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# DEVELOPMENT OF WHITE COMMON BEANS FOR THE PROCESSING INDUSTRY IN EAST AFRICA: ADAPTABILITY, RESISTANCE TO SELECTED DISEASES, COOKING TIME AND CANNING QUALITY

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## ABSTRACT

Common bean (*Phaseolus vulgaris* L.) provides dietary protein, energy, fiber, and micronutrients, especially iron and zinc to over 800 million people in Africa and Latin America. The crop has various seed types. White beans are very popular for the processing industry. This study aimed to investigate the agronomic performance, canning quality, cooking time (COOKT) and response to root rots (*Fusarium cuneirostrum* and *Pythium ultimum*) and angular leaf spot (ALS; *Pseudocercospora griseola*) diseases among 151 drought tolerant small and large seeded white bean genotypes from trials conducted between 2013 to 2018 in East Africa. Significant (P<0.001) differences existed among the genotypes for response to the three pathogens, COOKT and canning quality traits. Resistance to each of the pathogens was expressed in 24-75% of the genotypes, while dual resistance to any two pairs of the pathogens occurred in 10-44% of the genotypes. Four genotypes; ICNBunsixSxB405/4C-1C-1C-88, RAZ-11, ETSNAP18 and ETSNAP3 expressed resistance to the three pathogens but had COOKT of 46-56 minutes (based on a Matson cooker), and below average canning quality. They are recommended as sources of diseases resistance but could be further improved for COOKT and canning quality. Sixty-eight genotypes had COOKT <50 minutes while 24 expressed good to excellent visual canning quality. Some phenotypes: RAZ-120, RAZ36-Caballero, NavyLine-60, NavyLine-25, ZABR16573-25F22, ZABR16575-60F22, ETSNAP33, Bifortsmallseeded-15 and ZABR16574-37F22, that were cooked in <45 minutes, exhibited good to excellent canning quality and expressed resistant to intermediate diseases resistance responses. These may be used as parental lines and/or fast tracked for variety release through regional trials.

*Key Words*: Fusarium, multiple resistance**,** *Phaseolus vulgaris*, Pythium

**RÉSUMÉ**

Le haricot commun (*Phaseolus vulgaris* L.) fournit des protéines alimentaires, de l'énergie, des fibres et des micronutriments, en particulier du fer et du zinc à plus de 800 millions de personnes en Afrique et en Amérique latine. La culture a divers types des graines, mais les haricots blancs sont très populaires dans l'industrie de la transformation. Cette étude visait à étudier la qualité agronomique et de mise en conserve, le temps de cuisson et la réponse des haricots blancs aux pourritures des racines et à la tache angulaire (ALS, angular leaf spot) qui provoquent des pertes de rendement importantes dans la production des haricots en Afrique de l'Est. Les haricots à petites et grandes graines améliorés pour la tolérance à la sécheresse ont été évalués de 2013 à 2018. Des différences significatives (P<0,001) existaient entre les 151 génotypes pour la réponse à trois agents pathogènes (*Fusarium cuneirostrum, Pythium ultimum* and *Pseudocercospora griseola*), le temps de cuisson et les caractéristiques de qualité de mise en conserve. Il était possible de sélectionner une résistance à la maladie simple, double et triple. La résistance à chacun des agents pathogènes a été exprimée dans 24 à 75 % des génotypes ; tandis qu'une double résistance à deux paires des agents pathogènes s'est produite dans 10 à 44 % des génotypes. Les quatre génotypes ; ICNBunsixSxB405/4C-1C-1C-88, RAZ-11, ETSNAP18 et ETSNAP3 qui ont exprimé une résistance à trois agents pathogènes ont été cuits en 46-56 minutes et sont recommandés comme sources de résistance pour la reproduction, mais pourraient être encore améliorés pour une cuisson rapide et la qualité de la mise en conserve étant donné qu'une qualité générale de mise en conserve inférieure à la moyenne a été observée. Les soixante-huit génotypes ont été cuits en moins de 50 minutes tandis que 24 exprimaient une qualité visuelle de mise en conserve bonne à excellente. Les génotypes comme RAZ-120, RAZ36-Caballero, NavyLine-60, NavyLine-25, ZABR16573-25F22, ZABR16575-60F22, ETSNAP33, Bifortsmallseed-15 et ZABR16574-37F22, cuits en moins de 45 minutes, présentaient une bonne à excellente mise en conserve la qualité et la résistance à une réponse intermédiaire aux maladies évaluées ont été recommandées à des fins de sélection et pour une évaluation plus approfondie en vue d'une promotion éventuelle.

*Mots Clés* : Fusarium, résistance multiple, *Phaseolus vulgaris*, Pythium

## INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is the most important directly consumed food legume in the world. The crop is an important source of dietary protein, energy, fiber and micronutrients, especially iron, zinc, thiamin and folic acid for normal body and mental functionality (Imran *et al*., 2014; Robinson and McNeal, 2019).

Large and small white (pea or navy) beans are very popular in the canning and baking industry, although other bean colours are also canned, prepared as snacks, or processed into flour (Loggerenberg, 2004; Zanovec *et al*., 2011; CBI, 2019). The canning quality of black (Cichy *et al*., 2014) and kidney (Posa-Macalincag *et al*., 2002; Guzel and Sayar; 2012) beans have been previously analysed. However, there are more earlier studies directed to white beans (Teshome and Emire, 2012; Warsame and Kimanni, 2014; Buzera *et al*., 2018) showing its importance to this industry. Grain market class drives the common bean market segmentation in Africa and needs to be considered early in the breeding pipeline to produce genotypes relevant to the market. White beans are preferred in certain areas because of short cooking time (Cichy *et al*., 2015), for increasing the nutritional quality of composite products (Hoxha *et al*., 2020) and for their aesthetic appearance on the plate. Fast cooking time and canning quality are key traits that the processing industries demand.

Different users of beans including farmers, traders, processors and consumers have diverse preferences based on their unique needs (Buruchara *et al*., 2011). These include

resilient varieties, seed colour such as red, white, black, red-mottled, cream, cream-mottled or yellow; small or large grain size, bush or climbing growth habits and their use either as dry bean, fresh, canned, or green/snap bean and flour (Buruchara *et al*., 2011).

Ethiopia and Kenya have made good progress in identifying and commercialising several white bean varieties, which has seen this industry grow and make great economic impact in these countries. Reports by Teshome and Emire (2012), Warsame and Kimanni (2014) and Buzera *et al*. (2018) mentioned white bean varieties of preferred canning quality in Ethiopia, Kenya and Democratic Republic of Congo, respectively.

Factors like the genetics of the genotypes, environment, genotype by environment interactions, the seed handling after harvest, and the processing method (Nyawira and Macharia, 2017; Mendoza *et al*., 2018) were reported to influence cooking and canning processes of beans. Cichy *et al*. (2019) reported high heritability for cooking time and limited crossover of Genotype × Environment interactions in trials established in 10 to 15 environments, which showed that fast cooking beans could be developed with evaluation in few environments. This indicates that improvement of germplasm for this trait is possible within a short time.

Low productivity and poor seed quality due to diseases, such as common bacterial blight, root rots, angular leaf spot, anthracnose, bruchids, bean steam maggot, and water stress affect the utilisation of beans by processors. In Kenya, decrease in production of white beans was linked to poor quality seeds mainly due to foliar diseases and other stresses that influence proper seed filling (Karanja *et al*., 2011). The low production consequently resulted in the collapse of production agreements between processors and producers (Chemining'wa *et al*., 2014). In addition to the effect of bruchids in storage (Tigist *et al*., 2020),seed discolouration due to disease infection is one of the major factors affecting the canning industry in Ethiopia (Yayis *et al*., 2019; Kidane *et al*., 2020).

White bean genotypes that are resistant to common plant stressors in eastern Africa are important for the sustainability of dry bean and its value-added products such as pre-cooked snacks, flour and canned beans. With the exception of Ethiopia and Kenya, the canning industry in eastern Africa is poorly developed due to lack of adapted varieties, with good canning quality that may interest the market players (C. Mukankusi, personal communication, 2020). However, in the last five years, demand of these varieties by the private sector has drastically increased and countries such as Uganda, Burundi and Tanzania have revived breeding white beans as a priority product; this paper highlights some of the efforts to respond to this demand.

Diseases are a major constraint to bean production in eastern Africa among which are root rots caused by a complex of pathogens (*Fusarium, Pythium, Sclerotium and Rhizoctonia* spp), and foliar diseases such as anthracnose (*Colletotrichum lindemuthianum*), angular leaf spot (*Pseudocercospora griseola*), rust (*Uromyces appendiculatus*) and bean common mosaic virus and its necrotic strain, bean common mosaic necrotic virus (BCMV/BCMNV).

Root rots can cause severe yield loss of up to 100% in susceptible varieties grown under conducive conditions (Paparu *et al*., 2017). Recent studies show that root rots are still a major bean production challenge in Africa (Mitiku, 2017; Paparu *et al*., 2017; Were, 2019). Four root rots, including Fusarium spp., Pythium spp., *Rhizoctonia solani*,and *Macrophomina phaseolina* were reported on farms in Western Kenya (Were, 2019). *Rhizoctonia solani, Fusarium solani* and Pythium spp. root rots are also problematic in Ethiopia (Mitiku, 2017). In Uganda, root rots occur in all agro-ecologies, with the most widespread root rot pathogen being *Sclerotium rolfsii* Sacc.; followed by *Fusarium* spp., *Pythium* spp. and *Rhizoctonia solani* (Paparu

*et al*., 2017). Root rots are also reported as major diseases in DRC, Rwanda, Burundi and Tanzania. Most of the adapted bean cultivars in East and Central Africa are susceptible to roots rot especially *Pythium* and *Fusarium* that commonly occur in the same bean field (Tusiime, 2003; Mukankusi, 2008).

Among the foliar diseases, angular leaf spot (ALS) is among the most devastating disease which cause significant yield losses in eastern and central Africa (Ddamulira *et al*., 2014a; Mongi *et al*., 2016; Gudero and Terefe, 2019). The disease can cause up to 80% yield loss by reducing photosynthetic area and normal plant growth, and injuring seeds (DeJesus-Junior *et al*., 2001; Paparu et al., 2014). Infection occurs on leaves, and spreads to pods and seeds leaving scars that reduce the quality of harvested seeds (Strenglein *et al*. 2003; Mongi *et al*., 2016). Appropriate fungicides lessen yield loss due to ALS when applied correctly (Lemessa*et al*., 2011), but they are often expensive or not readily available to smallholder farmers in eastern and central Africa. Resistant cultivars to ALS disease are in circulation in Africa (Ddamulira *et al*., 2014a; Mukamuhirwa *et al*., 2017). However, due to the diverse nature of the pathogens, and changing weather conditions that favour a complex occurrence of multiple species, disease resistance is often broken down over time (Brown, 2015). Ddamulira *et al*. (2014b) evaluated Ugandan landraces and commercial varieties against four of the most virulent ALS pathotypes collected from farmer fields in Uganda. Only one landrace (U00297) expressed complete resistance. Hence, continuous breeding and evaluation for new sources of resistance for adoption and improvement of susceptible commercial varieties is required as a sustainable coping strategy. This study aimed at investigating the agronomic and canning quality, cooking time and the response of white beans to root rots and angular leaf spot (ALS) that cause significant yield losses in bean production eastern Africa.

## MATERIALS AND METHODS

**Germplasm.** Twenty-five large and 126 small seeded white bean genotypes, developed to thrive under drought conditions by the International Centre for Tropical Agriculture (CIAT) and the Ethiopia Institute of Agricultural Research (EIAR), were evaluated in this study. The small beans included those with 13.0-29.6 g for 100 seed weight; while the large beans were 43.6-66.6 g; all at 13% moisture content.

**Agronomic evaluation.** Field experiments were conducted at three locations, namely (i) National Agricultural Research Laboratories (NARL)-Kawanda in central Uganda, (ii) Kachwekano Zonal Agricultural Research and Development Institute (Kachwekano-ZARDI), Kabale in southwestern Uganda and at (iii) Kitengule prison farm in northwestern Tanzania under the collaboration of the Tanzania Agricultural Research Institute (TARI), Maruku in Bukoba, Kagera.

Kawanda - NARL is located at 32° 31'E, 0°252 N with an altitude of 1190 m above sea level (asl). Kachwekano - ZARDI is located at 1°152 S, 29°572 E at an elevation of 2200 m asl. Kitengule is located at 2°08' S, 33°26' E at an elevation of 1,320 m asl. All the three locations are characterised by a bimodal rainfall pattern represented by "a" for the first rainy season (March-June) and "b" for the second rainy season (September-December).

The field study was conducted in the growing season of 2013b/2014a and b at Kawanda, 2015b/2018a at Kachwekano and 2018a and b at Kitengule. The genotypes were laid out in an alpha lattice design, with two replications. Plots representing each genotype, within a replication were of 3 rows by 3 m in length; row and plant spacing were 50 and 10 cm, respectively. Each trial was weeded thrice and an insecticide, Dimethoate was applied weekly until flowering following the recommended manufacturer's rate. Granular N:P:K 17:17:17 fertiliser was hand applied just before planting, at the rate of 125 kg $ha^{-1}$.

Data on yield, disease and growth variables were collected at specific intervals, based on the bean trait dictionary (IBP, 2013). Field disease, including angular leaf spot (ALS), common bacterial blight (CBB), bean common bacterial blight (BCMV), rust and aschochyta blight on leaves were recorded on a 1 to 9 scale. For field diseases, 1-3 = no visible or very light symptoms, 4-6 = visible conspicuous symptoms resulting only in limited economic damage and 7-9 = severe to very severer symptoms causing considerable yield losses or plant death (CIAT 1987; IBP, 2013).

Days to flowering (DF) and physiological maturity (DPM) were recorded as the number of days from planting to the day when 50% of plants had at least one flower and number of days from planting to the day when the first pods began to discolour in 50% of the plants, respectively (CIAT 1987; IBP, 2013). Seed collection for yield began when 90% of the pods had changed from green to yellow colour. The following varieties were included as yield checks; NABE6, Awashmelka, Awash1, MEXICAN142, Bifortsmallseeded-15 and RANJONOMBY.

**Screening for root rot and angular leaf spot resistance**

Targeted disease screening studies were established in a netted screen house at NARL-Kawanda.

**Resistance to Fusarium root rot (*Fusarium cuneirostrum*).** Isolate FSP-3 (Rossman *et al*., 2017) stored on agar plants at NARL-Kawanda, was sub-cultured onto potato dextrose agar (PDA) plates and grown for 21 days, under 12:12 light and darkness photoperiods on laboratory benches at room temperature (22 ± 2°C). Thereafter, the cultures were transferred onto steam-sterilised sorghum (*Sorghum bicolor* L.) grains which were used to prepare the inocula, as described by Mukankusi *et al*. (2011).

To develop the infected planting medium (sick seed beds), the pathogen-colonised grains were mixed thoroughly and added to steam sterilised loamy sand soil at a rate of one 500 ml bottle of inoculum into wooden trays of dimensions 0.74 m x 0.42 m x 0.115 m filled to 66% capacity.

To facilitate sporulation and maximum pathogen soil colonisation, each tray was covered with polyethylene bag for a week. Inoculum levels were increased by repeatedly planting the susceptible control genotype, CAL96 until a disease score of 9 (on a scale of 1-9, where 1 = resistant and 9 = very susceptible) was attained. The plants were uprooted and the soil was mixed before planting the experiment in a randomised complete block design, with three replications. Ten seeds of the same genotype were planted per replication. A row of the resistant (MLB-49-89A) and susceptible (CAL96) control genotypes were planted in each tray.

Disease severity was assessed at 21 days after planting, by carefully uprooting each individual plant and washing the hypocotyls and roots using tap water to remove soil, before visually rating the lower hypocotyl discolouration on a 1 to 9 scale where 1 = resistant and 9 = very susceptible (Abawi and Pastor-Corrales, 1990; IBP, 2013).

**Resistance to *Pythium ultimum*.** The isolate, MS61, maintained at NARL-Kawanda (Mukalazi *et al*., 2001), was reactivated by sub-culturing onto corn meal agar (CMA) media. Finger millet (*Eleusine coracana*) grains weighing 300 g, were placed in several plastic autoclavable polyethylene bags and to each bag was added 300 ml of tap water prior to double sterilisation in an autoclave at 121 °C for 60 minutes. Each bag was inoculated with 3-4 discs of agar blocks bearing actively growing pathogen cultures, by placing the discs at different positions in the finger millet bag.

To allow uniform Pythium growth over the millet grains, the bags were incubated in a sterile

environment in darkness, at room temperature (22 ± 2 °C) for at least 12 days.

After incubation, the colonised millet grains with *Pythium* inoculum were mixed in steam sterilised soil, at a ratio of 1:8 v/v inoculum to soil and then placed in wooden flat trays of 0.74 m x 0.42 m x 0.115 m, and left to stabilise in the soil for 7 days. To increase inoculum levels, the susceptible control genotype, CAL96, was repeatedly planted in the soil until a score of 9 was reached. Thereafter, CAL96 was uprooted and discarded and the infected soils were mixed and placed back in the trays to 66% capacity. The test genotypes, the resistant (RWR719) and susceptible control (CAL96) genotypes were planted in a randomised complete block design with two replications in the wooden trays. Each tray was planted with 10 test and two control bean genotypes, with each genotype having one row of 10 seeds.

After three to five days from planting, the test genotypes, the trays were flooded with water and this was maintained for about 10 days to create a favourable microclimate for the pathogen to move through the soil pores and infect the seedlings. The soil water level was slowly reduced in the 3rd week, by decreasing the frequency of watering to approximately 3 times a week. Using a 1-9 scale, Pythium root rot symptoms were evaluatedat 21 days from planting by uprooting the genotypes, washing the roots with tap water, and then scoring the disease symptoms using a 1-9 scale (Abawi and Pastor-Corrales, 1990; IBP, 2013).

**Resistance to *Pseudocercospora griseola*.** Genotypes were screened for resistance to a virulent race 61:63 identified by Ddamulira *et al*. (2014a). The isolate, KA060, which stored at NARL was cultured on V8 media (200 ml V8, 800 ml water, 20 g Agar, 3 g Calcium Carbonate) for 2 weeks to allow more sporulation (Castellanos *et al*., 2011).

Inoculum was prepared by scraping the fungal growth from plates into sterile bottles using water and a toothbrush. The inoculum was filtered through a sterile cheesecloth and the number of spores was determined using a haemocytometer, before adjusting the concentration to 3 x $10^4$ per ml, using distilled water containing 0.05% (v/v) Tween 80 (polyoxyethylene sorbitan monooleate). Inoculum was sprayed onto and below the first trifoliate leaf, until run off, at 21 days from planting (Castellanos *et al*., 2011) in two replications. The plants were then covered with plastic transparent bags for three days to create moist conditions for disease development, prior to evaluation.

Data on disease severity were scored 5 times at an interval of three days from 5 different plants per entry using CIAT standard scales (CIAT, 1987; IBP, 2013). Genotype MEXICO54 was used as a resistant check, and MCM5001 and CAL96 as susceptible checks.

**Cooking time assessment.** Cooking time was determined using seeds harvested from Kitengule in 2018a season. Analysis was performed within three months from harvest on seeds with moisture contents of 10-13% that had no mechanical or insect damage.

Randomly sampled 30 seeds per genotype were soaked, in distilled water at room temperature (22 ± 2 °C), for 12 hours. Water was then drained from all samples and seeds kept in sealed bottles. Seeds were positioned into each of the 25 holes of the Matson cooker so that the piercing tip of the 90 g rod was in contact with the surface of the bean. This was then placed in a five-litter beaker containing boiling distilled water (Wang and Daun, 2005). The optimum cooking time was defined as the time required for 80% of the plungers to penetrate the seeds (Wang and Daun, 2005).

**Canning quality assessment.** Canning quality was determined using seeds harvested from Kitengule in 2018a season. A protocol based on the canning industry standards was followed (Kelly and Cichy, 2013). The

procedures involved cold and hot soaking of bean samples, brine preparation, autoclaving, storage and evaluation for consumer traits. Freshly harvested beans were sorted to remove foreign matters, physically damaged and undesirable types. In the pre-canning phase, the moisture content (%) for each sample was obtained using a SINAR Model 6095 AgriPro Moisture Analyser, and the dry bean weight (DBW) for canning, were recorded per sample. DBW is the fresh weight of beans equivalent to 90 g of total solids at a given moisture content (Equation 1).

$$\text{DBW (g)} = \frac{\text{90 g (i.e. solids required)}}{1 - \left(\frac{\text{MC \%}}{100}\right)\ \text{(i.e. MC = moisture content)}} \quad \text{..... Equation 1}$$

During the canning process, the soaked bean weight (g) was recorded after cold and hot soak. This is the measure of both the weight of water and total solids in the sample. Hydration coefficient (HC) was determined as:

$$\text{HC} = \frac{\text{Weight of soaked beans (g)}}{\text{Dry bean weight (g)}} \quad \text{..... Equation 2}$$

After canning, the beans were stored in boxes at room temperatures (22 ± 2 $^{o}$C) for two weeks and then visually evaluated. The brine and seeds were poured in plates and were assessed for colour, appearance, brine clarity, bean splitting, and free starch/clumps using a 7-point scale where; 1 = Unacceptable, 2 = Very bad, 3 = Bad, 4 = Fair, 5 = Good, 6 = Very good and 7 = Excellent. Five people rated the canned beans and the scores were averaged.

**Data analysis.** Data were analysed in GenStat (VSN International, 2019). The linear model for the analysis of variance (ANOVA) was:

$Yijk = GM+S_i+R/S_{ij}+G_k+GS_{jk}+e_{ijk}$ for disease resistance and

$Yijk = GM+R_i+B_j+G_k+e_{ijk}$ for canning quality, cooking time, and for yield.

Where:

$Y_{ijk}$ described the observed value, GM the Grand Mean, $S_i$ the Screening cycle effect, $R/S_{ij}$ the effect of Replication nested within Screening, $G_k$ the Genotype effect, $GS_{jk}$ the Genotype x Screening effect and $e_{ijk}$ the error.

Genotype mean data per season was used to determine GE interactions for yield in Breeding View Standalone statistical tool, available in Breeding Management System (IBP, 2013). The interactions for GE were examined using the Additive Main Effects and Multiplicative Interaction (AMMI) model. In this model, a two-way ANOVA additive model is performed (additive main effects), followed by a principal component analysis on the residuals (multiplicative interaction). As a result, the interaction is characterised by Interaction Principal Components (IPCA), where genotypes and environments can be simultaneously plotted in biplots (IBP, 2013). Stability for yield was calculated for each genotype using Cultivar Superiority (CS), and according to Lin and Binns (1988), CS is the sum of the squares of the difference between the genotypic mean in each environment and the mean of the best genotype, divided by twice the number of environments. Genotypes with the smallest values of CS tend to be more stable, and closer to the best genotype in each environment.

## RESULTS AND DISCUSSION

**Yield performance.** Bean genotypes that are suitable for canning or pre-cooked industry need to be agronomically resilient in the field for bean growers to adopt and obtain meaningful yields to make economic sense. The across location yield for small white beans was generally high based on the grand mean (1704 kg ha$^{-1}$), and 42% of the genotypes yielded higher than all the check genotypes

NABE6 (1730 kg ha$^{-1}$), Awashmelka, Awash1, MEXICAN142, Bifortsmallseeded-15 and RANJONOMBY (1373 kg ha$^{-1}$). Yield ranged from 1372.7-2264.0 kg ha$^{-1}$, and seven genotypes that yielded between 2000 (ETSNAP28) - 2264 kg ha$^{-1}$ (SSW13) were considered superior (Table 1). Among the large beans (Table 2), nine genotypes yielded higher than the checks (RANJONOMBY (1124 kg ha$^{-1}$), SAB713 (1276 kg ha$^{-1}$)) and above the grand mean (1226 kg ha$^{-1}$). The most superior yielding genotypes were F14Population-6 (1633 kg ha$^{-1}$) and F14Population-21 (1472 kg ha$^{-1}$). The yield (889.5-1632.9 kg ha$^{-1}$) for the large seeded beans were all below the mean yield for small white beans and no further selection based on yield maybe beneficial. Recently released bush bean varieties in Tanzania and Uganda had yield potentials of > 1500 kg ha$^{-1}$ and 1500 - 2200 kg ha$^{-1}$ in low to mid altitude areas (Nkalubo *et al*., 2016; Binagwa *et al*. 2018). The genotypes that yielded above or within the range of these recently released varieties show that it should be possible to select for acceptable yield during further evaluation.

Based on stability estimates, only four of the genotypes identified for good canning quality (ZABR16575-60F22, ZABR16574-37F22) and fast cooking trait (SSW13 and ZABR16575-36F22) were among the most stable 20 genotypes (Table 3). This showed the existence of several high yielding and stable genotypes that were not necessarily superior in specific disease resistance, canning quality or cooking time but that may possess broad resistance to field disease and are also recommended for further evaluation. Several large white genotypes superior in other traits such as Bifortsmallseeded-15 (1577 kg ha$^{-1}$), RAZ-120 (1572 kg ha$^{-1}$), RANJONOMBY (1373 kg ha$^{-1}$), F14Population-3 (1477 kg ha$^{-1}$) and NavyLine-25 (1556 kg ha$^{-1}$) that were better performers in canning quality than the industry checks (MEXICO142 (1670 kg ha$^{-1}$) and Awash1 (1671 kg ha$^{-1}$) yielded below the mean and lower than these check genotypes. Nonetheless, it was possible to select for genotypes superior in both yield and other key traits. Although they were not necessarily the best yielders in the evaluated germplasm. In a study of black bean populations, selection for superiority in canning traits was reported as unlikely to cause yield drag (Cichy *et al*., 2014). This is very important for breeding because in spite of other qualities, yield remains a key trait for farmers.

The IPCA 1 and IPCA 2 were significant ($P<0.01$) for both small and large seeded genotypes, and according to the Additive Main effects and Multiplicative Interaction (AMMI), the G x E accounted for 72.2% and 64.8% respectively (Table 4) of the variation for yield. The joint analysis grouped the seven environments into three mega-environments based on similar yield behaviour of the small white genotypes, namely, ENV1 (KAC18a, KIT18a and KIT18b), ENV2 (KAW13b), and ENV3 (KAC15d, KAW14a and KAW14b). Yield ranges were 979.9-2321.3 kg ha$^{-1}$ (ENV1), 1329.0-2317.0 kg ha$^{-1}$ (ENV2) and 1188.9-2858.9 kg ha$^{-1}$ (ENV3) (Table 3). For the large white beans, four mega-groups including ENV1 (KAW14a, KAG18a and KAG18b), ENV2 (KAC15b), ENV3 (KAW13b and KAW14b) and ENV4 (KAC16a) were generated. Yield ranges were 996.1-1616.8 kg ha$^{-1}$ (ENV1), 573.6-2014.2 kg ha$^{-1}$ (ENV2), 842.8-1595.1 kg ha$^{-1}$ (ENV3) and 783.7-1596.7 kg ha$^{-1}$ (ENV4) (Table 3). The AMMI-2 winning genotypes for mega environments 1, 2, and 3 were ETSNAP6, RAZ-11-1 and SSW13, respectively for the small white genotypes (Fig. 1), and F14Population-12, F14Population-22, F14Population-6 and SAB713 for environments 1, 2, 3 and 4, respectively for the large seeded genotypes (Fig. 2). Based on cultivar superiority, genotypes ZABR16574-44F22 and ZABR16575-60F22 (small white) and F14Population-6 and F14Population-22 (large white) combined high performance and consistency better than the other evaluated genotypes (Table 3).

TABLE 1. Response of selected small white beans to Pythium root rot (PRR), Fusarium root rot (FRR) and Angular leaf spot (ALS), cooking time, canning quality and yield performance

| Genotypes | PRR_1 | PRR_2 | PRR_3 | FRR_1 | ALS_1 | ALS_2 | ALS_3 | PRR | FRR | ALS | SW100 | COOKT | HC | Clumping | Splitting | Appearance | Viscosity | Colour | Free starch | WDW (g) | YDHA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ICN Bunsi/S/B405/4C-1C-1C-88 | 2.4 | 3.4 | 2.5 | 3.4 | 2 | 2.2 | 2.2 | R | R | R | 21.9 | 56.3 | 2.0 | 3.4 | 4.0 | 2.0 | 2.0 | 7.0 | 5.0 | 271 | 1784.1 |
| RAZ-11 | 2.9 | 2.6 | 2.4 | 2.9 | 2 | 2.2 | 2.4 | R | R | R | 23.0 | 49.8 | 2.0 | 3.0 | 2.5 | 1.5 | 6.0 | 7.0 | 5.0 | 278 | 1613.7 |
| ETSNAP18 | 3.3 | 2.9 | 2.5 | 3.1 | 2.5 | 2.2 | 2.7 | R | R | R | 19.4 | 46.2 | 2.0 | 3.5 | 3.5 | 2.5 | 3.5 | 7.0 | 4.5 | 261 | 1745.2 |
| ETSNAP3 | 2.7 | 2.6 | 2.5 | 3.4 | 3 | 2.7 | 2.7 | R | R | R | 17.0 | 53.1 | 2.1 | 4.6 | 3.0 | 1.5 | 4.4 | 7.0 | 4.0 | 282 | 1751.1 |
| IBC-2 | 2 | 2.7 | 2 | 2.7 | 2 | 2.1 | 3.6 | R | R | I | 17.5 | 72.3 | 2.0 | 5.5 | 2.5 | 4.0 | 5.0 | 7.0 | 4.0 | 283 | 1654.4 |
| ETSNAP30 | 2.7 | 2.6 | 3.1 | 2.8 | 2.5 | 2.3 | 3.6 | R | R | I | 24.1 | 40.2 | 2.0 | 2.5 | 2.5 | 1.0 | 5.0 | 7.0 | 1.0 | 277 | 1924.7 |
| RANJONOMBY | 2.7 | 2.2 | 2 | 2.9 | 2 | 2.1 | 4.3 | R | R | I | 13.0 | 74.4 | 2.2 | 7.0 | 5.0 | 7.0 | 7.0 | 7.0 | 6.0 | 304.8 | 1372.7 |
| F14Population (3) | 2.6 | 2.4 | 2.8 | 2.9 | 2 | 2.1 | 4.8 | R | R | I | 13.0 | 89.2 | 2.2 | 6.5 | 6.0 | 5.0 | 7.0 | 7.0 | 6.5 | 303.4 | 1477.4 |
| ICN Bunsi/S/B405/2C-1C-1C-23 | 2 | 2.5 | 3 | 3.4 | 6.8 | 6.7 | 3.5 | R | R | S | 28.2 | 38.1 | 2.0 | 4.0 | 2.0 | 1.5 | 4.5 | 7.0 | 6.0 | 243 | 1772.8 |
| ZABR16573-25F22 | 2 | 2.8 | 3 | 2.8 | 6.9 | 6.7 | 2.9 | R | R | S | 20.4 | 43.0 | 2.0 | 6.5 | 6.5 | 7.0 | 4.5 | 7.0 | 7.0 | 272.0 | 1567.9 |
| RAZ-120 | 2 | 2.5 | 2.8 | 3.5 | 2.7 | 2.2 | 2.6 | R | I | R | 26.7 | 39.7 | 2.1 | 6.5 | 6.0 | 7.0 | 7.0 | 7.0 | 6.0 | 282.3 | 1572.2 |
| ZABR16576-20F22 | 3.1 | 3 | 2.4 | 3.8 | 6.9 | 6.4 | 5.7 | R | I | S | 22.1 | 36.0 | 1.9 | 4.0 | 4.5 | 3.5 | 6.5 | 7.0 | 6.0 | 293.1 | 1704.1 |
| Navy Line-43 | 3.2 | 2.3 | 2.7 | 4 | 2.7 | 2.2 | 2.3 | R | I | R | 26.3 | 39.0 | 2.0 | 5.5 | 2.5 | 3.0 | 5.0 | 7.0 | 6.0 | 281 | 1481.9 |
| ETSNAP12 | 3.2 | 2.5 | 3.3 | 4 | 2.3 | 2.3 | 2.3 | R | I | R | 21.8 | 46.3 | 2.1 | 5.5 | 5.0 | 4.5 | 5.5 | 7.0 | 5.5 | 294.6 | 1609.5 |
| SSW13 | 2.4 | 3.1 | 3.7 | 4 | 2 | 2.2 | 2.2 | I | I | R | 21.6 | 38.0 | 2.1 | 4.0 | 4.0 | 3.0 | 4.0 | 7.0 | 3.0 | 265.0 | 2264.0 |
| Navy Line-60 | 3.1 | 2.4 | 3.9 | 2.5 | 2.7 | 2.2 | 2.1 | I | R | R | 20.9 | 42.0 | 2.1 | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.0 | 296.0 | 1602.2 |
| Navy Line-51 | 6 | 3.8 | 4.7 | 2.5 | 2.9 | 2.7 | 4.7 | I | R | I | 25.4 | 39.1 | 2.0 | 6.0 | 4.0 | 4.5 | 4.5 | 7.0 | 6.5 | 271 | 1592.6 |
| ETSNAP34 | 6.3 | 5 | 2.7 | 2.7 | 6.8 | 6.2 | 3.6 | I | R | S | 22.8 | 38.7 | 2.0 | 5.5 | 3.5 | 3.0 | 5.5 | 7.0 | 5.5 | 288 | 1919.4 |
| ZABR16575-36F22 | 7.5 | 7.2 | 2.8 | 3.1 | 2.7 | 1.9 | 2.1 | S | R | R | 21.0 | 37.4 | 2.1 | 6.0 | 3.0 | 3.5 | 4.0 | 7.0 | 7.0 | 270 | 1910.7 |
| ZABR16574- 17F22 | 2.7 | 3.4 | 4.2 | 3.4 | 3.1 | 2.6 | 4.4 | I | R | I | 28.2 | 56.1 | 2.0 | 6.0 | 4.5 | 5.0 | 5.5 | 7.0 | 5.5 | 276 | 1843.4 |
| Navy Line-46 | 4.3 | 2.5 | 5.8 | 3.4 | 2.7 | 2.4 | 4.7 | I | R | I | 18.5 | 47.4 | 1.9 | 5.0 | 4.5 | 4.5 | 5.0 | 7.0 | 6.5 | 299.5 | 1558.9 |
| ZABR 16574- 37F22 | 2.6 | 4.9 | 3 | 3.7 | 2 | 2.1 | 2.1 | I | I | R | 28.4 | 44.4 | 2.0 | 7.0 | 5.0 | 6.0 | 7.0 | 7.0 | 7.0 | 272 | 1960.1 |
| Bifort small seeded-15 | 2.6 | 2.9 | | 3.9 | 2 | 2.2 | | R | I | R | 18.7 | 44.2 | 2.0 | 6.5 | 6.5 | 7.0 | 7.0 | 7.0 | 6.5 | 292.7 | 1577.2 |
| Awash-1 | 2.5 | 3.7 | 2.4 | 4.1 | 3.4 | 2.5 | 5.9 | I | I | I | 22.8 | 42.4 | 2.0 | 4.5 | 4.5 | 4.5 | 6.0 | 7.0 | 5.5 | 241.7 | 1670.6 |
| SSW9 | 3.2 | 3.9 | 4.1 | 4.5 | 3.5 | 2.9 | 5.4 | I | I | I | 20.7 | 38.8 | 2.0 | 3.5 | 3.5 | 3.0 | 3.5 | 7.0 | 6.0 | 272 | 1593.7 |
| ETSNAP19 | 6 | 2.7 | 3.3 | 4.8 | 2 | 2.2 | 2.4 | I | I | R | 20.8 | 34.1 | 2.0 | 3.5 | 4.0 | 2.0 | 5.0 | 7.0 | 3.0 | 277 | 1918.3 |
| ICN Bunsi/S/B 405/9C-1C-1C-70 | 5.7 | 4.8 | 2 | 5.5 | 2 | 2.2 | 2.1 | I | I | R | 23.3 | 38.9 | 2.0 | 5.5 | 6.0 | 4.0 | 4.0 | 7.0 | 5.0 | 275 | 1792.8 |
| ETSNAP2 | 2.4 | 2.6 | 4 | 5.6 | 3.1 | 2.6 | 4.2 | I | I | I | 17.3 | 28.5 | 2.0 | 3.5 | 1.5 | 1.5 | 4.5 | 7.0 | 5.0 | 290 | 1637.2 |
| Navy Line 47 | 2.1 | 2.2 | 4.0 | 5.7 | 2.8 | 2.4 | 3.8 | I | I | I | 19.5 | 51.3 | 1.9 | 5.5 | 5.0 | 5.0 | 5.0 | 7.0 | 6.0 | 242.7 | 1710.9 |
| Navy Line-25 | 2.7 | 5.6 | 2.1 | 5.9 | 6.8 | 6.6 | 6.7 | I | I | S | 20.3 | 42.2 | 2.1 | 6.0 | 4.5 | 5.5 | 6.0 | 7.0 | 6.0 | 280.1 | 1556.0 |
| RAZ44 - Navy | 3.2 | 3.6 | 2.3 | 6.0 | 6.9 | 6.5 | 3.6 | I | I | S | 21.3 | 60.2 | 2.0 | 6.5 | 5.5 | 6.5 | 7.0 | 7.0 | 7.0 | 277.2 | 1530.5 |
| MEXICO142 | 2.0 | 5.6 | 2.9 | 2.4 | 3.3 | 2.2 | 4.6 | 1 | R | 1 | 15.9 | 61.5 | 2.0 | 5.0 | 4.0 | 4.5 | 6.0 | 7.0 | 5.0 | 283 | 1643.7 |
| ETSNAP33 | 2.8 | 2.3 | 4.2 | 3.5 | 2.8 | 2.7 | 3.4 | R | I | R | 19.4 | 43.9 | 2.1 | 6.5 | 5.5 | 5.0 | 4.5 | 7.0 | 7.0 | 253.8 | 1723.2 |
| ZABR16574-37F22 | 2.6 | 4.9 | 3.0 | 3.7 | 2.0 | 2.1 | 2.1 | I | I | R | 28.4 | 44.4 | 2.0 | 7.0 | 5.0 | 6.0 | 7.0 | 7.0 | 7.0 | 272.1 | 1960.1 |
| ZABR16575-60F22 | 2.0 | 6.7 | 2.6 | 3.0 | 2.7 | 2.2 | 3.5 | I | R | R | 19.8 | 43.7 | 2.1 | 4.5 | 5.0 | 4.5 | 5.0 | 7.0 | 5.0 | 288.3 | 2095.0 |
| RAZ36-Caballero | 3.3 | 3.2 | 4.7 | 4.2 | 4.9 | 3.7 | 4.9 | R | I | I | 19.0 | 40.7 | 1.9 | 5.6 | 4.5 | 5.5 | 6.0 | 7.0 | 6.1 | 275.4 | 1638.3 |
| ETSNAP20 | 3.6 | 3.0 | 3.4 | 4.6 | 6.9 | 6.6 | 3.8 | I | I | S | 23.1 | 43.2 | 2.0 | 5.0 | 4.5 | 3.9 | 4.4 | 7.0 | 5.5 | 272.5 | 1850.1 |
| ETSNAP8 | 2.4 | 4.4 | 2.0 | 4.1 | 6.7 | 6.5 | 3.4 | I | R | S | 19.9 | 42.2 | 2.0 | 4.5 | 4.5 | 3.0 | 6.0 | 7.0 | 5.5 | 310.5 | 1777.0 |
| ETSNAP2 | 2.4 | 2.6 | 4.0 | 5.6 | 3.1 | 2.6 | 4.2 | R | I | I | 17.3 | 28.5 | 2.0 | 3.5 | 1.5 | 1.5 | 4.5 | 7.0 | 5.0 | 290.1 | 1637.2 |
| Awash melka | 4.7 | 6.2 | 3.4 | 3.3 | 2.1 | 2.1 | 2.2 | I | R | R | 18.3 | 42.1 | 2.0 | 4.0 | 6.5 | 5.5 | 5.0 | 7.9 | 6.5 | 283.0 | 1669.6 |
| NavyLine-52 | 2.5 | 2.2 | 3.1 | 4.2 | 2.1 | 2.1 | 4.8 | R | R | I | 20.1 | 53.0 | 2.1 | 6.5 | 3.5 | 6.5 | 60 | 7.0 | 7.0 | 277.9 | 1588.3 |
| SSBr1 | 2.3 | 3.6 | 4.1 | 2.5 | 6.8 | 6.7 | 5.7 | 1 | R | S | 27.4 | 44.1 | 2.0 | 6.0 | 5.0 | 6.0 | 7.0 | 4.0 | 7.0 | 214.9 | 1525.4 |
| RAZ-2 | 4.0 | 5.6 | 3.9 | 2.6 | 2.0 | 2.4 | 5.3 | 1 | R | I | 24.5 | 42.7 | 2.1 | 5.5 | 3.9 | 5.5 | 5.5 | 7.0 | 6.5 | 272.4 | 1554.0 |
| ZABR16577-39F23 | 5.8 | 5.2 | 2.2 | 3.4 | 3.0 | 2.1 | 3.9 | 1 | R | I | 20.2 | 50.0 | 2.0 | 4.5 | 4.5 | 5.0 | 4.0 | 7.0 | 6.5 | 276.2 | 1670.9 |
| ETSNAP31 | 2.8 | 2.8 | 3.1 | 4.0 | 2.4 | 2.5 | 2.8 | R | 1 | R | 20.2 | 46.9 | 2.1 | 5.5 | 4.0 | 5.0 | 7.0 | 7.0 | 6.0 | 290.9 | 1856.7 |
| SSW5 | 3.9 | 3.2 | 3.2 | 4.9 | 6.7 | 6.7 | 3.4 | I | I | S | 24.6 | 45.0 | 1.9 | 7.0 | 4.0 | 5.5 | 5.4 | 7.0 | 6.0 | 283.8 | 1746.3 |
| ZABR16574-21F22 | 3.1 | 2.0 | 2.3 | 2.2 | 6.7 | 6.7 | 4.2 | R | R | I | 18.5 | 42.2 | 2.0 | 6.5 | 4.0 | 5.5 | 5.0 | 7.0 | 6.0 | 286.9 | 2014.9 |

TABLE 1. Contd.

| Genotypes | PRR_1 | PRR_2 | PRR_3 | FRR_1 | ALS_1 | ALS_2 | ALS_3 | PRR | FRR | ALS | SW100 | COOKT | HC | Clumping | Splitting | Appearance | Viscosity | Colour | Free starch | WDW (g) | YDHA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CAL96 | 9 | 9 | 8.8 | 8.9 | 7 | 6.8 | 4.7 | S | S | S | | | | | | | | | | | |
| RWR719 | 2.1 | 2.2 | 2.1 | - | - | - | - | R | - | - | | | | | | | | | | | |
| MLB-49-89A | - | - | - | 2.2 | - | - | - | - | R | - | | | | | | | | | | | |
| MCM5001 | - | - | - | - | 6.7 | 6.7 | 3.7 | - | - | S | | | | | | | | | | | |
| MEXICO54 | - | - | - | - | 1.7 | 2 | 1 | - | - | R | | | | | | | | | | | |
| Minimum | 2 | 2 | 2 | 2 | 1.7 | 1.9 | 1 | | | | 13.0 | 28.5 | 1.8 | 1.0 | 1.0 | 1.0 | 1.0 | 4.0 | 1.0 | 214.9 | 1372.7 |
| Maximum | 9 | 9 | 8.8 | 8.9 | 7 | 6.8 | 8.8 | | | | 29.6 | 89.2 | 2.2 | 7.0 | 6.5 | 7.0 | 7.0 | 7.0 | 7.0 | 437.0 | 2264.0 |
| Mean | 3.7 | 3.7 | 3.5 | 3.9 | 3.8 | 3.6 | 3.7 | | | | | 47.6 | 2.0 | 4.3 | 3.6 | 3.4 | 4.7 | 7.0 | 5.0 | 280.4 | 1707.2 |
| %cv | 19.5 | 23.9 | 40.5 | 25.2 | 9 | 4.7 | 17.1 | | | | | 16.1 | 4.0 | 37.5 | 31.1 | 48.0 | 36.1 | 0.0 | 30.9 | 10.1 | |
| s.e | 0.72 | 0.89 | 1.43 | 0.99 | 0.34 | 0.17 | 0.63 | | | | | 7.68 | 0.10 | 1.60 | 1.13 | 1.60 | 1.70 | 0.00 | 1.60 | 28.20 | |
| lsd (5%) | 1.4 | 2.5 | 2.8 | 2.0 | 0.7 | 0.3 | 1.2 | | | | | 21.5 | 0.2 | 4.5 | 3.2 | 4.5 | 4.8 | 0.0 | 4.4 | 79.3 | |

SW100 = weight (g) of 100 seedsat 13% moisture content, %cv = coefficient of variation (%), se = standard error of the mean, lsd (5%) = least significant difference, R = resistant (1.0-3.4), I = intermediate (3.5-6.4), S = susceptibility (6.5-9.0), CAL96 = susceptible check for FRR, PRR and ALS, RWR719 = resistant check for PRR, MLB-49-89A = resistant check for FRR, MCM5001 = susceptible check for ALS, MEXICO54 = resistant check for ALS, COOKT = cooking time in minutes, HC = Hydration coefficient, WDW = washed drained weight in g, Clumping, Splitting, Appearance, Viscosity and Color rating scale = 1 (Unacceptable) to 7 (Excellent),YDHA = yield in kgha$^{-1}$

The groupings of both small and large white beans into mega environments showed a lot of variation in seasons even if some physical locations were grouped together like in group1 and 3 for small whites where Kitengule (KIT) and Kawanda (KAW) were each grouped together in 2018 and 2014, respectively. These results indicate the importance of testing over more seasons to define GE patterns that could improve trial testing site decisions and eventual varietal selection. Relatively large GE for common bean yield was previously reported (Carbonell *et al*., 2004; Amongi *et al*. 2019; Katuuramu *et al*. 2020) further emphasizing the relative importance of GE. When GE is large and consistent over seasons, it is important to define target environments for multi-location yield evaluations to make effective selection.

**Days to flowering (DF) and physiological maturity (DPM).** The DF ranged from 36 to 50, and DPM from 71 to 91 (Kawanda), 56-62 and 108-117 (Kachwekano) and 40-48and 72-81 (Kitengule) for small seeded beans (Fig. 3a), respectively. The DF and DPM were generally the highest at Kachwekano; followed by Kawanda and Kitengule for large seeded beans ranging from 33-49 and 80-91 (Kawanda), 47-57 and 92-101 (Kachwekano) and 34-42 and 63-75 (Kitengule) (Fig. 3b). Majority of the large bean genotypes flowered and matured from 40-50 (91%) and 60-80 (65%) days at Kawanda, >50 (56%) and >80 (100%) days at Kachwekano and < 40 (92%) and 60-80 (100%) days at Kitengule (Fig. 3a). Although no genotype matured exceptionally early (< 60 days) in any environment, the observed days to flowering (36-62) and physiological maturity (71-117) (Fig. 3) were within the range for market class bush bean varieties. Maturity days of 67 to 90 and 58 to 68 for bush beans were reported for released bush bean varieties in Tanzania (Binagwa *et al*., 2018) and Uganda (Nkalubo *et al*., 2016) respectively. Thus, it is possible to select for farmer acceptable days to maturity in the evaluated genotypes.

TABLE 2. Response of selected large white beans to Pythium root rot (PRR) and Angular leaf spot (ALS), cooking time, canning quality and yield performance

| Genotypes | PRR_1 | PRR_2 | ALS_1,2 | SW100 | COOKT | HC | Clumping | Splitting | Appearance | Viscosity | Colour | Free starch | WDW (g) | YDHA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F14POPULATION-13 | 2.0 | 2.0 | 2.5 | 63.5 | 65.0 | 2.1 | 4.5 | 3.5 | 3.5 | 5.0 | 7.0 | 4.5 | 274 | 1405.6 |
| F14POPULATION-5 | 2.0 | 2.4 | 2.3 | 51.3 | 35.5 | 2.0 | 4.5 | 3.5 | 4.0 | 5.0 | 7.0 | 4.5 | 286 | 977.4 |
| F14POPULATION-18 | 2.0 | 2.4 | 2.5 | 50.2 | 39.4 | 1.9 | 6.5 | 5.5 | 5.5 | 6.5 | 7.0 | 5.5 | 285 | 1376.2 |
| F14POPULATION-12 | 2.1 | 2.0 | 2.7 | 51.4 | 49.7 | 1.8 | 5.0 | 5.0 | 4.5 | 4.0 | 7.0 | 4.5 | 274 | 1369.5 |
| NAVY LINE-9 | 2.1 | 2.8 | 2.4 | 62.4 | 52.2 | 2.0 | 5.5 | 4.0 | 4.5 | 5.5 | 7.0 | 6.5 | 288 | 1117.8 |
| NAVY LINE-28 | 2.2 | 2.7 | 2.8 | 60.0 | 50.0 | 2.0 | 5.0 | 4.5 | 4.5 | 5.5 | 7.0 | 5.0 | 289 | 889.5 |
| F14POPULATION-15 | 2.5 | 2.0 | 2.8 | 61.9 | 52.9 | 2.0 | 4.0 | 3.0 | 4.0 | 3.5 | 7.0 | 3.0 | 287 | 1105.3 |
| F14POPULATION-11 | 2.6 | 2.0 | 2.7 | 43.9 | 61.7 | 2.0 | 5.5 | 5.0 | 5.0 | 4.0 | 7.0 | 5.0 | 291 | 1098.6 |
| F14POPULATION-4 | 2.6 | 2.5 | 2.4 | 59.0 | 40.7 | 2.0 | 4.5 | 4.5 | 4.0 | 4.5 | 7.0 | 4.0 | 285 | 1340.7 |
| F14POPULATION-1 | 2.6 | 3.0 | 2.4 | 62.7 | 40.2 | 1.9 | 5.5 | 4.5 | 4.0 | 4.0 | 7.0 | 4.0 | 278 | 1326.8 |
| NAVY LINE-8 | 2.7 | 3.4 | 2.4 | 64.0 | 54.5 | 2.1 | 6.0 | 5.0 | 5.0 | 4.5 | 7.0 | 5.5 | 256 | 997.7 |
| F14POPULATION-20 | 3.4 | 2.1 | 2.6 | 64.4 | 54.1 | 1.9 | 2.0 | 2.0 | 1.0 | 1.5 | 7.0 | 2.0 | 295 | 1225.6 |
| F14POPULATION-23 | 2 | 3.0 | 3.7 | 58.9 | 44.6 | 2.0 | 5.0 | 4.0 | 4.5 | 3.5 | 7.0 | 4.5 | 272 | 1354.5 |
| SAB 713 | 3.3 | 2.0 | 3.8 | 46.2 | 45.1 | 2.0 | 5.5 | 5.0 | 4.0 | 5.0 | 7.0 | 5.5 | 279 | 1276.4 |
| F14POPULATION-21 | 6.4 | 3.2 | 2.1 | 66.6 | 34.0 | 2.0 | 4.5 | 4.0 | 2.0 | 2.0 | 7.0 | 2.5 | 265 | 1472.2 |
| F14POPULATION-6 | 4.4 | 3.7 | 6.8 | 57.6 | 36.6 | 1.9 | 5.0 | 4.5 | 4.5 | 4.5 | 7.0 | 4.0 | 252 | 1632.9 |
| F14POPULATION-3a | 3.4 | 4.8 | 2.7 | 50.0 | 59.2 | 2.0 | 5.5 | 5.5 | 6.0 | 5.5 | 7.0 | 6.0 | 291 | 1136.7 |
| F14POPULATION-19 | 2.1 | 3.2 | 6.8 | 60.5 | 44.2 | 2.0 | 5.5 | 5.5 | 4.5 | 5.5 | 7.0 | 5.5 | 264 | 1137.4 |
| F14POPULATION-16 | 3.8 | 2.0 | 2.1 | 43.7 | 61.7 | 2.0 | 6.0 | 5.0 | 4.5 | 5.5 | 7.0 | 5.5 | 293 | 1251.8 |
| CAL96 | 9.0 | 9.0 | 6.9 | | | | | | | | | | | |
| RWR719 | 2.5 | 2.1 | - | | | | | | | | | | | |
| MCM 5001 | - | - | 6.7 | | | | | | | | | | | |
| MEXICO 54 | - | - | 1.8 | | | | | | | | | | | |
| Minimum | 2.0 | 2.0 | 1.8 | 43.7 | 34.0 | 1.8 | 2.0 | 2.0 | 1.0 | 1.5 | 7.0 | 2.0 | 242 | 889.5 |

TABLE 2. Contd.

| Genotypes | PRR _1 | PRR _2 | ALS _1,2 | SW100 | COOKT | HC | Clumping | Splitting | Appearance | Viscosity | Colour | Free starch | WDW (g) | YDHA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maximum | 9.0 | 9.0 | 6.9 | 66.6 | 65.0 | 2.1 | 6.5 | 5.5 | 6.0 | 6.5 | 7.0 | 6.5 | 295 | 1632.9 |
| Mean | 3.5 | 3.5 | 3.3 | | 49.5 | 2.0 | 4.9 | 4.3 | 4.0 | 4.3 | 7.0 | 4.4 | 275 | 1225.9 |
| %cv | 15.4 | 15.2 | 6.1 | | 31.7 | 4.8 | 26.8 | 34.0 | 47.5 | 30.0 | 0.0 | 30.6 | 7.9 | |
| s.e | 0.50 | 0.50 | 0.20 | | 15.70 | 0.10 | 1.31 | 1.45 | 1.90 | 1.29 | 0.00 | 1.40 | 21.70 | |
| l.s.d (5%) | 1.1 | 1.1 | 0.3 | | 33.3 | 0.2 | 2.8 | 3.1 | 4.1 | 2.7 | 0.0 | 2.9 | 45.9 | |

*SW100* = weight (g) of 100 seeds at 13 % moisture content, *%cv* = coefficient of variation (%), se = standard error of the mean, lsd = least significant difference, PRR and ALS disease rating scale = resistant (1.0-3.4), intermediate (3.5-6.4), susceptibility (6.5-9.0), *CAL96* = susceptible check for FRR, PRR and ALS, *RWR719* = resistant check for PRR, *MLB-49-89A* = resistant check for FRR, *MCM5001* = susceptible check for ALS, *MEXICO54* = resistant check for ALS, COOKT = cooking time in minutes, HC = Hydration coefficient, WDW = washed drained weight in g, Clumping, Splitting, Appearance, Viscosity and Color rating scale = 1 (Unacceptable) to 7 (Excellent), YDHA = yield in kg ha$^{-1}$

**Reaction to field diseases.** Angular leaf spot (ALSF), and common bacterial blight (CBBFL) were the major diseases in all the three sites (Table 5). Mild to medium Aschohyta blight was only observed at Kachwekano; while rust was mainly a challenge at Kawanda and anthracnose was generally mild in all sites and seasons. Bean common mosaic virus was mild to intermediate with the highest mean of 3.2 (2014A) and 4.2 at Kawanda (2013B) for small and large bean genotypes. The ALSF severity among the small bean genotypes ranged from 1 to 9 with a mean of 6.5 at Kachwekano in 2018B. The genotypes' response to CBBFL ranged from 1.1 to 6.9 with a mean of 4.7 in 2014A at Kawanda on a 1-9 scale. For the large seeded genotypes, the disease ratings for ALSF ranged from 2.0 to 6.8 with highest mean of 5.2 reported at Kawanda during 2014A.

The severity for CBBFL ranged from 1.2 to 6.6 at with the highest mean of 5.2 recorded at Kachwekano (Table 5). Broad resistance to field diseases was observed in the evaluated germplasm (Table 5) although disease pressure highly varied across environments. The field evaluations showed that ALS, CBB and BCMV were major foliar diseases in all sites and Ascochyta blight was an emerging challenge at Kachwekano highland. Breeding for multiple resistance to these major diseases is recommended. Varieties with multiple disease resistance would maintain stable yields, despite occurrence of different diseases within or across growing seasons.

**Resistance to *Pythium* and *Fusarium* root rots.** Under screen house conditions, the small seeded genotypes were significantly different ($P<0.001$) in response to both Pythium (PRR) and Fusarium (FRR) root rot pathogens (Table 6). For PRR, genotype x screening cycle interaction was significant ($P< 0.01$). Thirty-one (24.3%) and 51 (39.5%) genotypes were resistant to PRR and FRR, respectively; in the three screening rounds (Fig. 4). Fourteen genotypes (10.9%) expressed dual resistance to both root rots (Table 1). The large seeded

TABLE 3. Stability superiority measure coefficients for 20 most stable small and large white bean genotypes and their yield performance in the mega environment groups

| Genotype | SSMC | ENV1 | ENV2 | ENV3 | ENV4 |
|---|---|---|---|---|---|
| **Small – white beans** | | | | | |
| ZABR16574-44F22 | 122974 | 1872.8 | 2188.7 | 2192.4 | |
| ZABR16575-60F22 | 178407 | 1930.0 | 1871.8 | 2475.3 | |
| ZABR16574-37F22 | 189174 | 1599.4 | 2225.6 | 1964.8 | |
| ZABR16574-59F22 | 189253 | 1783.2 | 2136.9 | 2014.2 | |
| ZABR 16575-29F22 | 204506 | 1953.6 | 1862.3 | 2363.7 | |
| SSW13 | 217399 | 1857.7 | 1760.1 | 2858.9 | |
| ZABR16575-52F22 | 228368 | 1905.0 | 1799.4 | 2416.2 | |
| ZABR16574-21F22 | 243800 | 1764.7 | 1792.5 | 2312.4 | |
| ZABR16575-36F22 | 289495 | 1319.4 | 1841.7 | 1981.5 | |
| ZABR16575-73F22 | 295223 | 1771.1 | 2035.7 | 1819.8 | |
| ETSNAP19 | 296544 | 1855.8 | 1791.1 | 2133.7 | |
| ZABR16574-17F22 | 302422 | 2009.9 | 1903.0 | 1960.7 | |
| ETSNAP28 | 328490 | 1223.0 | 1637.3 | 2239.7 | |
| ETSNAP30 | 331236 | 1721.3 | 1714.0 | 2154.2 | |
| ICN BunsixSxB405/7C-1C-1C-30 | 332838 | 1552.4 | 1872.5 | 1861.9 | |
| ETSNAP9 | 334482 | 1582.0 | 1800.4 | 1955.8 | |
| ICN BunsixSxB405/3C-1C-1C-87 | 342166 | 1729.8 | 1788.0 | 1977.6 | |
| ETSNAP31 | 343278 | 1287.8 | 1813.5 | 1876.7 | |
| RAZ44-Alubia | 352384 | 1194.2 | 1701.6 | 2008.7 | |
| SSB1 | 352505 | 1894.9 | 1901.5 | 1824.2 | |
| Mean | | 1707.2 | 1707.2 | 1707.2 | |
| Minimum | | 979.9 | 1329.0 | 1188.9 | |
| Maximum | | 2321.3 | 2317.0 | 2858.9 | |
| **Large-white beans** | | | | | |
| F14Population (6) | 109991 | 1399.9 | 1440.2 | 1314.3 | 1596.7 |
| F14Population (22) | 130149 | 1167.9 | 1845.2 | 1144.8 | 1383.9 |
| F14Population (18) | 164956 | 1334.0 | 1451.1 | 1160.3 | 1303.2 |
| F14Population (13) | 170868 | 1347.6 | 1643.6 | 1031.7 | 1232.1 |
| SAB713 | 171815 | 996.2 | 1732.3 | 1079.7 | 1563.5 |
| F14Population (21) | 174728 | 1258.9 | 1373.6 | 1091.8 | 1368.3 |
| F14Population (4) | 205222 | 1242.2 | 1240.7 | 1119.9 | 1472.9 |
| F14Population (17) | 222321 | 1242.1 | 1345.6 | 1417.1 | 1337.0 |
| F14Population (9) | 248405 | 1056.0 | 2014.2 | 1263.6 | 1133.1 |
| F14Population (16) | 249825 | 1228.1 | 1334.3 | 1559.9 | 1345.8 |
| Navy Line- 9 | 280332 | 1039.9 | 1705.3 | 1290.3 | 1104.0 |
| F14Population (23) | 324579 | 1297.1 | 895.2 | 1078.8 | 1541.3 |
| F14Population (1) | 340894 | 1385.0 | 999.0 | 977.5 | 1205.1 |
| F14Population (15) | 352483 | 1071.9 | 1484.5 | 1093.3 | 1040.8 |
| F14Population (20) | 384689 | 1079.7 | 889.2 | 842.8 | 1552.9 |
| F14Population (7) | 408641 | 1159.0 | 1071.3 | 1397.3 | 1147.2 |

TABLE 3. Contd.

| Genotype | SSMC | ENV1 | ENV2 | ENV3 | ENV4 |
|---|---|---|---|---|---|
| F14Population (2) | 436961 | 1266.0 | 1242.4 | 1407.4 | 853.2 |
| F14Population (19) | 482569 | 1313.4 | 951.1 | 1408.6 | 972.8 |
| F14Population (3) | 504432 | 1247.3 | 890.8 | 1078.9 | 1031.0 |
| F14Population (11) | 512291 | 1149.5 | 887.3 | 1563.0 | 1276.2 |
| Mean | | 1215.7 | 1215.7 | 1215.7 | 1215.7 |
| Minimum | | 996.1 | 573.6 | 842.8 | 783.7 |
| Maximum | | 1616.8 | 2014.2 | 1595.1 | 1596.7 |

SSMC = Stability superiority measure coefficients (genotypes with smaller values are more stable)

TABLE 4. Analysis of variance for AMMI model for small and large white bean genotypes

| | d.f. | Small white | | Large white | |
|---|---|---|---|---|---|
| Source | | SS | Variance | SS | Variance |
| Genotypes | 125 (24) | 21556604 | 172453*** | 3951412 | 164642 |
| Environments | 6 | 488968814 | 81494802*** | 58640054 | 9773342*** |
| Interactions | 750 (144) | 57090616 | 76121 | 19121678 | 132789 |
| IPCA 1 | 130 (29) | 29959361 | 230457*** | 7908512 | 272707*** |
| IPCA 2 | 128 (27) | 11267431 | 88027*** | 4482081 | 166003** |
| Residuals | 492 (88) | 15863824 | 32244 | 6731086 | 76490 |

Degree of freedom (d.f.) in parentheses is for large white beans, *SS* = sums of squares, *, **, *** = significant at P d" 0.05, P<0.01 and P<0.001, respectively

genotypes also differed significantly (P <0.001) in response to PRR (Table 6) and the majority (59.3%) expressed resistance (Fig. 5) with seven outstanding genotypes (Table 2). The PRR resistant control genotype, MLB-49-89A, maintained resistance in all the screenings, and 58 small and 13 large seeded genotypes were not significantly different from it (Tables 1 and 2). For FRR, NABE6 was not significantly different from the resistant control genotype, RWR719.

A similar pattern of resistance level was observed in both the small and large seeded genotypes for Pythium root rot (PRR) in all the repetitions (Figs. 4 and 5). The largest percentage of the genotypes expressed resistance (>58% and >70%), followed by intermediate response (<40% and <25%) and susceptibility (<10% and <13%) for small and large white beans, respectively (Figs. 4 and 5). Most of the evaluated genotypes are thus useful for Pythium root rot breeding undertakings and are recommended for further evaluations. Based on percentages, higher levels of resistance to PRR was observed in large than small seeded genotypes.

Only small seeded genotypes were assessed for FRR resistance and most genotypes expressed intermediate response (55%), and 5% were susceptible (Fig. 4). Overall, more resistance to PRR than FRR was observed in the evaluated genotypes and

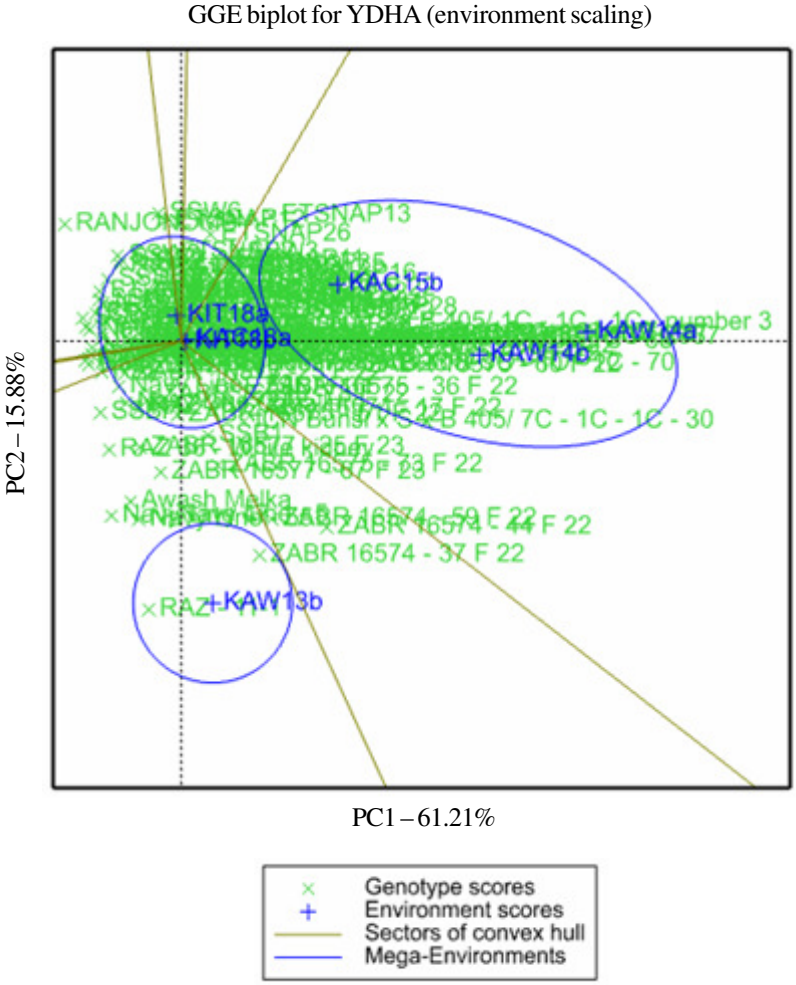


Figure 1. GGE biplots for yield of small-white bean genotypes in six environments.

resistance to a single root rot pathogen was more evident. The 11% of the small seeded genotypes that expressed dual resistance to root rots suggests the existence of combined and independent resistance mechanisms in the evaluated genotypes.

**Resistance to Angular leaf spot.** Under screen house conditions, significant differences (P<0.001) existed among the small seeded genotypes in their response to the *P. griseola*race 61:63 (Table 6). The genotype x screening cycle interaction was significant (P <0.01). Forty-nine genotypes (38.0%) were resistant to ALS in all the three screening rounds (Fig. 5). The ALS resistant control genotype, MEXICO54, maintained resistance in the three screenings and five genotypes (ZABR16574-37F22, ICNBunsixSxB405/1C-1C-1C-B, ICNBunsixSxB405/9C-1C-1C-70, ZABR16575-57F22 and F14Population-17), were not significantly different from it. Ten genotypes were the most outstanding in ALS resistance level including Awash Melka released in Ethiopia (Table 1). Similarly, the large seeded genotypes significantly (P< 0.001) differed in ALS resistance levels (Table 6). The genotype x screening cycle interaction was also significant (P<0.01). The majority of the genotypes (75.0%) expressed resistance

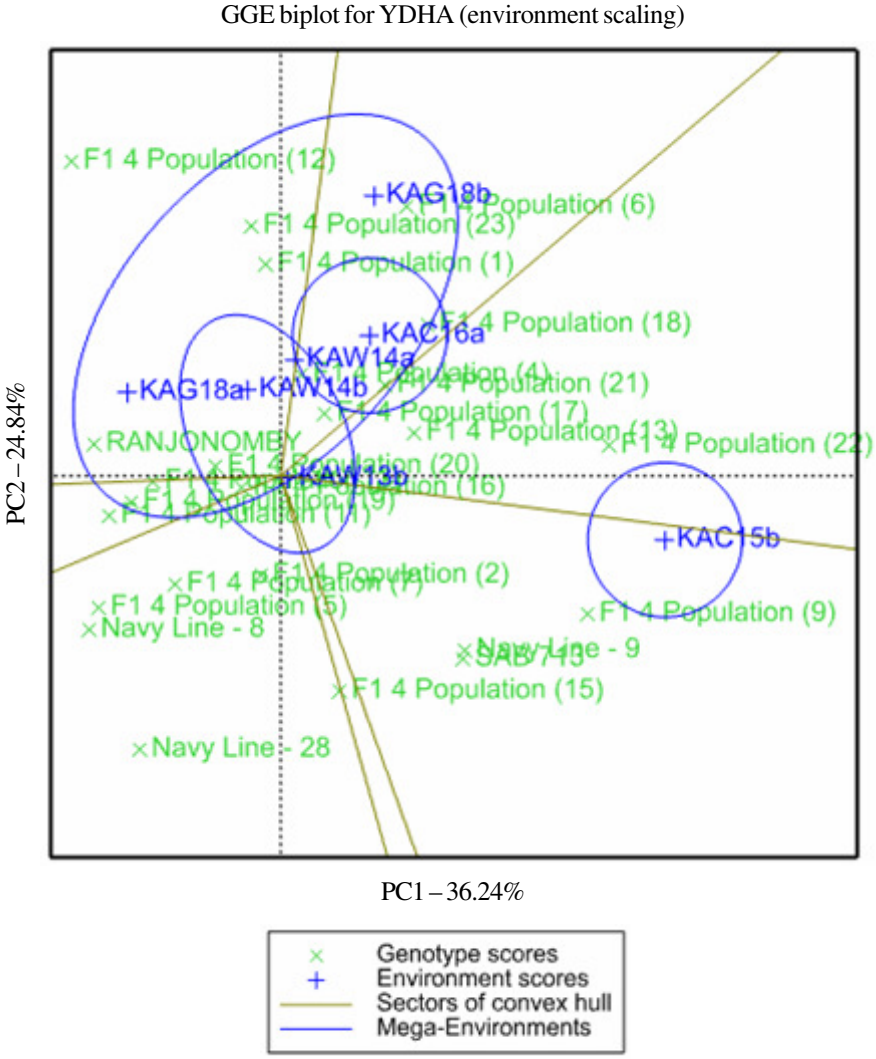


Figure 2. GGE biplots for yield of small-white bean genotypes in six environments.

to ALS (Fig. 5) including RANJONOMBY, a variety released in Madagascar (Table 2). More large seeded genotypes (75%) expressed resistance to ALS compared to the small white beans (38%), (Figs. 4 and Fig. 5) but in terms of numbers, more resistant small white beans were identified than the large counterparts. The genotypes resistant to ALS are very useful for varietal improvement and further evaluation for other important traits could lead to identification of genotypes able to thrive in farmers' fields. Infection of pods and seeds by ALS lowers the quality of harvested seeds which is very noticeable especially in white beans.

**Combined resistance to root rots and angular leaf spot.** Different levels of resistance to Pythium (PRR) and Fusarium (FRR) root rots, and angular leaf spot (ALS) were observed. Majority of the genotypes exhibited resistance to intermediate response to at least a pathogen. However, those that exhibited dual or triple resistance provide more durable disease protection. Dual resistance was expressed in 14 (PRR/FRR), 13 (PRR/

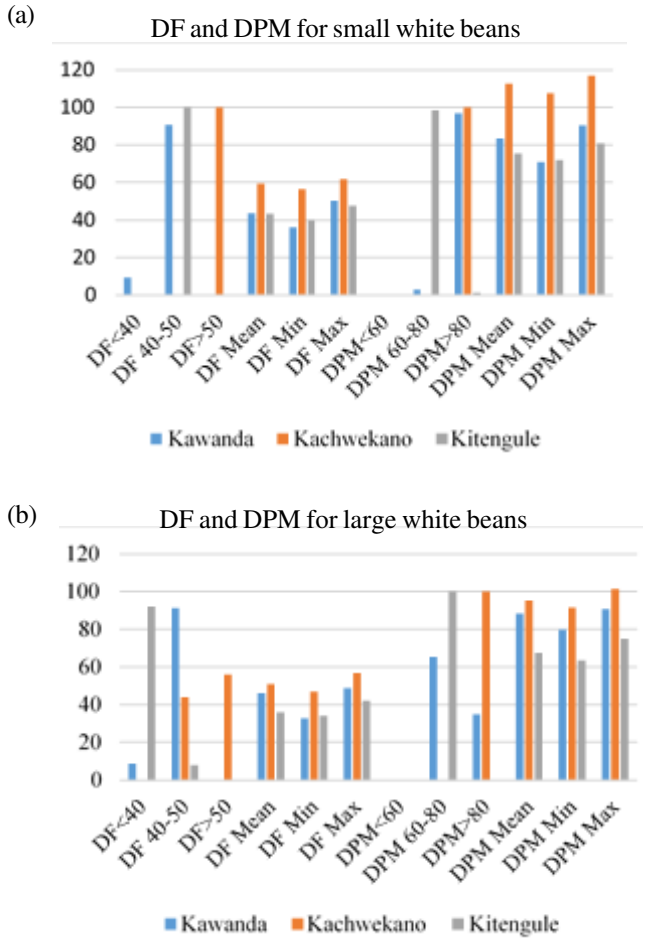


Figure 3. Days to flowering (DF) and physiological maturity (DPM) for evaluated germplasm at Kawanda, Kachwekano and Kitengule.

ALS) and 16 (FRR/ALS) small white; and in 9 (PRR/ ALS) large white bean genotypes (Tables 1 and 2). Resistance to the three pathogens was expressed in four small seeded genotypes, namely, ICNBunsi/S/B405/4C-1C-1C-88, RAZ-11, ETSNAP18 and ETSNAP3, in all the screening cycles (Table 1). These genotypes could be used in breeding for broad resistance, and further assessed for resistance mechanism (s). Except for RAZ-11, the genotypes yielded above the grand mean of 1707.2 kg $ha^{-1}$ which make them better parental lines. The time taken to cook these genotypes ranged from 46 to 56 min, and the genotypes hydrated properly during soaking (HC > 2.0) although were below average in visual canning quality especially in splitting and appearance (Table 1). Similar to this study, Mukamuhirwa *et al*. (2017) also found combined resistance to Fusarium root rot, Pythium root rot, and ALS in one black bean genotype, ACC714 from an evaluation of 57 genotypes under screen house conditions in Uganda using the same isolates for root rots and different isolates for ALS (Andean-KAK3 and MesoAmerican-2A) and recommended it for breeding purpose. Understanding the mechanism causing triple resistance in the genotypes could provide useful information for breeding purpose. Among the large white beans, the nine genotypes (44%) expressed dual resistance to PRR and ALS (Fig. 5).

TABLE 5. The response of small and large bean genotypes to field diseases in the different environments

| Genotypes | Environment | ALSF | ANTFP | BCMV | CBBFL | RUSTFL | ASCFL | ALSF | ANTFL | BCMV | CBBFL | RUSTFL | ASCFL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Small white | | | | | | Large white | | | | | |
| Resistant:1.0-3.4 | KAW13B | 80.2% | 100.0% | 56.8% | 33.1% | 96.7% | | 20.8% | 100.0% | 4.2% | 0.0% | 20.8% | |
| Intermediate:3.5-6.4 | | 19.8% | 0.0% | 43.2% | 66.1% | 2.5% | | 79.2% | 0.0% | 95.8% | 100.0% | 79.2% | |
| Susceptible:6.5-9.0 | | 0.0% | 0.0% | 0.0% | 0.8% | 0.8% | | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | |
| Mean | | 2.8 | 1.4 | 3.2 | 3.7 | 1.7 | | 3.7 | 1.0 | 4.2 | 4.9 | 4.0 | |
| Min | | 2.0 | 0.9 | 0.8 | 2.0 | 1.0 | | 3.0 | 1.0 | 3.0 | 3.7 | 2.4 | |
| Max | | 4.5 | 2.5 | 5.3 | 6.5 | 6.5 | | 4.5 | 1.5 | 5.1 | 6.0 | 6.0 | |
| Heritability | | | | | | | | 0.0 | 0.0 | 0.2 | 0.4 | 0.6 | |
| Resistant:1.0-3.4 | KAW14A | 6.6% | 100.0% | 55.7% | 0.0% | 96.7% | | 0.0% | 100.0% | 66.7% | 4.3% | 95.7% | |
| Intermediate:3.5-6.4 | | 93.4% | 0.0% | 44.3% | 100.0% | 3.3% | | 91.3% | 0.0% | 33.3% | 95.7% | 4.3% | |
| Susceptible:6.5-9.0 | | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | | 8.7% | 0.0% | 0.0% | 0.0% | 0.0% | |
| Mean | | 4.4 | 1.8 | 3.4 | 4.7 | 2.1 | | 5.2 | 1.6 | 3.2 | 4.5 | 2.4 | |
| Min | | 2.8 | 1.0 | 0.9 | 3.5 | 1.5 | | 3.7 | 0.8 | 2.9 | 3.1 | 2.0 | |
| Max | | 6.1 | 3.0 | 5.1 | 6.0 | 4.5 | | 6.8 | 2.0 | 4.1 | 5.5 | 3.5 | |
| Heritability | | 0.4 | 0.2 | 0.3 | 0.3 | 0.6 | | 0.4 | 0.5 | 0.4 | 0.1 | 0.0 | |
| Resistant:1.0-3.4 | KAW14B | 71.1% | 100.0% | 59.1% | 62.5% | 91.4% | | | | | | | |
| Intermediate:3.5-6.4 | | 28.9% | 0.0% | 40.9% | 37.5% | 8.6% | | | | | | | |
| Susceptible:6.5-9.0 | | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | | | | | | | |
| Mean | | 3.0 | 1.5 | 3.2 | 3.2 | 2.5 | | | | | | | |
| Min | | 1.8 | 0.9 | 1.5 | 1.9 | 1.4 | | | | | | | |
| Max | | 4.9 | 2.5 | 5.7 | 5.1 | 5.5 | | | | | | | |
| Heritability | | 0.5 | 0.3 | 0.0 | 0.4 | 0.4 | | | | | | | |
| Resistant:1.0-3.4 | KAC15D | 45.4% | 99.2% | 93.8% | 99.2% | 96.9% | | 76.0% | 100.0% | | 100.0% | 100.0% | 28.0% |
| Intermediate:3.5-6.4 | | 51.5% | 0.8% | 6.3% | 0.8% | 2.3% | | 24.0% | 0.0% | | 0.0% | 0.0% | 72.0% |
| Susceptible:6.5-9.0 | | 3.1% | 0.0% | 0.0% | 0.0% | 0.0% | | 0.0% | 0.0% | | 0.0% | 0.0% | 0.0% |
| Mean | | 3.8 | 1.3 | 2.2 | 2.1 | 1.4 | | 3.0 | 1.1 | 2.6 | 2.4 | 1.2 | 3.9 |
| Min | | 1.0 | 0.9 | 0.4 | 1.5 | 1.0 | | 2.0 | 1.0 | 1.5 | 1.2 | 0.8 | 2.4 |
| Max | | 7.3 | 4.0 | 6.1 | 3.5 | 4.5 | | 4.0 | 2.5 | 4.0 | 3.2 | 2.9 | 5.5 |
| Heritability | | 0.6 | 0.2 | 0.5 | 0.4 | 0.1 | | 0.0 | 0.3 | 0.5 | 0.4 | 0.4 | 0.8 |
| Resistant:1.0-3.4 | KAC18B/ 2016B | 0.0% | 98.4% | | 50.8% | 54.0% | 96.8% | 56.0% | | | 0.0% | | 100.0% |
| Intermediate:3.5-6.4 | | 42.9% | 1.6% | | 48.4% | 41.3% | 3.2% | 44.0% | | | 88.0% | | 0.0% |
| Susceptible:6.5-9.0 | | 57.1% | 0.0% | | 0.8% | 4.8% | 0.0% | 0.0% | | | 12.0% | | 0.0% |
| Mean | | 6.5 | 1.3 | | 3.5 | 3.6 | 2.4 | 3.4 | 1.3 | | 5.2 | | 1.1 |
| Min | | 4.2 | 0.4 | | 1.1 | 0.9 | 1.0 | 2.0 | 0.9 | | 3.8 | | 1.0 |
| Max | | 9.0 | 4.1 | | 6.9 | 8.2 | 4.0 | 5.0 | 4.7 | | 6.6 | | 2.0 |
| Heritability | | 0.2 | 0.0 | | 0.4 | 0.5 | 0.2 | 0.0 | 0.0 | | 0.4 | | 0.0 |
| Resistant:1.0-3.4 | KIT18D | 55.9% | | | 77.3% | 97.7% | | | 72.0% | | 100.0% | 96.0% | |
| Intermediate:3.5-6.4 | | 42.5% | | | 22.7% | 2.3% | | | 28.0% | | 0.0% | 4.0% | |
| Susceptible:6.5-9.0 | | 1.6% | | | 0.0% | 0.0% | | | 0.0% | | 0.0 | 0.0% | |
| Mean | | 3.5 | | | 3.0 | 1.3 | | | 3.1 | | 2.2 | 1.4 | |

TABLE 5. Contd.

| Genotypes | Environment | ALSF | ANTFP | BCMV | CBBFL | RUSTFL | ASCFL | ALSF | ANTFL | BCMV | CBBFL | RUSTFL | ASCFL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Small white | | | | | | Large white | | | | | |
| Min | | 2.0 | | | 2.0 | 1.0 | | | 2.0 | | 1.5 | 0.8 | |
| Max | | 8.0 | | | 5.5 | 5.5 | | | 5.5 | | 3.0 | 3.5 | |
| Heritability | | 0.7 | | | 0.6 | 0.4 | | | 0.7 | | 0.2 | 0.6 | |

KAW = Kawanda, KAC = Kachwekano, KIT = Kitengule, A = 1st season, B = 2nd season

These included genotypes such as F14POPULATION-13, F14POPULATION-12 and F14POPULATION-15 (Table 2). The study focused on identification of resistant genotypes but those that expressed resistant to intermediate response to two or three pathogens are equally useful for further evaluation for possible release. Examples of such genotypes were RAZ-120 and ETSNAP12 that expressed resistance to PRR and ALS, but had an intermediate response to FRR.

There are not many studies that have assessed combined foliar and root rot disease resistance in the same background possibly because the two diseases occur at different bean development stages. Root rots frequently affect seed germination and radicle emergence; while ALS is a post seedling disease (CIAT, 1987). However, the occurrence of root rots and ALS on the same farm most especially under different weather conditions is not uncommon. Mukankusi *et al.* (2015) reported multiple disease occurrence, including root rots and ALS in fields of nine farmer groups selected from two sub counties of Rakai and Hoima districts in Uganda, and emphasized the need for farmers to have access to a widely adapted bean variety or a diverse range of bean varieties in order to address the effects of different production challenges. Mondo *et al.* (2019) also reported coinfection of beans with several diseases on-farm and bred five genotypes combining multiple resistance to ALS, root rots, anthracnose and common bacterial blight using marker assisted selection although none of them possessed dual resistance to Pythium and Fusarium root rot. These are possible sources of genes for multiple resistance and broadening diversity. Similarly, Okii *et al.* (2017) successfully pyramided resistance to four diseases including ALS, Pythium root rot, anthracnose and virus through marker assisted breeding while maintaining high yield of 270 - 290 seed per plant and early maturity (95-100 days) in small to medium seeded climbing beans. This showed that breeding for broad-spectrum

TABLE 6. Analysis of variance for cooking time and canning quality traits of small and large white beans

| Change | d.f. | Pythium root rot | Fusarium root rot | Angular leaf spot |
|---|---|---|---|---|
| **Small white** | | | | |
| Screening | 2 | 2.50 | 30.68*** | 2.32 |
| Replication/ Screening | 3 | 1.33 | | 0.41 |
| Genotype | 128 | 6.98*** | 3.21*** | 13.49*** |
| Genotype x Screening | 256 | 3.26*** | | 2.70*** |
| Residual | 384 | 1.13 | 0.96 | 0.17 |
| Total | 773 | 2.81 | 2.17 | 3.22 |
| **Large white** | | | | |
| Screening | 1 | 0.00 | | 1.22*** |
| Replication /screening | 2 | 1.42* | | 0.001 |
| Genotype | 26 | 13.17*** | | 11.76*** |
| Genotype x Screening | 26 | 2.30*** | | 0.09** |
| Residual | 52 | 0.29 | | 0.04 |
| Total | 107 | 3.92 | | 2.91 |

d.f = degree of freedom, *, **, *** = significant at P<0.05, P<0.01 and P<0.001, respectively

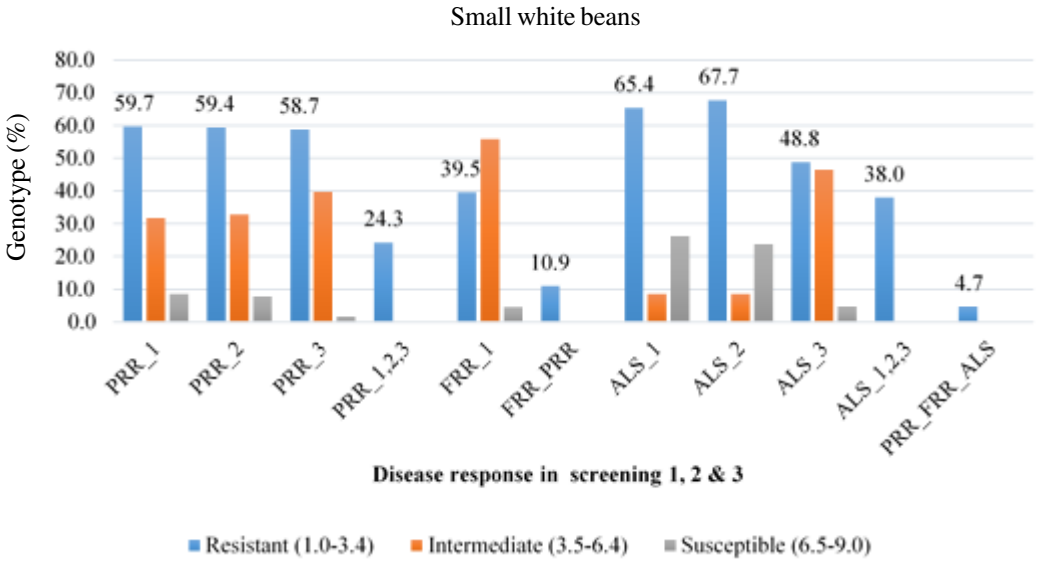


Figure 4. Percentage of small white bean genotypes that were resistant, intermediate or susceptible to Pythium (PRR), Fusarium (FRR) root rot and Angular leaf spot (ALS).

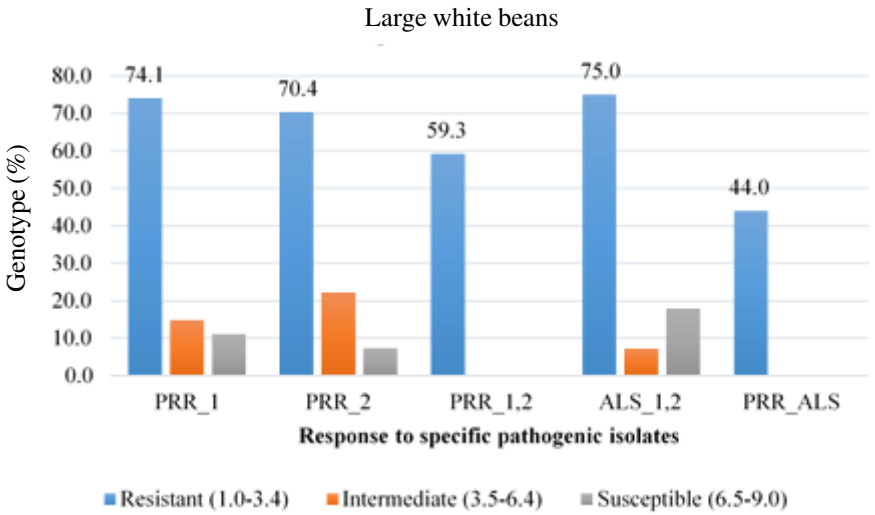


Figure 5. Percentage of large-white bean genotypes that were resistant, intermediate or susceptible to Pythium (PRR) root rot and Angular leaf spot (ALS).

resistance which is highly desirable for crop improvement is achievable without negative yield penalty when optimised approaches are utilised.

**Cooking time.** The difference between the cooking times of the earliest and latest genotype was 61 and 31 min for small and large beans respectively. The small white beans significantly ($P<0.001$) differed in cooking time but the large white beans did not (Table 7). The correlation of cooking time to weight of 100 seeds was weak and non-significant ($r = -0.04$), which suggested unlikely influence of seed size on cooking time. The earliest (29 minutes) genotype to be cooked was ETSNAP2 and the latest (89 minutes) was F14population-(3) for the small seeded genotypes (Table 1), and F14Population-21 (34 min) and F14Population-13 (65 min) for the large seeded ones (Table 2). This highlighted diversity in cooking time could be utilised to breed even faster cooking beans. The majority of the small seeded genotypes were cooked within 41 to 50 min (Fig. 6). A total of 58.7% of the genotypes cooked in less than the mean time of 48 min, and 11 genotypes were cooked in less than 40 min (Table 1). For the large beans, 48% of the genotypes cooked in less than the average time of 50 min of which five cooked in less than 40 min (Table 2). Three genotypes ECAPAN021, NABE6 and Awash melka which were cooked in 42 to 45 min had initially been categorised as fast cooking beans (35-47 min) by Mughi, (2015). The genotypes showed consistency in earliness to cook and are recommended for breeding purpose. Bean genotypes with short cooking time not only conserve energy, water and save time of consumers and processors of dry beans (Ugen *et al.*, 2017), but also retain more iron and zinc during the cooking process (Cichy *et al.*, 2015). Hence, the identified fast cooking beans are very valuable.

In addition to the potential to reduce cooking time through breeding, the study also identified genotypes that could be fast tracked towards variety release and commercialisation in eastern Africa. Genotypes such as ETSNAP2, ETSNAP19, ZABR16576-20F22, F14Population-21, F14Population-5, with cooking time <" 36.0 min (Table 1 and 2) would not only greatly serve as good parental lines but could be attractive to end users if further evaluated for possible promotion as they had yields in the range of 977-1918 kg

TABLE 7. Analysis of variance table for cooking time and canning quality traits of small and large seeded white bean genotypes

| Change | d.f. | COOKT | HC | Clumping | Splitting | Appearance | Viscosity | Colour | Free starch | WDW |
|---|---|---|---|---|---|---|---|---|---|---|
| **Small white** | | | | | | | | | | |
| Rep | 1 | 232.06* | 0.0140 | 2.6 | 1.88 | 0.95 | 7.47 | 0.0370 | 13.26* | 1250.8 |
| Block/ rep | 16 | 113.29* | 0.0082 | 1.8 | 2.63* | 2.78 | 3.50 | 0.035 | 3.49 | 560.2 |
| Genotype | 125 | 127.98*** | 0.0076 | 4.0* | 2.63*** | 4.87*** | 3.53 | 0.038*** | 4.69*** | 897.6 |
| Residual | 105 | 58.95 | 0.0065 | 2.5 | 1.28 | 2.57 | 2.87 | 0.070 | 2.4 | 797.3 |
| Total | 247 | 98.10 | 0.0072 | 3.2 | 2.07 | 3.77 | 3.27 | 0.038 | 3.7 | 835 |
| **Large white** | | | | | | | | | | |
| Rep | 1 | 300.3 | 0.0203 | 5.12 | 4.50 | 18.0* | 4.50 | 0.0 | 9.7* | 486.2 |
| Block/ Rep | 8 | 277.8 | 0.0091 | 2.22 | 1.74 | 3.1 | 2.60 | 0.0 | 3.0 | 320.8 |
| Genotype | 24 | 153.7 | 0.0090 | 2.212 | 2.23 | 2.8 | 3.36 | 0.0 | 3.4 | 503.3 |
| Residual | 16 | 246.6 | 0.0091 | 1.708 | 2.10 | 3.7 | 1.66 | 0.0 | 1.8 | 468.8 |
| Total | 49 | 207.3 | 0.0093 | 2.108 | 2.16 | 3.5 | 2.70 | 0.0 | 2.9 | 461.9 |

*, **, *** = significant at $P<0.05$, $P<0.01$ and $P<0.001$, respectively, Rep = replication, COOKT = cooking time in minutes, HC = Hydration coefficient, WDW = washed drained weight

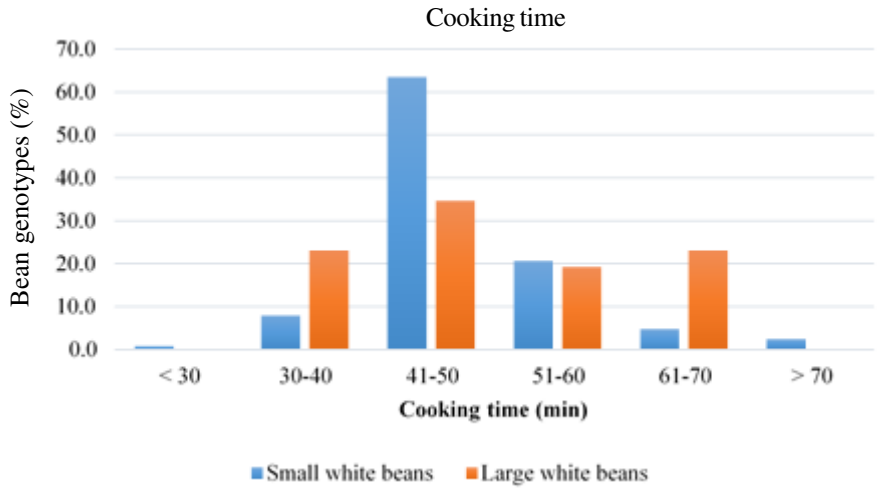


Figure 6. Percentage of cooking time for small and large seeded white bean genotypes belong to different cooking time groups

$ha^{-1}$. In particular, ETSNAP19 and F14Population-21 yielded above the mean and the yield checks, Awash melka (1697 kg $ha^{-1}$) and SAB713 (1276 kg $ha^{-1}$) for small and large bean genotypes respectively, which make them more superior than the other identified fast cooking beans. The response of the fast cooking five genotypes above was resistant to intermediate for both root rots and ALS, except for genotype ZABR16576-20F22 that showed susceptibility to ALS and could be improved by hybridisation with suitable parents. Although poor in visual canning quality, several fast cooking beans were resistant to at least two pathogens and these could be further evaluated for promotion as fast cooking beans. Genotypes like RANJONOMBY and F14Population-3 were cooked in 74-89 min but combined high canning quality with dual disease resistance. Several of the identified genotypes combined high yield performance with these attributes that could increase their attractiveness to farmers.

**Canning quality.** The evaluated germplasm consisted of those with unacceptable to excellent canning quality. The small white beans were significantly different ($P<0.05$) in clumping, splitting, appearance and free starch but the large seeded genotypes did not significantly differ (Table 7). Hydration coefficient (HC) ranged from 1.8 in genotype SSW19 to 2.2 in four genotypes, including RANJONOMBY with an average of 2.0 in the small white genotypes (Table 1), and 1.8 to 2.1 in the large seeded ones (Table 2). A minimum value of 1.8 for HC is recommended for selection for soaking ability by the canning industry because soaking uncooked dry beans normally causes a mass increase of 80% (Balasubramanian *et al.*, 2000; Hosfield, 1991), and 99.2% of the genotypes exhibited HC of above the 1.8 and were considered as potential genotypes for canning because they would produce a high can yield. Washed drained weights ranged from 214.9 g in SSBr1 to 437 g in ZABR16575-29F22, and 242.1 to 294.8 g for the small and large white beans respectively. The small seeded genotypes that were rated excellent for visual quality (clumping, splitting, appearance, viscosity, colour and free starch) ranged from 2.4% for splitting to 99.2% for colour (Fig. 7). Eighteen genotypes, including RANJONOMBY (released in Madagascar), and Awash1 (released in Ethiopia) exhibited good (5) to excellent (7) visual quality (Table 1). In the large seeded beans, excellence in visual

quality ranged from 0.0% for appearance and viscosity to 100% for colour (Fig. 8). Six genotypes; were rated good (5) to excellent (7) in all visual quality (Table 2). Overall, a higher percentage of the evaluated large beans (36%) compared to the small ones (14%) possessed acceptable canning quality if all visual qualities are considered. The above mentioned 18 small and six large seeded genotypes (Tables 1 and 2) are recommended for further evaluation for possible promotion to the canning industry but several other genotypes such as NavyLine-52 (1588.2 kg ha$^{-1}$) and ETSNAP31 (1856.7 kg ha$^{-1}$) that had only one trait rated fair in visual quality and expressed resistant to intermediate disease response like in this case also have good potential for canning. Considering all canning quality traits, 14 genotypes including Bifortsmallseeded-15 and Awash-1 (both released in Ethiopia), RAZ-120, ZABR16574-37F22, NavyLine-60, NavyLine-25, RAZ36-

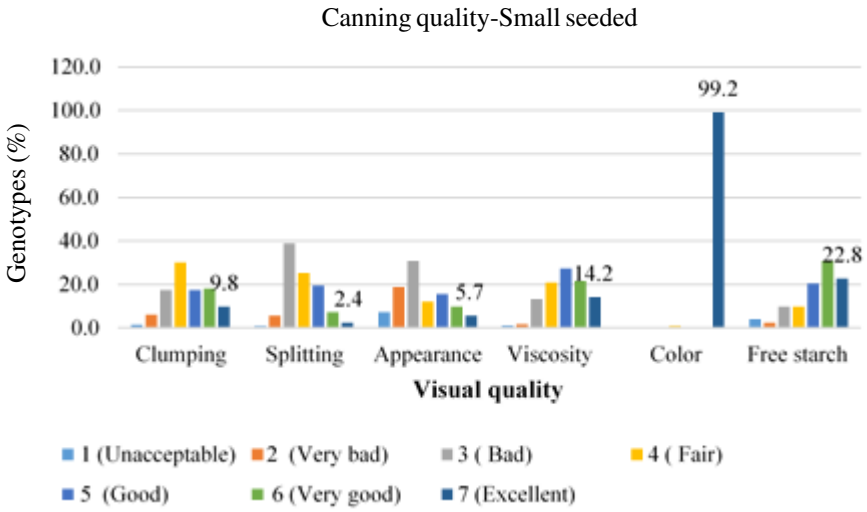


Figure 7. Percentage of small-white genotypes showing the different visual canning quality.

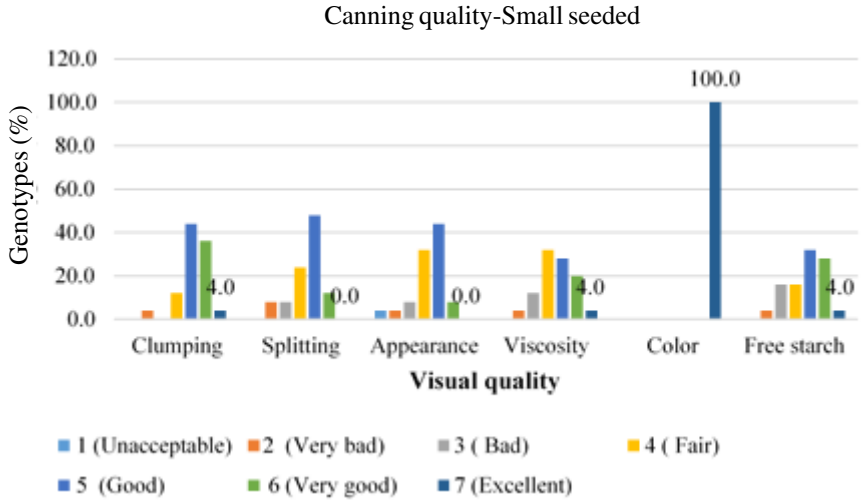


Figure 8. Percentage of large-white genotypes showing the different visual canning quality.

Caballero, and ETSNAP12 were cooked in less than 48 min, had HC of e" 2 and expressed good (5) to excellent (7) attributes for all visual traits (Table 1). Such genotypes are recommended as parents in breeding programmes targeting these traits.

For the small-seeded beans, two industry check genotypes MEXICO142 (1670 kg $ha^{-1}$) and Awash1 (1671 kg $ha^{-1}$), that were popular in canning industry in Kenya (Warsame and Kimani, 2014) and Ethiopia (Teshome and Emire, 2012) respectively were included to determine better performing genotypes. On average, these two industry checks exhibited between fair (4.0) to excellent (7.0) visual canning quality, high soaking ability (>2) and were cooked in 42-44 minutes (Table 1). In addition, MEXICO142 and Awash1, showed resistant to intermediate response to all three pathogens in this study. Earlier studies reported both genotypes as resistant to ALS in the fields in Ethiopia (Fininsa and Tesso, 2007) and to most of the 44 virulent races of *P. griseola* from Kenya under screen house (Wagara *et al*., 2011). This study showed that both genotypes still possess resistance to ALS, in addition to resistance to Fusarium root rot and moderate resistance to Pythium root rot. In addition, the reported good canning qualities (Katungi *et al*., 2010; Teshome and Emire, 2012) are still intact but levels of resistance to ALS and root rots could be improved by hybridisation with the four genotypes that expressed triple resistance. The varieties, MEXICO142 and Awash1 could be fast tracked for variety commercialisation in other countries although several other identified genotypes are potentially great candidates.

**Association of selected traits.** Significant (P<0.001) moderate to strong associations were observed between most traits for canning quality for both small and large white beans (Table 8). The strongest positive correlations [r = 0.82*** and 0.81***] was between viscosity and free starch, and between splitting and appearance of small-white beans. This reflected the consistency in the canning processes. Uniformity in canning procedure, and consistent quality determined by visual

TABLE 8. Correlation for cooking time and canning quality traits for small and large seeded white beans

| | COOKT | HC | Clumping | Splitting | Appearance | Viscosity |
|---|---|---|---|---|---|---|
| Small white | - | | | | | |
| HC | 0.166 | - | | | | |
| Clumping | 0.039 | 0.215* | - | | | |
| Splitting | 0.016 | 0.118 | **0.304*** ** | - | | |
| Appearance | 0.105 | 0.241** | **0.793*** ** | **0.521*** ** | - | |
| Viscosity | -0.033 | 0.192* | **0.500*** ** | 0.184* | **0.392*** ** | - |
| Free starch | 0.004 | 0.069 | **0.676*** ** | 0.293*** | **0.659*** ** | **0.326*** ** |
| | | | | | | |
| Large white | - | | | | | |
| HC | **0.411*** | - | | | | |
| Clumping | -0.041 | 0.236 | - | | | |
| Splitting | -0.234 | -0.087 | **0.753*** ** | - | | |
| Appearance | 0.049 | 0.031 | **0.743*** ** | **0.811*** ** | - | |
| Viscosity | -0.128 | 0.099 | **0.700*** ** | **0.736*** ** | **0.740*** ** | - |
| Free starch | 0.027 | 0.130 | **0.730*** ** | **0.724*** ** | **0.744*** ** | **0.818*** ** |

Number of observations: small white = 123, large white = 25; Two-sided test of correlations different from zero *, **, *** = significant at P <0.05, P<0.01 and P<0.001, respectively

rating was suggested as a necessity for a variety to be commercially successful because bean genuineness is assessed (Butler and Cichy, 2011). Although weak, the correlation of hydration (HC) was positive and significant for clumping [r = 0.22*], appearance [r = 0.24**] and viscosity [r = 0.19*] for small white beans implying genotypes with high HC tended express better qualities in these traits. A positive moderate association [r=0.44***] existed between cooking time and HC (Table 8). This showed that genotypes which absorbed more water during soaking tended to cook fast.

Seven small-seeded genotypes; including RANJONOMBY, exhibited more superiority to both checks in all the visual canning quality traits (Table 1) and are potential candidates for further evaluation for variety replacement or improvement. Two large-seeded genotypes, F14Population-18 and F14Population-3a also expressed very good (6) or excellent (7) quality in all attributes (Table 2). Most of these genotypes possessed dual resistance that increases their value; but could still be improved in resistance levels. Three of these genotypes expressed dual resistance to PRR and ALS, but intermediate to FRR; two including RANJONOMBY and F14Population-3 were resistant to PRR and FRR and intermediate to ALS, NavyLine-60 was resistant to FRR and ALS and intermediate to PRR, NavyLine-25 was intermediate to PRR and FRR and susceptible to ALS, F14Population-18 was resistant to PRR and ALS and F14Population-3a was resistant to ALS intermediate to PRR (Tables 1 and 2). In addition, Bifortsmallseeded-15, RAZ-120, ETSNAP33, NavyLine-60 andNavyLine-25 were cooked in > 45 min (Tables 1 and 2).

Eighteen small and six large seeded genotypes expressed good to excellent canning quality in all the visual traits (Tables 1 and 2). Out of the 18 small seeded beans, 15 were resistant or intermediate to root rots and ALS, and six of these genotypes including ZABR16574-17F22 (1843 kg $ha^{-1}$), ZABR16574-37F22 (1960 kg $ha^{-1}$), NavyLine47 (1711 kg $ha^{-1}$), ETSNAP33 (1723 kg $ha^{-1}$), ZABR16574-37F22 (1960 kg $ha^{-1}$) and ZABR16575-60F22 (2095 kg $ha^{-1}$) yielded above the mean (1704 kg $ha^{-1}$) and are thus more preferable. In addition, nine of the 18 genotypes such as ZABR16574-37F22, ETSNAP33, ZABR16574-37F22 and ZABR16575-60F22 cooked in less than 45 min and were identified as part of the fast cooking genotypes (Table 1). Of the six large seeded beans (Table 2), four genotypes were resistant to both PRR and ALS and two (F14POPULATION-18 (1376 kg $ha^{-1}$) and F14Population-16 (1251 kg $ha^{-1}$) yielded above the mean (1226 kg $ha^{-1}$) and were cooked in 39 and 62 min, respectively.

## CONCLUSION

The study sought to identify adapted white seeded genotypes for the processing industry in eastern Africa and parental lines for breeding programmes targeting the processing market segment. One hundred and fifty-one genotypes that included 25 large and 126 small seeded types were evaluated for yield, resistance to two major diseases; angular leaf spot and bean root rot and processing traits; cooking time and canning quality. Fourteen candidates for the processing bean market were identified. These lines also expressed resistance to ALS, root rot and were agronomically adaptable with acceptable yield performance. Few genotypes such as Bifortsmallseeded-15, RAZ-120 and ZABR16574-37F22, which were superior over the canning industry checks, MEXICO142 and Awash1 could be considered for further evaluation especially for variety replacement purpose. The study also identified fast cooking genotypes such as ETSNAP2 (29 min), ETSNAP19 (34 min), ZABR16576-20F22 (36 min), F14Population-21 (34 min), F14Population-5 (36 min) that would not only greatly conserve resources but also make beans more attractive to end users if further evaluated for possible promotion. Four genotypes (ICNBunsi/S/B 405/4C-1C-1C-88, RAZ-11, ETSNAP18 and ETSNAP3) that

expressed resistance to Pythium and Fusarium root rots and ALS are recommend as sources of disease resistance for the white bean breeding pipelines. The findings from this study could also support white bean breading product profile development.

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