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Abstract

Anthracnose caused by *Colletotrichum lindemuthianum* is the major common bean disease worldwide. This study aimed to determine phenotypic traits associated with anthracnose resistance for future use in breeding programmes. Twenty-two common bean varieties (CBVs) were planted in anthracnose hotspot fields and the same CBVs were planted in a screen house to validate resistance to anthracnose. Anthracnose infection score, leaf length, leaf width, length of fifth internode, length of petiole, plant vigour, canopy height and canopy width were recorded. Data on (i) number of plants emerging; (ii) days to flowering; (iii) days to maturity; (iv) plant stands at harvest; and (v) grain yield were also collected and analysed using R and GenStat software.

Phenotypic traits evaluated differed significantly among genotypes, environment and genotype by environment interaction. Seventy-five per cent of phenotypic traits evaluated were positively correlated to anthracnose resistance. Highly-strong correlations were observed on number of days to maturity, plant stands at harvest, plant vigour and grain yield. Leaf length, leaf width, length of fifth internode, length of petiole and number of stands emerging were strongly correlated to anthracnose resistance. Based on study results, four traits – plant vigour, number of days to maturity, number of plant stands at harvest and grain yield – are recommended for selecting anthracnose-resistant varieties. NUA 48, NUA 64 and RWR 2154 were superior varieties, resistant to anthracnose and high yielding, while Sweet Violet and VTT 923-23-10 were most stable varieties across environments. Further on-farm research is suggested to assess their performance and identify traits preferred by farmers.

Introduction

Common bean (*Phaseolus vulgaris L.*) is the most important grain legume produced worldwide, providing essential nutrients for human health. East Africa is among the global leaders in common bean production, where Tanzania ranks first in Africa and seventh worldwide (FAOSTAT, 2021). Over 75 per cent of the rural households in Tanzania depend on beans for their daily subsistence (Katungi et al., 2019; Sperling et al., 2021). Despite common bean's potential as a food crop, for nutrition and as source of income, on-farm productivity in Tanzania remains low, at 1.4 t/ha (FAOSTAT 2021) compared with on-station productivity of 2–2.5 t/ha (Kiriba et al., 2019; Binagwa et al., 2020). Diseases, drought and poor crop management significantly contribute to low production. Anthracnose, angular leaf spot and common bean mosaic virus are the major diseases affecting productivity in Tanzania (Mwaipopo et al., 2017; Masunga et al., 2020). Anthracnose (*Colletotrichum lindemuthianum*) is the most devaststing disease causing grain yield loss of up to 80 per cent (Masunga et al., 2020), and some improved varieties are also susceptible to anthracnose disease (Muthoni et al., 2017; Kadege et al., 2022). Farmers in major agroecosystem, substantially rely on local cultivars for commercial farming (Sperling et al., 2021). Although; anthracnose resistance has been the focus of research (Kazimoto, 2016; Masunga et al., 2020), little is known about the phenotypic traits associated with anthracnose resistance of common bean. Thus, this study aimed to determine phenotypic traits associated with anthracnose resistance among common bean genotype (G), environment (E) and genotype by environment interaction (GE) aimed at increasing productivity, nutrition and income generation opportunities in Tanzania.

Results

2.1 Climate variation, anthracnose severity and grain yield during the study period

Seasonal rainfall, temperature and relative humidity in trial locations are shown in Table 3 between March and August 2022. During the cropping season, TACRI Lyamungo site recorded higher values compared with the TARI Selian site for mean rainfall (135.4 mm / 96.3 mm), maximum temperature (25.1 ^{o}C / 23.7 ^{o}C) and mean relative humidity (78.7 per cent / 72.7 per cent). High rainfall, temperature and relative humidity resulted in a significant increase in anthracnose severity in TACRI Lyamungo compared to TARI Selian. The TACRI Lyamungo treated trial had a severity scale of 1.6 and the untreated trial had severity scale of 2.8. The TARI Selian treated trial had a severity scale of 1.3 while the untreated trial had a severity scale of 1.7. The fungicide-treated trial had low anthracnose severity (1.4) compared with the untreated trial (2.5). NUA 48, NUA 64, Sweet Violet, VTT 923-23-10, COD MLB 0033, KAB 36, RCB 593, RWR 2154, SCR 61 and SMC 18 varieties were resistant to anthracnose. While Selian 13, Lyamungo 90, Njano gololi, Rose coco and Soya Kijivu varieties were moderately resistant to anthracnose (Table 4). High rainfall resulted to significant increase in grain at TACRI Lyamungo compared to TARI Selian. At TACRI Lyamungo, the mean grain yield for the treated trial was 1200 kg/ha, while it was 835 kg/ha for the untreated trial. The mean grain yield for the treated trial in TARI Selian was 869 kg/ha and 643 kg/ha for the untreated trial. Average grain yield was therefore significantly higher in treated trials (1035 kg/ha) compared to untreated trials (739 kg/ha).

2.2 Variation in phenotypic traits among treated trial and untreated trial

The combined analysis of variance shows that, with the exception of the anthracnose severity score, all other phenotypic and agronomic variables were significantly different ($P \leq 0.05$) between G, E & GE (Table 2). Phenotypic variables differed significantly among genotype and particularly between treated and untreated trials: mean anthracnose score was 1.4 and 2.5 for treated and untreated trials, respectively; mean leaf length was 13.6 cm and 13 cm for treated and untreated trials, respectively; mean leaf width was 10 cm and 9.4 cm for treated and untreated trials, respectively; mean length of the fifth internode was 13 cm and 12 cm for treated and untreated trials, respectively; mean canopy height was 46 cm and 44 cm for treated and untreated trials, respectively; mean canopy width for treated trials was 16 cm compared with 15.5 cm for untreated trials; mean petiole length was 11 cm and 10 cm for treated and untreated trials, respectively; plant vigour was scored as 4.7 compared with 4.2 for treated trials and untreated trials, respectively. Significant differences were also revealed on agronomic traits among genotype, treated and untreated trials, whereby the mean number of days to 75 per cent flowering for the treated trials was 45 while it was 44 for untreated trials. The mean number of days to 75 per cent maturity for treated trials was 75 while it was 72 for untreated trials, and the mean number of plant stands at harvest for treated trials was 157, while it was 147 for untreated trials. Resistant genotypes showed higher phenotypic trait values than susceptible genotypes. For instance, mean leaf length of resistant genotypes was 11–14 cm compared with 9–10 cm for susceptible genotypes; mean leaf width for resistant genotypes was 10–12 cm compared with 8–9 cm for susceptible genotypes; mean length of fifth internode for resistant genotypes was 11–13 cm, while for susceptible genotypes it was 9–10 cm; and mean plant vigour for resistant genotypes was in the range of 4–5, while it was 2–3 for susceptible genotypes. Significant variation was also noted for agronomic traits between genotypes, whereby the germination rate for resistant genotypes was 98.7 per cent and 82 per cent for susceptible genotypes. The mean number of days to 75 per cent maturity for resistant genotypes was 73 compared with 68.6 for susceptible genotypes, and the mean per cent of plant stands at harvest was 90 and 55 for resistant and susceptible genotypes, respectively.

2.3 Correlation of phenotypic traits associated with anthracnose resistance

Significant correlation of signals was revealed for some of the phenotypic traits evaluated, with the extent of correlation ranging from 0.0 to 0.90 (Table 6), where 0.0—0.19 = very mild, 0.20–0.39 = mild, 0.40–0.69 = moderate, 0.70–0.89 = strong and 0.90–1.00 = highly strong (Gonçalves *et al.,* 2017). To optimize results, the mean of untreated trials was used to calculate phenotypic traits associated with anthracnose resistance.

2.3.1 Traits highly-strongly correlated with anthracnose resistance

The number of days to 75 per cent maturity and number of plant stands at harvest were very strongly ($P \leq 0.001$) correlated to anthracnose resistance. Common bean varieties needing more days to maturity were resistant to anthracnose compared to genotypes needing fewer days to maturity. COD MLB 0033, KAB 36, NUA 48, NUA 64, RCB 593, RWR 2154, SCR 61 and SMC 18, Sweet Violet and VTT 923-23-10 varieties with their 72—76 days to maturity were significantly resistant to anthracnose, while Lyamungo 90, Selian 13, Gloria, kipapi, njano gololi and soya kijivu varieties, maturing in 65—71 days, were moderately affected by anthracnose. Varieties that were moderately affected by anthracnose had stunted growth and eventually died in advance of harvesting. The varieties that were moderately resistant to anthracnose had an average stand of 129 plants at harvest, while the resistant genotypes had an average stand of 150 plants at harvest.

2.3.2 Traits strongly correlated with anthracnose resistance

The number of plant stands emerging, length of fifth internode, plant vigour and grain yield were the traits that were strongly ($P \leq 0.01$) correlated to anthracnose resistance.Tested CBVs with a higher germination percentage were significantly resistant to anthracnose compared to varieties with a low(er) germination rate. The average number of resistant genotype plants emerging were 176, while for those with moderate resistance were 171.

Discrimination among the tested varieties was observed. For example, the length of the fifth internode ranged from 10 cm to 14 cm, and the longer the length of the fifth internode, the greater the resistance to anthracnose was observed. Variability on plant vigour was observed among genotypes, whereby common bean genotypes that had recorded a plant vigour score of 4–5 were showed resistance to anthracnose while genotypes with a plant vigour of 2–3 cm showed anthracnose susceptibility.Varieties that were resistant to anthracnose delivered more grain yield compared with varieties that were moderately resistant to anthracnose, in both trial locations. For instance, NUA 48 (1315 kg/ha), NUA 64 (1252 kg/ha) and RWR 2154 (1124 kg/ha), respectively, were high yielding and resistant to anthracnose across locations, followed by COD MLB 0033, KAB 36, Sweet Violet, SMC 18, SCR 61 and VTT 923-23-10 (Table 4)

2.3.3 Traits moderately correlated with anthracnose resistance

Leaf width and petiole length were moderately ($P \leq 0.05$) correlated with anthracnose resistance. Significance of variation was observed among the common varieties where petiole length was in the range of 9—12 cm. Varieties with longer petiole length were more resistant to anthracnose compared to varieties with shorter petiole length. Varieties with a leaf width of 10—11 cm (COD MLB 0033, KAB 36, NUA 48, NUA 64, RCB 593, RWR 2154, SCR 61, SMC 18, Sweet Violet and VTT 923-23-10) showed a very low anthracnose infection score. Varieties with a leaf width of 8—9 cm (Lyamungo 90, Njano gololi, Rosecoco and Selian 13) were significantly influenced by anthracnose.

2.4. Validation of anthracnose resistance

The analysis of variance on validation of anthracnose resistance revealed significant difference at $P \leq 0.05$ between varieties. For example, NUA 48, NUA 64, RWR 2154, SCR 61, SMC 18, Gloria, Sweet violet, VTT 923-23-10, COD MLB 0033, KAB 36, RCB 593, Calima Uyole and Uyole 03 were resistant to anthracnose, while Kipapi, Selian 12, Uyole 18 and Boroto were moderately resistant to anthracnose, and Selian 13, Lyamungo 90, Njano gololi, Rosecoco and Soya Kijivu were susceptible to anthracnose (Table 6). Regarding validation of phenotypic traits associated with anthracnose resistance, positive correlation was revealed among the phenotypic traits evaluated (Table 5). The magnitude of correlation ranged from negative 0.10 to positive 0.92 with significant difference for most of the phenotypic traits evaluated.

Of 12 phenotypic traits evaluated, 33.3 per cent (number of days to maturity, number of plant stands at harvest, plant vigour and grain yield) were highly strongly ($P \leq 0.001$) correlated with anthracnose resistance. Five variables — leaf length, leaf width, length of fifth internode, petiole length and number of plant stands emerging — equivalent to 41.7 per cent were strongly ($P \leq 0.01$) correlated to anthracnose resistance.

Discussion

TACRI Lyamungo site recorded high rainfall, temperature and relative humidity in contrast to TARI Selian site (Table 3). Through comparative analysis, high rainfall, temperature and relative humidity resulted in significant increase in anthracnose infection score in TACRI Lyamungo compared to TARI Selian. Padder *et al.* (2017) and Masunga *et al.* (2020) reported similar findings, concluding that rainfall is an important environmental factor for the establishment, infection and development of common bean anthracnose. Significant anthracnose invasion was also reported by other authors (Awori *et al.,* 2018; Kiptoo *et al.,* 2019) among common bean genotypes. Treatment with fungicide spray reduced the severity of anthracnose disease across locations. Similar findings were reported by Mohammed (2013), Gillard and Ranatunga (2013), Polanco *et al.* (2014), and Hirpa and Selvaraj (2016). However, fungicide spray may only provide short-term solutions because most of the smallholder farmers in developing countries cannot regularly obtain or purchase fungicides due to poor distribution channels, lack of technical knowledge on their use and low incomes.

Under field conditions, NUA 48, NUA 64, Sweet Violet, VTT 923-23-10, COD MLB 0033, KAB 36, RCB 593, RWR 2154, SCR 61 and SMC 18 were resistant to anthracnose, while Selian 13, Lyamungo 90, Njano gololi, Rose coco and Soya Kijivu were moderately resistant. Validation of the same varieties for anthracnose found that NUA 48, NUA 64, RWR 2154, SCR 61, SMC 18, Gloria, Sweet Violet, VTT 923-23-10, COD MLB 0033, KAB 36, RCB 593, Calima Uyole and Uyole 03 were resistant to anthracnose. Kipapi, Selian 12, Uyole 18 and Boroto were moderately resistant to anthracnose, while Selian 13, Lyamungo 90, Njano gololi, Rosecoco and Soya Kijivu were susceptible to anthracnose. This implies that the resistance shown by certain varieties in certain environments needs to be reconfirmed in other environments because some factors could be favouring and others hindering resistance. Three important factors influencing disease occurrence are: (i) Pathogens – degree of pathogen virulence or abundance; (ii) Environmental conditions – all those favouring the disease; and (iii) Host – all conditions favouring susceptibility. Therefore, when any of these three influencing factors, either singly or in combination, are favourable, anthracnose establishment/infection, disease development and colonization can take hold. Moreover, genotypes that showed resistance implies that these genotypes have genes that confer broad-spectrum resistance to *C. lindemuthianum.* Resistant genotypes could be used as donor parents in breeding programmes for increased spectrum and durability of resistance to common bean anthracnose. Resistant genotypes could also be used as commercial varieties to generate data for improved breeding decisions, for the release of convincing varieties for increased adoption and market commercialization. Varieties showing moderate resistance to anthracnose, implies that their genes of reaction to anthracnose are less broad spectrum. These genes may be useful for breeding programmes targeting pyramidal resistance genes for specific and broad-spectrum resistance. Genotypes showing susceptibility to anthracnose means they carry genes with very low broad-spectrum resistance to anthracnose disease. These genotypes would be best used as susceptible checks when evaluating varieties for anthracnose resistance.

Phenotypic and agronomic variables differed significantly among genotypes, treated and untreated trials, with treated trials showing significantly higher values of leaf length, leaf width, length of the fifth internode, canopy height, canopy width, petiole length and plant vigour compared with untreated trials. Higher values were also observed on germination percentage, number of days to 75 per cent flowering and maturity, as well as number of plant stands at harvest. The higher the phenotypic and agronomic variable, the higher the resistance to anthracnose disease were revealed, and vice versa. Resistance to anthracnose is a desirable trait, which can help reduce yield losses caused by the disease.

Hypersensitive response or hypersensitive cell death is one of the strategies used by the host plant to defend itself against pathogens; when the plant cell is injured, the affected part dies rapidly, causing necrosis of adjacent tissue. This defence strategy stops the fungal pathogen from extracting nutrients; thus, unable to spread or multiply, it will die. Therefore, when the plant part or the phenotypic variables are large, it allows some tissue to continue living and developing, receiving nutrients and protecting the plant from pathogen attacks. Moreover, common bean plants contain biochemical and structural defences that protect them from disease, whereby the plants begin to receive signal molecules indicating a pathogen's presence; when physical establishment is completed, cell membrane recognize the pathogen. After pathogen recognition, a series of biochemical reactions and structural changes are set in motion within the plant cells, in an effort to fend off the pathogen, its enzyme and toxins. The time in which the pathogen sends alarm signals and the plant mobilizes its defences determines the difficulties and/or possibilities that cause infection and severe symptoms. Therefore, when a phenotypic part of the plant is large, it leaves ample space for the plant to be resistant, as described below.

From the screen house study, 75 per cent percent of the phenotypic traits evaluated were positively correlated with anthracnose resistance, whereby 33.3 per cent were highly-strongly correlated and 41.7 per cent were strongly correlated to anthracnose resistance.

The number of days to 75 per cent maturity, number of plant stands at harvest, plant vigour and grain yield were highly strong correlated with anthracnose resistance. In the case of number of days to maturity**,** when the plant is heavily infected, it becomes weaker; as a means to survive, it will speed up vegetative growth, reproductive growth and maturity to complete its life cycle (Carmit *et al.,* 2018). Moreover, short-cycle maturing plants are more susceptible, as their growth coincides with the disease infection window; thus, when disease pressure is high, the plant is affected, while the long-maturing varieties delay anthracnose symptom development. This delay can afford the plant more time to mount an effective defence against the pathogen. Regarding number of plant stands at harvest,when the bean plant is attacked by *C .lindemuthianum* the stem, leaves, pod and seeds are affected, destroying the zylem and phoem, interrupting translocation of water and nutrients, which often reduce plant growth and eventually cause plant death (Miedes *et al.,* 2014). In addition, anthracnose-resistant plants exhibit reduced seedling mortality compared to susceptible plants. This helps ensure that the common bean plant reaches maturity and produces grain yield, despite being exposed to the disease. Regarding plant vigour,*C. lindemuthianum* attacks tissue and weakens common bean plants, resulting in the plant remaining smaller in size, producing few flowers, setting fewer pods and seeds, often causing poor plant vigour. And if the seeds from the same plant are planted, they may produce much weaker plants (Miedes *et al.,* 2014; Dagla *et al.*, 2015). It was also noted that resistance to anthracnose is associated with enhanced plant vigour, including increased shoot and root growth. This can help the plant to withstand the stress caused by the disease and maintain its yield potential.Regardinggrain yield,under disease pressure, resistant cultivars fair better and are able to remain healthy and produce a higher number of healthy grains compared to susceptible cultivars (Dagla *et al.*, 2015). Healthy grain is of good quality, with enough weight compared to poor-quality grain, resulting in high productivity compared with the susceptible cultivars (Carmit *et al.,* 2018).

Leaf length, leaf width, length of fifth internode, length of petiole and number of plant stands emerging were strongly correlated to anthracnose resistance. Leaf length: when the leaf length is long it means the surface of the leaf is large, which is the first line of defence against *C. lindemuthianum* (Miedes *et al.,* 2014). The longer the leaf, the larger the outermost layer of the leaf (cuticle) responsibly protects the common bean plant against anthracnose (Carmit *et al.,* 2018). The longer the leaf length the higher the density of hairs on the leaves, which physically impede the penetration and spread of anthracnose (Gonçalves *et al.,* 2017). Leaf width:resistance to anthracnose is often associated with the development of necrotic lesions on the leaves of infected plants. These lesions can limit the spread of the disease by preventing growth and reproduction of the fungal pathogen. The broader the leaf width, the greater the resistance to anthracnose, as the wide leaf extends pathogen invasion time, enabling the plant to survive and escape complete infection (Miedes *et al.,* 2014). Moreover, each leaf surface is covered by cuticle wax to prevent dehydration, as well as preventing fungal pathogens from entering into direct contact with epidemic cells, thereby limiting infection (Carmit *et al.,* 2018). Therefore, the area covered by cuticle wax on wide leaves is large, enhancing efficient prevention of fungal pathogens like *C. lindemuthianum*. Additionally, waxes form a water-repellent surface, preventing formation of stagnant water where *C. lindemuthianum* can be deposited, germinate and multiply.

The study found a strong correlation between petiole length and anthracnose resistance; the longer the length of the fifth internode, the stronger the resistance to anthracnose, and vice versa. According to Maras *et al.,* (2016) the length of the fifth internode of the main stem of bean genotypes is linked with anthracnose incidence and severity. Anthracnose-resistant CBVs tended to have an upright plant architecture, with long internode, strong stems and more open canopy. This helped to reduce humidity and moisture levels within the plant, which reduced the incidence of anthracnose (Miedes *et al.,* 2014). The longer petiole lengths revealed resistance and strongly correlated to anthracnose resistance in comparison with short petioles. Long petioles have larger photosynthetic surface areas, prevent water loss and fungal pathogens from coming into direct contact with the epidemic cells thereby limiting infection (Nassar *et al.,* 2010; Carmit *et al.,* 2018). During the growing season, susceptible plants had stunted growth, shrivelled and died prematurely, which eventual reduced the number of plant stands at harvest. Similarly, Mohammed (2013) and Masunga *et al.* (2020)reported significant anthracnose invasion, stunted growth and bean plant death on cultivars susceptible to anthracnose disease.

Significant differences were revealed on grain yield and yield component between G, E and GE. Significant variation shows the need for further evaluation in different environments to support genotypic selection of ideal breeding material, based on performance and correlation values. Yan and Kang (2002) documented that the existence of various mega environments was inferred when significant variation in genotypes was found by environmental interaction (Babic *et al.,* 2008). From this study, the crossover of genotype by environment was obtained (Figures 1 & 2), showing that different genotypes were superior in different environments. NUA 48, NUA 64 and RWR 2154 were superior genotypes, which were resistant to anthracnose and high yielding. Sweet Violet and VTT 923-23-10 were the most stable across environments, followed by RWR 2154, SMC 18 and RCB 593, respectively (Figure 2). The most ideal genotype should be highly significant in mean performance and show great stability (Tonk *et al.,* 2011).

Based on the results and discussion, the number of days to 75 per cent maturity, number of plant stands at harvest, plant vigour and grain yield are recommended traits for the selection of anthracnose-resistant varieties of common bean. Different CBVs expressed resistance to anthracnose disease under different environments, NUA 48, NUA 64 and RWR 2154 were the superior varieties for breeding with dominating traits for anthracnose resistance and high grain yield. Sweet Violet and VTT 923-23-10 could be the second options, as they performed well and were stable across mega environments. We recommend that the selected genotypes be further evaluated under real farm conditions to understand their performance and farmers' preferred traits for adoption, increased productivity, nutrition and income.

Materials And Methods

4.1 Breeding material and locations

The study used 22 (Table 1) common bean varieties (CBVs) (advanced breeding lines, released varieties and farmers' varieties) to determine the phenotypic traits (Table 2) associated with anthracnose resistance. We obtained 18 varieties from the Tanzania Agricultural Research Institute (TARI) and four local farmers' varieties (used as checks) widely grown by farmers in Tanzania were collected from farmers. Disease screening trials were planted in anthracnose hotspots fields (TARI Selian, Arusha region and at the Tanzania Coffee Research Institute (TACRI), Lyamungo) during the March to August 2022 cropping season. The same CBVs were planted in a screen house (TARI Selian site) to validate their resistance to anthracnose.

4.2 Description of the study area

TARI Selian is found at a medium—high altitude of 1407 meters above sea level (m.a.s.l) at latitude (S) 03°21.690 and longitude (E) 36°37.879 in Tanzania's Arusha region. Lyamungo is situated at an altitude of 992 m.a.s.l at S03°19.905' and E037°14.067. Both study locations have eutrophic brown, medium-texture (loamy) soils (Brady and Weil, 2002; Landon 1991). The soils are moderately suitable for bean cultivation and contain 0.53 per cent organic carbon, 0.92 per cent organic matter, 0.079 per cent total nitrogen, 0.17 cmol (+)/kg exchangeable potassium and 8.0 mg/kg phosphorus). The two sites were close to a weather station, where weather data (Table 3) were collected.

4.3 Experimental design, planting and management

4.3.1 Field study

The 22 CBVs were arranged in a Randomized Complete Block Design (RCBD) with three replications. The seeds were sown at a spacing of 50 cm between rows and 20 cm between plants; six rows and ten holes per row were made on each plot, then two seeds were planted per hole. The four central rows were used for data collection and the two exterior rows — one on each side of the plot — were used as guard rows. Five grams of Di-ammonium phosphate (DAP) were applied in each hole and covered with a small amount of soil to avoid seed burn. Two rounds of weeding were conducted by hand, the first at 21 days after germination (DAG) and the second at 49 DAG. Two trials were planted per location; the first trial was sprayed with Chlorothalonil to control anthracnose disease (treated trial) and the second trial without fungicide spraying as a check (untreated).

4.3.2 Screen house study

Complete Randomized Design (CRD) with three replications was used for the screen house trials. The 22 testing varieties were arranged in ten-litre plastic pots containing sterilized and moist soil were used for planting. Five grams of Di-ammonium phosphate (DAP) was applied to each pot then covered with small amount of soil. In each replication, three pots per variety were sown, each pot sown with three bean seeds.

Two trials were planted per screen house; the first trial was sprayed with Chlorothalonil to control anthracnose disease (treated trial) and the second trial was not sprayed with fungicide spraying as a check (untreated). After 14 days, all the bean seedlings were inoculated with virulent anthracnose isolate using a hand sprayer. Inoculated plants were covered with a transparent plastic bag for 48 hours to maintain relative humidity of approximately > 92 per cent, followed by other management practices like irrigation at an interval of five days and hand weeding at 21 and 49 DAG.

4.4 Data collection

Anthracnose severity/resistance was evaluated at 21, 35and 49 DAG, using a scale of 1–9, whereby 1–3 indicated strong resistance or low severity (symptoms are not visible or are very light), 4–6 moderate resistance (implying visible, conspicuous symptoms resulting only in limited plant damage) and 7–9 indicating low resistance (implying severe to very severe symptoms causing considerable yield losses or plant death) (Kamiri *et al.,* 2021). Based on five randomly selected plants from each field plot and one randomly selected plant per plastic pot in the screen house trials, phenotypic traits like leaf length, leaf width, length of fifth internode, petiole length, canopy height, canopy width and plant vigour were recorded at 54 DAG. With the exception of canopy height, which was measured using a 100 cm ruler, all other phenotypic variables were measured using a 30 cm ruler. The lowest mark on the ruler (zero) was used as the marking point for the reading. Phenotypic traits were measured as follows: (i) Leaf length: three centre trifoliate leaves were measured from the base of the leaf to the apex; (ii) Leaf width: three centre trifoliate leaves were measured throughout the leaf veins and midrib; (iii) Length of fifth internode: the main stem was measured from the ground soil up to the fifth internode; (iv) Petiole length: the main stem was measured holding the three trifoliate leaves; (v) Canopy width: measured throughout the bean plant surface covering leaf circumference; (vi) Canopy height: the plant length was measured from the ground soil to plant apex; (vii) Plant vigour: was measured using a visual observation scale of 1–5, whereby 5=excellent, 4=very good, 3=good, 2=poor and 1=very poor. We also recorded the following agronomic traits: number of plant stands emerging, number of days to 75 per cent flowering, number of days to 75 per cent maturity, number of plant stands at harvest, number of pods per plant, number of grains per pod, 100 grain weight and grain yield per plot.

4.5 Statistical analysis

All data were subjected to an analysis of variance using R statistical software with the mean separation using Tukey's test at 5 per cent level of significance. AMMI Model and Biplot analysis were conducted to understand the influence of anthracnose infection on number of days to maturity, number of plant stands at harvest and grain yield between G, E and GE. In view of our study's objective, we conducted a correlation analysis on phenotypic traits associated with anthracnose resistance using GenStat software.

Methods were performed according to relevant guidelines and regulations in the method section.

Declarations

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Data availability: Information presented in this study will be available upon request to the corresponding author.

Ethics declarations: Permissions or licenses for collection of common bean seeds and collection of anthracnose diseased leaves were authorized by Tanzania Agricultural Research Institute.

Conflicts of Interest: The authors declare no conflicts of interest.

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Tables

Tables 1-6 is available in the Supplementary Files section.

Figures

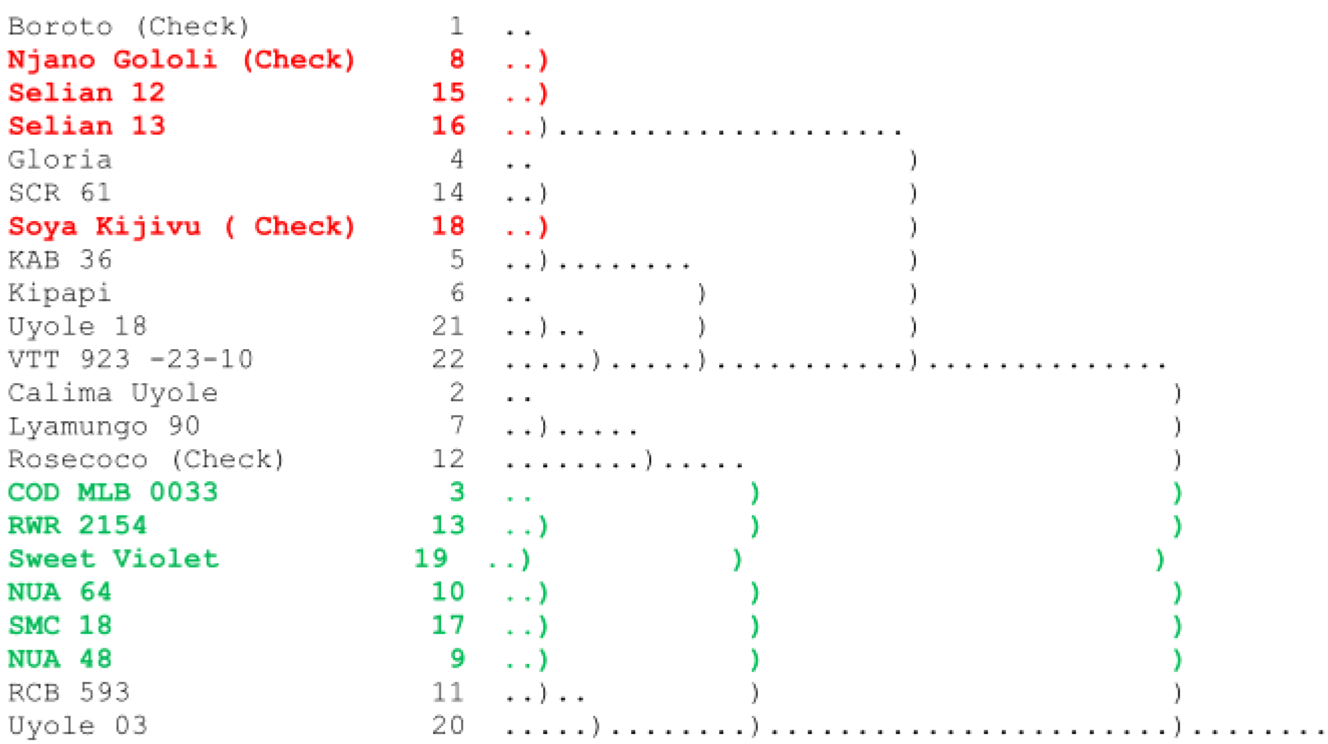

Figure 1

AMMI model Genotype & Environment means for number of days to maturity

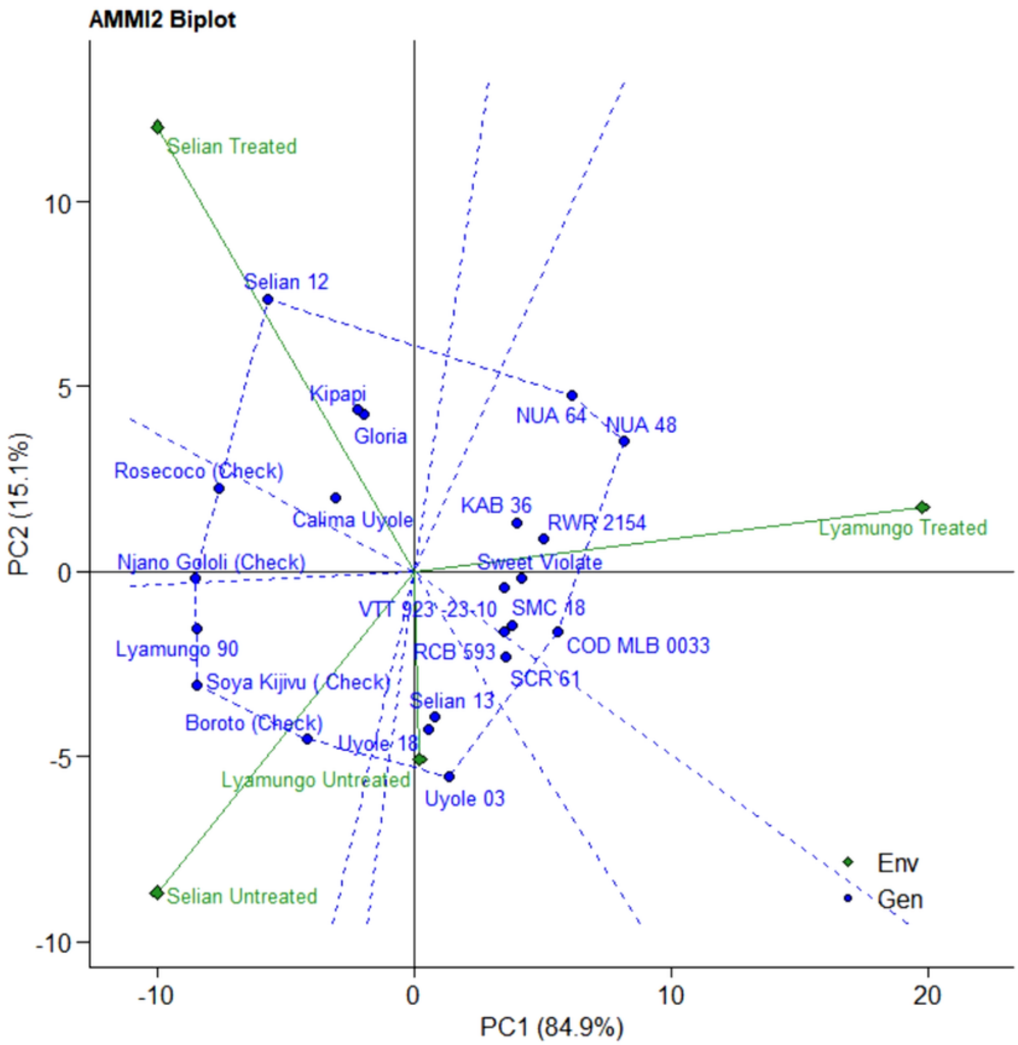

Figure 2

AMMI model Biplot presenting the mean grain yield of 22 genotypes by environment

Supplementary Files

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- Table16.docx