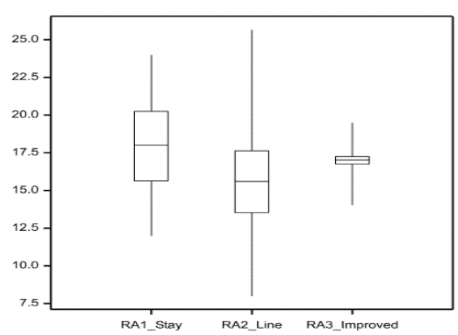

Figure 1. Box plot analysis of advanced lines, stay green traits and released sorghum

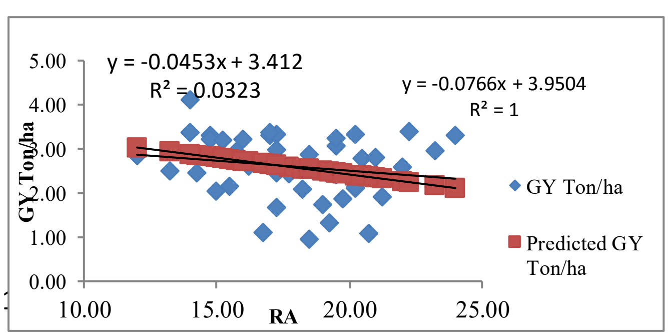

Figure 2: Association of RA and GY for stay green traits genotypes

1.1.2. Phenotyping of sorghum genotypes for Transpiration efficiency (TE) traits

In the face of climate change, availability of water resources is becoming a serious challenge and technological options are vital to utilize the available resources to address the food and feed demand in the world. Transpiration efficiency refers to biomass produced per unit water transpired. Sorghum is one of the drought hardy crops and has a potential to adapt and perform under water limited environments. Five sets of trials were conducted in Australia using a total of 1108 uniquely selected sorghum genotypes. The data generated for each run and across sets of trials was analyzed. The extent of variation in TE is relatively consistent between experiments over the past 25 years (6-9 g/kg). There is some evidence from earlier studies (Hammer et al., 1997) that wild sorghums are not a source of higher TE. Previous studies indicate that both TE and biomass components of TE are worth investigating (Geetika *et al.*, 2019).

Sorghum genotypes derived from the local breeding program were targeted for evaluation with the view to assess sorghum water use efficiency, genetic variability, and the correlation between traits for future improvement. The trial was conducted using 110 sorghum genotypes in 2022 at Melkassa Agricultural Research Center. The result showed the presence of genetic variability among tested genotypes. High heritability coupled with high genetic advance as percentage of the mean was recorded for plant transpiration efficiency and shoot transpiration efficiency. Moderate heritability coupled with high genetic advance as percentage of the mean were recorded for total dry biomass, shoot dry biomass, root dry biomass, shoot fresh biomass, water use, and leaf area. Overall, it is clear that there is considerable genetic variability among tested genotypes in water use efficiency which the program can tap in for future sorghum improvement to address adaptation to drought stress environments (Meron MSc thesis).

The ability of a plant to survive severe water stress depends on its ability to restrict water loss through leaves via both the epidermis and stomata. Hence leaf (and also root) anatomical traits that optimize the balance between water supply and demand are critical for production in water-limited environments. Histological work was done in Run 4 on a sub-set of 20 genotypes selected from the TE experiment. The genotypes selected were four racial backgrounds (Caudatum, Durra, Karfir and Guinea) and elite sorghum lines developed in Australia. Using nail varnish, stomatal imprints were taken from the middle of the leaf adjacent to the section taken for leaf anatomy. In each imprint, stomatal density and aperture lengths were recorded in three different fields of view. The overall result indicated that leaf and root anatomy contribute to functional aspects of transpiration efficiency. This will assist plant breeders to select for more drought-adapted types.

1.1.3. Genomic analysis to identify markers linked to RA and TE

The project supported development of Nested Association Mapping populations (NAM) derived from 15 selected lines based on the genetic distance and specific merits to be used as mapping population and line development. A total of 2074 recombinant inbred lines (RIL) were developed for future use of which 32 of the lines were selected and being tested in the advanced variety trials. A total of 1187 sorghum genotypes derived from the NAM population having more than

200 RIL and the sorghum genotypes phenotyped for RA and TE were sequenced using DArT seq platform in Australia. The data is being used as part of the PhD studies to identify marker linked to RA and TE. Bioinformatics support is required to undertake the genome wide analysis and identify diagnostic markers for the breeding program to be used in the future.

1.2. Identifying favorable combinations of varieties and management systems using crop simulation modeling and agronomy

1.2.1. Development of fertilizer and plant population management options for the newly released sorghum variety

Trials were conducted in Erer, Kobo, and Sheraro research centers representing the dry land areas of Eastern, Northeastern and Northern part of Ethiopia, respectively. The rainfall distribution in the Erer and Kobo areas is bimodal, whereas it is monomial in the Sheraro areas. For the growing season (July-October), cumulative rainfall at the three sites ranged from 392 mm at Erer to 429 and 797 mm at Kobo and Sheraro, with July and August accounting for more than 64% and 70% of the seasonal rainfall at Erer and Kobo and Sheraro. The on station trial conducted in 2019 and 2020 across the three test sites revealed that plant population had insignificant effect and varied response for P fertilizer. This could be related to the compensation effect of the plant through tillering for the low population and enough availability of P fertilizer in the soil. Hence, the plan was revised to determine the rate of N fertilizer with reduced rate of P levels. However, in 2021 because of security reason in the Northern part of the country trials was conducted in Oromia region at Fedis and Erer research stations. The nutrient rates evaluated were: 0, 23, 46, and 69 kg N ha-1; 0, 5, 10, and 15 kg P ha^{-1}.

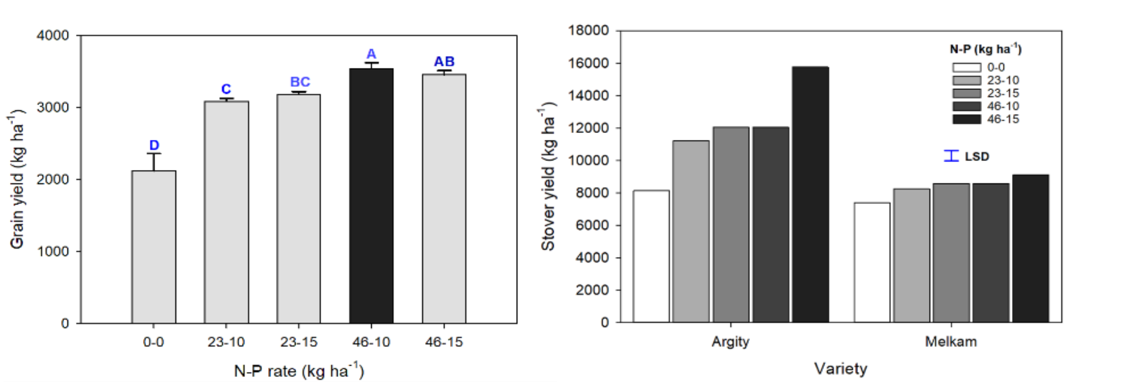

Figure 3. A) Effect of N-P fertilizer on: a) the grain yield and the interaction effect of variety by N-P Fertilizer rates and b) stover yields of Argity and Melkam in 2021 at Fedis and Erer districts, Eastern Ethiopia

The statistical analysis revealed that N and P rate and their interaction has showed significant variation, however varietal difference has not shown significant variability indicating the Melkam and Argity respond similarly for fertilizer application. There was increased sorghum yield in response to nitrogen application for both varieties. The yield increases due to N application ranged from 764 to 1871 kg ha^{-1} corresponding to an increase of 43 to 106% compared to the no N application. There was no form of statistical response curve found for P application, but generally grain yield increased up to 10 kg P ha^{-1} but it was inconsistent across the N rates and the varieties. Agronomic efficiency, for N and P (AENP) is defined as a kg of crop yield increase per kg of NP nutrient applied. The highest agronomic efficiency for fertilizer N and P was 32 kg ha^{-1} with 23 kg N and 10 kg P ha^{-1} and the lowest was 22 kg ha^{-1} with 46 kg N and 15 kg P ha^{-1}. The maximum VCR of 2.5 was achieved at the fertilizer rate of 46 kg N and 10 kg P ha^{-1}, followed by 23 kg N and 10 kg P ha^{-1} with a VCR value of 2.1. The grain yield from NP fertilizer over control ranged from 38% up to a maximum of 94% as the rates of NP were progressively raised (Figure 3a). The interactive effect of variety by NP rates was significant on the stover yield of sorghum. The stover yield of the Argity variety increased significantly with NP fertilizer application (Figure 3b).

1.2.2. Computer simulation for environmental characterization and crop adaptation (GxExM analysis)

In 2021, field experiments were set up under non-limiting (water and nitrogen) circumstances as part of environmental characterization activities to parameterize the APSIM-Sorghum crop development and growth model for the locally adapted variety, Argity. The main objective of the experiment was to develop predictive phenology models of a range of Ethiopian germplasm and parameterize and validate the APSIM-sorghum model for the development and growth of one of the improved sorghum varieties that was bred to achieve an ideotype with desirable adaptive traits for a dual-purpose both food and feed source in the mixed-smallholder farming systems of the semi-arid Ethiopia.

2. Enhance small-holder productivity by extending new varieties, improved agronomy, labor-saving threshing technologies and grain storage technologies

2.1. Increasing sufficient seed stocks of improved varieties for smallholder farmers

Getting quality sorghum seed is a critical challenge to farmers in Ethiopia because the private seed growers are not engaged in sorghum seed production. The informal seed system is the dominant seed delivery mechanism. The formal seed system has limited interest due to the self-pollinating nature of the crop and the lower seed rate (12 kg/ha). It is thus vital to create demand for improved technologies and create interest for seed growers to invest in sorghum seed business on demanded varieties by farmers. Demonstration of the improved sorghum varieties was conducted while engaging the formal and community seed growers for sustained accessibility of the varieties. The early generation seed (breeder and pre-basic seed) classes were targeted to multiply by the research centers while the certified seed by the regional seed enterprises and Quality Declared seed (QDS) by organized seed grower communities. Hence, 100 kg breeder and 2500 kg pre-basic seed were targeted annually to be multiplied by the research centers. Since the commencement of the project a total of 697 kg breeder seed 15,340 kg pre-basic seed for three preferred varieties (Melkam, Argity and Girana-1) was conducted to be used as a seed source for the certified and QDS seed multiplication (Table 1).

Multiplication of certified and quality declared seed (QDS) was to be promoted to users through demonstration and cluster-based promotion of the varieties to larger number of farmers. The varieties selected through demonstration with the participation of the farmers and regional collaborators multiplied with the support of the project. While the aim was to produce 225 tons of certified and QDS seed, 208 tons certified and QDS seed were multiplied, which was 92 % of the target.

Table 1. Seed multiplication plan and achievements for different seed classes, since 2019

1. Breeders seed multiplication (kg)				
Year	**Variety**	**Planned**	**Multiplied**	**Reporting center**
2019	Argity	100	110	
2020	Argity	100	110	Melkassa and Fedis
2021	Argity and Melkam	100	210	Melkassa and Fedis
2022	Melkam and Girana-1	100	267	Sirinka
	Total	**400**	**697**	174%
2. Pre basic seed multiplication (kg)				
2019	Argity	2500	3,000	Mehoni,
2020	Argity, Melkam	2500	3,000	MARC, SARC
2021	Argity, Melkam	2500	3,000	Melkassa. Kobo
2022	Argity, Melkam & Girana-1	2500	9,340	Sirinka
	Total	**10000**	**15,340**	**153%**
3. Certified/QDS seed multiplication (Tons)				
2020	Melkam and Dekeba	75	68.16	Melkam (67.4) Dekeba (0.76)
2021	Argity	75	27	Melkam
2022	Melkam and Argity	75	112	Melkam (108 tons Melkam and 4 tons Argity)
	Total	**225**	**208**	**92.4**

2.2. Extending new short-duration high-biomass sorghum varieties and management packages to smallholder farmers

Delivering climate resilient improved production technologies through on farm demonstration, training of the development agents and farmers is useful to create demand on the technologies thereby increase productivity. For improved varieties to be adopted by farmers, the varieties should meet the farmers most preferred traits. In sorghum grain yield, plant biomass and grain quality mainly for *injera* making are the must have traits while overcoming the drought stress for the varieties and acceptance allow for greater uptake. The variety *Argity* was developed to address the three required merits that the project targeted to demonstrate and promote to the dry lowland areas. In 2019 the demonstration was conducted in three of the project targeted regions (Amhara, Oromia and Tigray). In 2020 and 2022 the demonstration was conducted in two of the regions, Amhara and Oromia, while in 2021 the project could only work in Oromia due to the security situation in the other target regions. Accordingly, adjustments were made to meet the project target.

Demonstration was conducted using recently released varieties along with what farmers use ordinarily to identify the preferred varieties and adaptation to the different stress situations in the project target areas. In total, 323 demonstrations were conducted in farmers' fields and farmer training centers (FTCs), which was 90% of the project target (Table 2). In this activity farmers received the improved varieties and training on production management and considered also interventions to empower women in accessing technologies and decision making. From the total farmers engaged on demonstration activities 19% of them were women farmers who owned farmland, which is less than the 30% project target. This low participation of women farmers is related to the problem of getting women headed households who own land. Besides the demonstration activities on selected farmers, training was given to development agents on the improved package. Follow up and field days were organized to disseminate the good practices to the neighboring farmers and beyond. During the project period training was given to 247 development agents and experts from the bureau of agriculture. From these, 53 of them were female accounting for 21.4 % of the total participants.

The demonstration activities in 2022 were conducted in Kobo area in the North Wello zones and Kalu and Ambasel districts in the South Wello zones of the Amhara regional state; and in Fedis district in the Eastern Hararghe and Shenenkolu areas of the Arsis zone of the Oromia regional state. The results indicated that the variety Melkam had consistently superior performance ranging from 7 to 33% compared to the variety Argity and Tilahun except at Fedis in Eastern Hararghe (Figure 4). The variety Melkam gave 4.8 tons/ha at Kobo and Argity gave 4 tons/ha at Fedis indicating these varieties can be scaled up in areas adapted very well and is preferred by Farmers. Generally, the highest mean grain yield across the two regions was (3.9 tons/ha) obtained from Melkam followed by Argity (3.4 tons/ha). In comparison to the location and national productivity of sorghum which is 2.7 tons/ha, farmers obtained an average of 44% grain yield advantage (Figure 4). The variety Melkam has demonstrated early maturity which helps the variety to escape the late moisture stress and have better grain yield and wider adaptability as compared to the other varieties. Melkam is, therefore, the variety that can be taken up by the formal seed system to address the demand by farmers. The variety Argity and Tilahun were relatively late in flowering and were vulnerable to terminal drought stresses, which frequently occurs in the dry lowlands of Ethiopia (Tirfessa et al., 2023). However, the varieties were preferred by farmers for the better plant biomass (tall plant height) and equivalent grain quality like that of Melkam. Hence, integrating the variety with water conservation practices as well as improvement through transferring stage and narrow root angle genes would help the variety to resist the terminal drought.

Table 2: Summary of number of demonstrations established in the project target areas farmers field and farmers training centers (FTC)

Year	Region	# of demonstration	Number of demonstrations		FTCs
			Men	Women	
2019/	Amhara	31	20	1	10
2020	Oromia	5	0	0	5
	Tigray	24	17	7	5
2020/	Amhara	42	26	7	9
2021	Oromia	62	45	11	6
	Tigray	80	66	14	0
2021/	Oromia	54	41	12	1
2022	Amhara	25	15	10	
Total		323	230	62	36

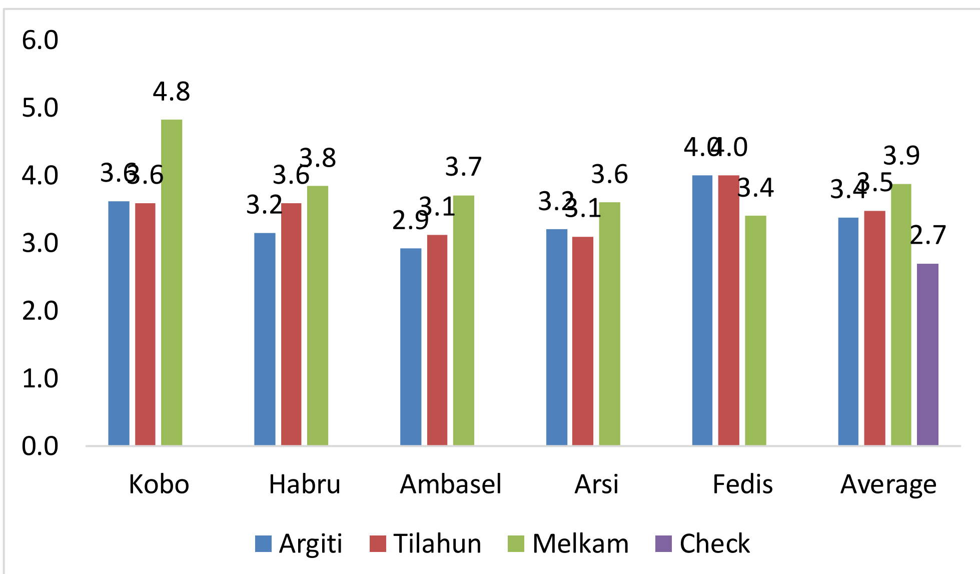

Figure 4. Mean performance of demonstrated improved varieties in the project target areas,

2.3. Scaling up of improved sorghum production technologies (Clustered farmers)

Based on the demand from the demonstration activities scaling up of the preferred improved varieties and production package was undertaken in different sorghum producing areas of the targeted regions. The varieties were scaled up by using large scale demonstration (LSD) through clustering neighboring farmers based on their interest to use the same technologies with the farm size ranging from 5 to 10 ha land and small seed pack approaches with the volume of 2 kg per pack. In the large-scale demonstration, 2806 ha of land was covered by 8523 farmers of whom

1308 were women accounting for 15% of the total beneficiaries (Table 3). In addition, seed of the preferred varieties were also distributed through the formal extension through the bureau of Agriculture, estimated at more than 12000 farmers. This implies that the project benefited 20,523 farmers who have accessed the technologies directly with the support of the project. The technology promotion activities were accompanied by distribution of promotion materials (brochures and leaflets) of the improved technologies. In addition to this, a total of 5579 participants attended the field days of which 1151 of them were women farmers.

Table 3. Large scale demonstration participant and area coverage

Year	Region	Area covered	Number of participant farmers		Total
			Men	Women	
	Amhara	240	566	44	677
2020/ 2021	Oromia	303	552	178	730
	Tigray	1480	4237	810	5055
2021/2022	Oromia	477	980	245	1225
	Amhara	306	725	111	836
Total		2806	7060	1388	8523

2.4. Demonstration of thresher and post-harvest storage technologies

The traditional mode of threshing sorghum is very inefficient and leads to quantitative losses and production of poor-quality grains. The harvesting, drying and threshing losses reported for sorghum in Ethiopia was 11.3 % (FAO 2017). It is well known that the traditional manual sorghum threshing and cleaning is a most tedious and time-consuming task. Getting labor for such kind of task is a challenge in many rural communities and it is a burden for women and school children. Three different threshers were identified and tested for improvement; i) Melkassa made auger type maize sheller, ii) Melkassa improved IITA axial type thresher, originally developed for maize and later adapted for small cereals (teff and wheat) and iii) Melkassa made pulse thresher. Based on the efficiency of the thresher and feedback from farmers and other beneficiaries the IITA thresher was selected, redesigned and fabricated for demonstration.

The newly modified thresher incorporated a cleaning unit by adding a blower component and an oscillating sieve mechanism and evaluated for its performance on farmers' fields. The threshing capacity was improved from 1.15 to 1.63 t h-1 by increasing the feeding chute opening from 23 cm to 30 cm and providing a chaff cutter knife on the edge of the peg holder frame of the drum for quick chaff cutting. The thresher can be operated by men, women, and children above 18 years of age. Assuming an 8-hour working day at 50 % efficiency, the modified thresher requires 4 persons (32 man-hours) to feed and operate the machine and thresh 6.5 tons of clean grain in a day. Alternatively, it would take 12 working days (186 human-hours) to thresh the same quantity with the same number of people using manual beating method. Likewise, animal threshing methods demands 4 persons and 9 animals for about 3 working days (Table 4).

In 2019 a total of 1172 male and 456 female farmers and 62 experts of which 16 were female, participated in the demonstration of the threshing machines and gave their feedback. In the 2020 crop season, testing and demonstration of the sorghum thresher was conducted at Shenekolu and a total of 355 farmers constituting about 23% women farmers were involved. In the project period a total of 2155 of whom 571 of them were female farmers accounting for 27% of the beneficiaries were trained on the use of the threshing machine. To ensure reliable supply and maintenance service of the threshing machine, training was undertaken for six workshop technicians (selected from nearby major towns in the study area). As a result of this training three sorghum threshers were manufactured and delivered to the three collaborating centers (Sirinka, Fedis and Melkassa) to use for demonstration and provide services to the farmers in their areas.

Table 4. A comparison of sorghum threshing methods on performance parameters at Gololcha and Fedis districts, Ethiopia

Parameter	* Mean performance		
	Manual beating	Animal threading	Thresher
Threshing capacity	0.28 ton/man-days	2.5ton/day	6.574 ton/day
Threshing loss (%)	6.9	3.26	2.98
Cleaning efficiency (%)	97.8	97,8	99.6
Fuel consumption (liter/ton)	-	-	1.48
Number of livestock per ton in a day	-	9	-
**Labor for threshing (man-days per ton)	3.54	1.74	0.29

*Mean of three test runs;** labor required for threshing and cleaning

2.5. Extending small- and medium-scale grain storage solutions to smallholder farmers and unions

Traditional grain storage loss is one of the major contributors for post-harvest loss which is estimated at 12 % in Ethiopia. In most cases farmers are forced to sell the grain during peak time when the grain price is low and store it using the traditional means which results in deterioration of the grain due to insect damage or fungal infection. Therefore, safe storage of grains benefits farmers as they get better prices and maintain the quality of grain by protecting it from insect and fungal infection. The project introduced hermetic storage technologies such as PICS bags and household metal silos as a technological option to demonstrate and train farmers on how to use the technologies.

Between 2019 and 2022, a total of 4412 farmers, 216 development agents and 22 experts selected from eight districts of the project intervention areas were trained on hermetic grain storage principles and the practical application of PICs bag and household metal silo. From the total trainees 48% of them were female farmers and technicians working at district level. Development agents and experts trained at the initial stage were used as trainers in the consecutive years. As an important tool and step, extension materials (posters, operation manuals, leaflets) were prepared and shared to provide a guideline to the trainers. During the project period, along with farmer training, a total of 5500 PICS bags were distributed to a total of 2781 smallholder farmers. In addition, seven artisans selected from nearby major towns in the project intervention areas were trained in local fabrication of the household metal silo. The assessment made on the benefit of using the storage technologies indicated that the grain quality of sorghum maintained up to six months or higher and with economic benefit on average 58% higher income than the traditional storage practice. Farmers are now aware of the benefit they can get using the two technologies and linkage was established with the PICS bag suppliers. The training of local artisans will help interested farmers to get the household metal silo of different capacity.

2.6. Gender analysis and women empowerment in project target areas

The project undertook two surveys to analyze the gender gaps and women's empowerment in sorghum production and utilization. Focus group discussions (FGD) and key informant interviews (KII) were conducted for the gender analysis. In the survey, a total of 57 male headed households (MHH); 39 female headed households (FHH); 56 women headed households (WMHH), and 17 key informant interviews (KII) were undertaken in selected districts of the three regions. Different data was collected including gender roles and responsibilities, variety preference, seasonal calendar and daily activity representing dry and wet periods, access to and control over income, decision making, and constraints were some of the data collected through FGDs.

The result of the gender analysis showed that across the three regions women actively participate in productive, reproductive and community roles, while men mainly have productive and community management role. This result is also reflected in the daily activity profile indicating that women relative to men have work burden both in the peak and slack seasons. Compared to the women in male headed households, the women in female headed households contribute a greater percentage of labor to productive and community management roles. However, it is girls in women headed household that play a major role in reproductive activity than FHH this result is similar across all regions. Women work more hours per day in Oromia, Amhara and Tigray region. Across the regions extended drought, lack of drought tolerant varieties, striga and weed, shortage of improved seed, shortage of oxen to plough their land and farm implements, pests and rodents, stalk borer and fall army warm damage were raised as a key production challenges. In addition, lack of access to capital, increasing input cost and lack of adequate product market were also indicated as constraints in the survey areas.

Surveys were also conducted using the Pro-WEAI tool in Amhara and Oromia regional states. The survey was aimed at identifying the level of women empowerment in the project target areas and analyzing gender disparity within and between households. In this survey a total of 300 households, 86 female adults only households and 214 dual adult male household were selected. Since the pro-WEAI survey employed individual interview of DHHs (Dual households) primary male and primary female of dual households were interviewed. The total sample size of individual interviews was 514 (214men and 300 women).

The analysis showed that lack of membership in influential groups, group membership, access to and decision on credit, lack of autonomy in income and respect among HH members were the main sources of disempowerment among women and men. More than two thirds of men and women have not yet achieved adequacy in membership to influential groups, group membership, access to and decision on credit, and autonomy in income. Lower adequacy for autonomy in income may indicate that household incomes are inadequate to meet the needs of household members. This inadequacy could be a result of lack of income-generating activities. The project targeted to enhance group participation by involving women and men farmers in seed producers and LSD groups and training to empower them on input and productive decision making. In addition, involving women in the on-farmer demonstration to have access on the technologies and engaging them on post-Harvest technology use and access.

3. Enhancing demand for sorghum by enabling markets and small businesses

3.1. Developing sorghum-based products and deploying to women-owned small-scale injera and bread baking enterprises

Dehulling sorghum grain helps to remove the grain cover which contributes to the low quality of *injera*. Dehulling removes the outer cover or bran layers containing high crude fiber and anti-nutritional factors such as tannins and phytic acid. However, Sorghum dehulling is mostly done traditionally by using a mortar and pestle which is a tedious and time-consuming task. In the Ethiopian farming community women perform almost the entire in-house activities and dehulling is a back breaking task for the rural households. Sorghum is a preferred grain for *making injera* and the soaring price of teff increases the use of other options for daily consumption and for the *injera* business in the urban areas. Dehulling technologies are required to reduce drudgery at the household, reduce the cost of food and create market opportunities for farmers which would encourage them to use improved technologies and increase their productivity.

A preliminary observation and preparation of fabrication drawings of the available dehulling machine (obtained through IDRC Project long time ago), was done to generate design information and understand its operating mechanisms. The dehulling equipment was then locally manufactured in a reverse engineering process with some modification to utilize locally available material. Based on functional test runs the reproduced dehullers accomplished the dehulling process and showed promising results on dehulling efficiency and rate for a local variety. The prototype was tested to optimize the operating conditions for minimum losses and higher dehulling efficiency. The repeated test result showed that 93.5 % maximum dehulling efficiency was obtained at lower grain inlet opening using the variety Melkam.

Figure 5. Dehulling machine fabricated using reverse engineering, undehulled and dehlled sorghum grain

The use of composite flours has a long-time history. Even though sorghum alone or in combination with teff is used for staple food preparation in Ethiopia, the extent of its use is still limited. Particularly, the urban community does not consume sorghum-based products mainly due to the poor image they have about the grain. This showed that there is a need for awareness creation through developing *injera* and bread making standards. Besides, the price of teff based *injera* shows an increase and the productivity of this grain is still not matched with the demand on the ground. This situation has forced the urban community to look for optional grains like sorghum and others. Therefore, protocol development and improvement on the *injera* and bread making processes and demonstrating the protocols to organized women group supplying *injera* to hotels and residents would benefit both the growers and the consumers.

To determine the proportion of sorghum and tef, seven proportion treatments (containing 0 to 63.5% sorghum with teff) were tested. The optimum formula of *injera* in terms of colour, overall acceptability and L* (*injera* whiteness in colour) value consisted of 50% tef and 50% sorghum, with a desirability of 0.909. The optimized *injera* had colour, overall acceptability and L* values of 7.05, 7.78 and 67.21, respectively. Numerical optimization also indicated that better sensory, proximate and mineral qualities are directly related to the proportion of sorghum and tef. These findings suggested that the best quality *injera* would be achieved by mixing 50% sorghum with 50% tef and a manual was developed on optimized *injera,* making the protocol available for wider use. In addition, composite flours containing 10%, 20%, 30%, 40% and 50% sorghum with wheat were evaluated to identify physicochemical composition, dough properties and sensory analysis of the resultant bread. The addition of sorghum had a significant increase of protein, moisture and ash content of the composite flour. There was a significant decrease in bread volume with sorghum replacement of higher than 40%. Although increasing wheat replacement negatively affected the physicochemical and rheological properties, the sensory quality of the bread remained acceptable. In general, the result showed that 20% sorghum with 80% wheat can give acceptable quality bread.

The *injera* making protocol extended to enterprises targeting the project intervention areas to create market opportunity for sorghum growing farmers. In Oromia region five different women's groups of 10-15 women members were established. In total so far 84 members (77 female and 7 male individual) engaged in *injera* baking business and households' consumption at Harar, Babile, Adama, Gololcha and Shenenkolu benefited through the project by training on the improved *injera* making protocol and getting dehulled seed as a pilot to test the quality of *injera* in their business. Training was given on sorghum nutrition, major sorghum grain contaminants, purpose of sorghum grain de-hulling, *injera* making recipes and processes, and consumer preference of sorghum-based value added *injera* along with practical training on the manual. Assessment has been made to evaluate the perception and the use of sorghum based *injera* making protocol. The groups commonly mix up to 10% sorghum with tef and they found that dehulling would help to increase the proportion of sorghum up to 50% with improved *injera* quality. Accessibility of a small scale dehuller is the major challenge to the expansion of the technology to wider users. The dehuller, fabricated by the mechanization department, would be setup in central town (at Adama) to give dehulling service and deliver dehulled grain as a business model for youth in the urban areas. A low cost user-friendly dehuller would be a beneficial addition for the local community.

3.2. Developing and demonstrating sorghum-based feeds for chicken

The poultry farming industry in Ethiopia has made a dramatic development trend and availability of high quality and low-cost chicken feed is a major challenge for the industry. For this reason, the cost of chicken meat and eggs is unaffordable for most of the rural and urban consumers. It is widely known that sorghum is a major animal feed crop in the developing world; however, the crop is not used as a source of feed for the industry. Activities were conducted with the aim of addressing the possibility of using sorghum as a viable component for the chicken feed supply industry in Ethiopia. This involved research into the nutrient profile of sorghum varieties in Ethiopia, including the high-lysine sorghum varieties, and chicken feed conversion ratios of diet mixed with other grains, in addition to an economic analysis of the value-chain, considering both small holder farmer enterprises, and linking with larger-scale poultry farming enterprises.

The experiment conducted to develop sorghum-based chicken feed showed no significant difference on feed intake among the birds that were fed with the conventional (maize-based feed formulation) and sorghum-based diets (treatment diets formulated with different levels of sorghum). Partial budget analysis result in this study showed a significant difference. A better net benefit was obtained by treatment groups of Degalit Yellow at all levels than Melkam at the level of inclusion of 30-40%. From the results revealed by most parameters of egg production and egg qualities considered, it can be concluded that sorghum variety Degalit for egg production and sorghum variety Melkam produced better egg quality aspects. The sorghum-based chicken feed demonstrated to 10 women farmers in Western Hararghe were supported with 10 laying hens each and sorghum based scavenging feed supplement for their scavenging chicken, maize based feed also used as a reference. The farmers were selected purposively based on their interest to participate in the experiment and egg production over a month was tested. The sorghum based scavenging feed supplement results and the farmers' perceptions were promising for the extension of the technology to other farmer and farmers group.

Synthesis of results towards AFS themes

i. Increasing agricultural productivity:

Sorghum is the dominant crop in the dry lowland areas grown primarily for food, and its biomass is also equally important for animal feed and fuel sources. Climate change is the major challenge in the semi-arid tropics. Specifically, there is a high risk of crop failure in the dry lowland areas where there is high variability in the onset, distribution and cessation of rainfall. Development of climate change resilient sorghum variety and use of improved management practices is vital for increased sorghum productivity while addressing the feed demand in drought prone areas of Ethiopia. The project aimed to promote the recently released high grain and biomass yielding variety, Argity, along with the improved management practices. During the project period seven varieties released by federal and regional research centers were demonstrated to identify preferred varieties and varieties adapted to the target environment. The variety Melkam was found stable across target environments followed by the variety Argity for its additional merit of high plant biomass. The improved varieties had superior performance than that of the local varieties and management practices with the advantage ranging from 33 to 44% (2.7 VS 4.8 tons/ha). This indicated the possibility of increasing productivity using the improved technologies. Therefore, it is vital to scale up the improved varieties along with water management practices to increase sorghum productivity thereby improving the livelihood farmers in the drier areas.

The project also supported research to develop improved varieties that can adapt to drought stress by understanding the root architecture and transpiration efficiency of the breeding populations and developing tools to increase breeding efficiency. Optimization of the soil fertility management in view of the current climate change scenarios was targeted in the project. Awareness creation on the improved management practices through demonstration and training were integrated in the project for sustainable impact on sorghum production and productivity.

As a consequence of climate change, increased frequency and severity of drought is predicted in Ethiopia and Australia. One strategy for coping with this changing climate is to develop crop plants that are better adapted to hotter and drier conditions. This project demonstrated the availability of genes in sorghum with traits that can improve water extraction from depth (narrow root angle) and water use efficiency (transpiration efficiency). For both traits, heritability is sufficient for selection in breeding programs. Growing such drought-adapted varieties is a risk mitigation strategy for smallholder farmers in Ethiopia and for large-scale farmers in Australia. The study also revealed that selection of narrow root angles needs to be considered to make the varieties withstand drought stress. The genetic material and genomic data generated through the project will help the breeding programs to design targeted breeding and develop markers for important agronomic traits. Future investment is required to understand the effect of TE on drought adaptation and product development resilient to the risk of climate change.

The manual methods of threshing and traditional storage using ground pits and polyethylene sacks contribute to the post-harvest losses of sorghum. In addition, threshing is an arduous task that requires the entire family to spend the whole day to thresh one ha of sorghum. With the support of the project, a threshing machine with the capacity of threshing 1.6t/h and being 2.6 times more efficient than the threshing with animals was demonstrated, and farmers showed interest in accessing the services through rent. Creating access to this technology will help to reduce the burden of women engaging in threshing sorghum and reduce post-harvest losses by up to 30%.

Three of the key outcomes of this project are a) developing drought-adapted sorghum varieties, b) identifying sorghum-legume cropping systems, and c) recommended fertilizer application in drought risky and resource poor famers as a transformational intervention. Together, these options enable sustainable intensification of sorghum-based cropping systems, thereby positively contributing to ensure productivity and environmental sustainability in Ethiopia.

ii. Improving access to resources, markets and income

Farmers have limited options to know and access the improved sorghum production technologies. Through the project, farmers had a chance to evaluate the advantage of using improved technologies for increased productivity and also accessed seeds through demonstration, community-based multiplication and from the formal seed growers. Through the project support, 323 farmers directly benefited from the improved technologies through demonstration and 8523 farmers through LSD and small seed packs and 12000 farmers accessed the improved varieties. The created demand on the variety Melkam attracted the public seed enterprises to multiply certified seeds and deliver to farmers.

Current methods of sorghum grain storage used by smallholder farmers, such as hessian sacks or ground-pits, result in high losses due to insect pest damage and infection by fungal pathogens. Small-scale on-farm grain storage (e.g. PICS system) ensures that grain will be more readily available at any time of year, overcoming constraints of limited grain supply for sorghum-based industries. This assumes that surplus grain supplies will be generated by the new drought-adapted sorghum varieties. In this project, smallholder farmers were introduced to and accessed small-scale grain storage PICS bag of 50kg storage capacity and medium size metal silos. This helped farmers to get better income, to develop and maintain linkages between sorghum growers and end users. The assessment made on the benefit of using the storage technologies indicated that the grain quality of sorghum could be maintained for up to six months or more and with economic benefit on average 58% higher income over the traditional storage practices.

The project also tried to address the two end uses of sorghum as a market outlet for sorghum as a driver to enhance adoption of sorghum production technologies. The optimized 50:50 sorghum teff mixture and chicken recipe developed with up to 40% sorghum mix can be scaled up for wider use and could be a potential market for sorghum growing farmers. The technological interventions through production to marketing such as threshing, dehulling and the chicken feed are possible job opportunities for youth and women involved in the sorghum value chain.

This project contributed to improved income by the development of new higher-yielding drought-adapted sorghum varieties for smallholder farmers. These varieties exhibited early maturity and high biomass, thereby enhancing grain and stover yields. Increased farm incomes could also be achieved by double cropping of short-season legumes as a preceding crop to the main season sorghum crop, as demonstrated by long-term simulation modeling. This approach could be a transformational intervention in the dry lowlands where bi-modal rainfall patterns prevail as a pathway for sustainable intensification of sorghum-based systems.

iii. **Improving nutrition:**

The *injera* making protocol developed using sorghum mixed with teff could have significant impact on reducing the cost of food and increased nutritional quality due to dehulling of the seed coat and complementarity of the two crops. The use of sorghum as chicken feed can be a market outlet for surplus grain. This could reduce the cost of feed, thereby, increase access for chicken meat and egg and improve the nutrition level of society.

This project has shown that significant genetic variation exists for root system architecture in sorghum, with root angle ranging from 9-31^{o} from the main root. Roots are of fundamental importance for plant growth because they control the capacity of plants to take up water and nutrients. It is increasingly advocated that breeding programs should select root functional traits, such as root angle, with the idea that this will deliver root system architectures (RSAs, the spatial and temporal distribution of roots in the soil) that are better adapted to explore specific soil domains and acquire limiting soil resources (van der Bom et al., 2023). Notable examples of RSA targets are deeper rooting patterns for improved access to soil water at depth in drought conditions, and shallower rooting patterns for improved access to limiting nutrients that are often more concentrated in the top of the soil profile (Lynch 2019).

Plant breeders in Ethiopia and Australia will now have the capacity to select wide root angle for low-nutrient soils or narrow root angle to extract water from depth, or possibly select for a root architecture that does both. Increased nutrient extraction from the soil by improved RSA should increase nutrient levels in grain and stover. Increased nitrogen uptake during the grain-filling period has previously been demonstrated in stay-green drought-adapted sorghum lines (Borrell and Hammer, 2000; Borrell et al., 2001).

Sorghum-based cropping systems provide another pathway to increase nutritional requirements for smallholder farmers in Ethiopia. The most important issue for subsistence farmers is to provide sufficient food for their families. Not only is the volume of food important, but the quality of food must meet the nutritional needs of the household. Switching from a sorghum monoculture to a sorghum-based cropping system enhances the nutritional quality of the diet by the inclusion of legumes (which also improves soil quality).

iii. Informing policy:

The project organized annual planning and review meetings to present the progress made and share with the different stakeholders and government officials about the project's progress. In these annual meetings, critical issues were raised and discussed, and the final report compiled and documented. In addition, policy makers from federal and regional bureaus and media were invited for the field day events to demonstrate the performance of the technologies and the post-harvest technologies. In the field day farmers gave their testimonials on the technological options that reflected their interest to access the technologies with different arrangements. As the project did not have a media specialist knowledge sharing through documentaries, short videos, and mainstream and social media was a challenge. However, local and national media were invited to attend the field days and covered the stories as documentaries or news.

1. Documentary on the use of the improved technologies with project support in the national media in Amharic language: https://www.youtube.com/watch?app=desktop&v=frAv6jOvo2E#searching
2. Farmers feedback on the improved technologies in Oromia region in Afan Oromo language: https://drive.google.com/file/d/1b5ngIWjlVixwFl9P4cGSEwaNikt4rFQ8/view
3. News on the on-farm activities in Amhara regional state, 2022/23 in Amhara regional state https://www.facebook.com/AmharaMediaCorporation/videos/815033263085187/?mibextid=TfNwVoErvbAdloke (at 21-25 minutes).

Project outputs

Publications

1. A research report on: Gender Disparities in sorghum production and utilization. Annex 12 Gender analysis report.pdf

Planned to be published:

1. Genetic dissection of root architecture in sorghum
2. Genetic dissection of transpiration efficiency in sorghum
3. Canopy development drives water use and transpiration efficiency in sorghum
4. Leaf anatomy impacts transpiration efficiency in sorghum
5. Nutritional Evaluation and Feeding Value of Sorghum (Sorghum bicolor L. Moench) Varieties in the Performance of Layer Chicken
6. Root architecture analysis and its implication for drought adaptation in Ethiopian sorghum genotypes
7. Measuring Women empowerment in sorghum production: Pro-WEAI Results from Oromia and Amhara regions, Ethiopia
8. Exploring the On-Farm Potential of Improved Sorghum Varieties for Scaling In Dry Lowland Areas of Ethiopia

Posters and paper presentation

1. Australian Summer Grains Conference, March 2023) which are also attended by grain-growers.
2. To be presented in the 2023 Global sorghum conference
    a. Measuring Women empowerment in sorghum production: Pro-WEAI Results from Oromia and Amhara regional states, Ethiopia
    b. Site-specific N and P fertilizer for improving the productivity of the smallholder sorghum systems in semi-arid Ethiopia
    c. Root architecture analysis and its implication for drought adaptation in Ethiopian sorghum genotypes

Long term training: Two MSc students (one male and one female) students supported to do their post graduate studies at the local Universities and graduated. Thesis submitted to IDRC as annexes 8 and 11. One PhD student is finalizing his research and will graduate in 2024.

Problems and challenges

Global and local challenges occurred during the project implementation. Efforts were made to overcome the challenges through discussion with project partners and the IDRC project management team. The following are the major challenges the project faced during the implementation of the project.

1. **Project duration**

The project launched just at the commencement of the main crop season in Ethiopia, which created a challenge to properly plan the activities with the project partners. Through discussion with the project management team, implementation of the major activities commenced so as not to lose the first year of the project. In addition, as the project involved different disciplines and actors for the duration of the project, it would have benefitted from more time to ensure sustainability of the technological interventions.

2. **Covid-19 pandemic**

Covid-19 was a global incident that had an impact on project implementation due to restrictions on movement and gatherings that also delayed procurement processes. Different strategies were used following the safety standards to avoid infection and virtual means were used to communicate with partners in planning and monitoring the project activities. Some of the projects focusing on modeling and genomics research activities were to be implemented with technical support from the University of Queensland. The pandemic affected the implementation of those activities.

The Australian end of the project faced significant challenges, largely due to a global pandemic combined with a strong and rare 3-year La Nina event. Screening of root angle at UQ's St Lucia campus in Brisbane was delayed due to a) COVID lockdowns during 2020 and 2021 at UQ, and b) devastating flooding of the Brisbane River in Feb/Mar 2022 which inundated UQ glasshouses, including the root phenotyping platform. The root phenotyping platform subsequently had to be moved to another location to complete the screening (this required dis-assembling and re-assembling all 500 plates).

3. **Security problem**

The security situation in some part of the project implementation areas of the Tigray and Amhara regional states was a challenge to follow up the on-farm activities, involvement of highest officials on field days and demonstration of the post-harvest technologies. Based on the security situation planned activities were revised focusing on areas safe for traveling. In addition, the project focal persons assigned in each of the region took the responsibility to follow the local activities. Despite the challenge, the project management set up and coordination among the team contributed to the successful implementation of the project.

Overall assessment and recommendations

The project management staff is highly professional and helpful in addressing project matters. The continuous follow up and technical support in some of the project targets gave energy for the Ethiopian team to continue to implement the project with all the challenges. However, the commencement and end of the project did not consider the seasonality of the sorghum chain. Country specific adjustments and further extension of the project might have been useful. Engagement of the project management team in project planning and monitoring and evaluation was also beneficial for the successful implementation of the project. The Australian team was more familiar with the ACIAR model which encouraged a lot more interaction between scientists and fund managers at the technical level. Better communication with the UQ team would have also been beneficial.

As the budget was initially planned based on the local currency, the higher inflation in Ethiopia was a challenge for the implementation of the project. The budget needs adjustment considering the exchange rate for the local management team deliver their commitments.

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Annex

Annex 1. Sorghum Breeding and seed multiplication
Annex 2. Agronomy and modeling
Annex 3. Technology promotion
Annex 4. Post harvest technologies
Annex 5. Sorghum food utilization
Annex 6. Sorghum use as poultry feed
Annex 7. Gender analysis and Pro-WEAI
Annex 8. Genetic variability for TE Meron thesis
Annex 9. UQ final Technical Report IDRC May 2023
Annex 10. UQ Final Technical Report IDRC
Annex 11. Daniel thesis
Annex 12. Gender analysis report