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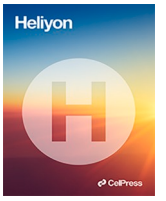

Research article

Characterization of phenotypic traits associated with anthracnose resistance in selected common bean (*Phaseolus vulgaris* L.) breeding material

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ABSTRACT

Anthracnose caused by *Colletotrichum lindemuthianum* is the major common bean disease worldwide causing complete yield loss under favourable disease conditions. This study aimed to determine phenotypic traits associated with anthracnose resistance for future use in breeding programmes. Twenty-two common bean varieties (CBVs) were selected basing on susceptibility to anthracnose, advanced breeding lines, improved variety resembling advanced breeding lines and the farmer variety widely grown in Tanzania. Selected varieties 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 number of plants emerging; days to flowering; days to maturity; plant stands at harvest; and grain yield were also collected and analysed using R software. Phenotypic traits evaluated differed significantly among genotypes, environment and genotype by environment interaction. Seventy-five percent of phenotypic traits evaluated were positively correlated to anthracnose resistance.

Highly-strong correlations to anthracnose 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. Additive main effects and multiplicative interaction analysis (AMMI) revealed highest contribution of environment on anthracnose infection-58.9% and grain yield −84.9% compared to genotype effects on anthracnose infection −32.7% and grain yield-15.7%. Based on these 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.

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1. 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 [1]. Over 75% of the rural households in Tanzania depend on beans for their daily subsistence [2,3]. 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 [1] compared with on-station productivity of 2–2.5 t/ha [4,5]. Diseases, drought and poor crop management significantly contribute to low production. Anthracnose (*Colletotrichum lindemuthianum)*, angular leaf spot (*Phaeoisariopsis griseola*) and common bean mosaic virus (*Bean common mosaic virus*) are the major diseases affecting productivity in Tanzania [6,7].

Anthracnose is the most devaststing disease causing grain yield loss of up to 80% [7]. The disease thrives in temperatures around 17 °C, relative humidity above 92% and soil pH range of 5.8–6.5. Bean anthracnose affects various parts of the bean plant, including leaves, stems, pods, and seeds leading to development of dark brown necrotic lesions on these plant components. These lesions have the detrimental effect of reducing the plant's ability to carry out photosynthesis in its leaves, ultimately leading to a reduction in the overall yield of grains. Some improved varieties are also susceptible to anthracnose disease [8,9]. Farmers in major bean growing agroecosystem, substantially rely on local cultivars for commercial farming [3].

Primarily, research effort have been focusing on introgression of anthracnose resistance genes in to susceptible varieties and detecting these resistant genes using molecular makers to validate the presence and absence of the genes in the genotypes intended to improve [10–13]. However, controlling anthracnose disease remain a challenge due to extensive diversity and virulence exhibited by pathogen. This complexity arises due to extensive diversity and virulence of *C. lindemuthianum*, where a single gene can influence the stability of resistance in bean plants, and another complementary gene affects the virulence of the pathogen. Insufficient studies have been conducted on phenotypic parameters used to measure anthracnose resistance in common bean.

Identifying phenotypic parameters that helps to phenotype anthracnose resistance helps breeders and other researchers to select the best genotypes resistant to anthracnose disease. Phenotypic parameters provide clear and measurable indicators to identify resistant varieties. By identifying key resistance-related traits, breeders can fast-track the development of robust common bean varieties. These phenotyping parameters enables the bean researchers to identify disease-resistant bean cultivars. The present study was therefore planned to reaffirm the performance of common bean genotypes resistant to anthracnose using phenotypic parameters and assess the relationship between anthracnose disease and phenotypic traits.

2. Materials and methods

2.1. Breeding material and locations

In this study 22 (Table 1) common bean varieties (CBVs) were used including 6 advanced breeding lines, 12 released varieties and 4 farmers' varieties. These genotypes were planted to measure the phenotypic parameters (Table 3) associated with anthracnose resistance. The varieties were selected based on the level of susceptibility to anthracnose. In addition genotypes were also selected based on market class demanded by consumers and market. These breeding lines and varieties were obtained from Tanzania Agricultural Research Institute (TARI), while the four local farmers' varieties, popularly grown in Tanzania were collected from farmers.

Table 1
Common bean breeding material used in the study.

Bean varieties	Collection point	Seed size	Market class	Remarks
Gloria	TARI Uyole	Medium	Purple	Advanced breeding line
Kipapi	TARI Uyole	Medium	Purple	Advanced breeding line
Nua 48	TARI Selian	Large	Red Mottled	Advanced breeding line
Nua 64	TARI Selian	Large	Red Mottled	Advanced breeding line
Sweet Violet	TARI Uyole	Large	Sugar	Advanced breeding line
VTT 923 -23-10	TARI Uyole	Large	Sugar	Advanced breeding line
COD MLB 0033	TARI Maruku	Medium	Red Mottled	Released 2020
KAB 36	TARI Maruku	Medium	Red Mottled	Released 2020
RCB 593	TARI Maruku	Medium	Red Mottled	Released 2020
RWR 2154	TARI Selian	Large	Sugar	Released 2020
SCR 61	TARI Maruku	Medium	Red	Released 2020
SMC 18	TARI Maruku	Small	White	Released 2020
Selian 12	TARI Selian	Medium	Red	Released 2018
Selian 13	TARI Selian	Medium	Yellow	Released 2018
Uyole 18	TARI Uyole	Medium	Purple	Released 2018
Calima Uyole	TARI Uyole	Large	Red Mottled	Released 2012
Uyole 03	TARI Uyole	Large	Sugar	Released 2013
Lyamungo 90	TARI Selian	Large	Red Mottled	Released 1990 (Susceptible check)
Boroto	Siha	Medium	Sugar	Local cultivar (Check)
Njano Gololi	Siha	Medium	Yellow	Local cultivar (Check)
Rosecoco	Karatu	Large	Red Mottled	Local cultivar (Check)
Soya Kijivu	Karatu	Medium	Purple	Local cultivar (Susceptible Check)

2.2. Description of the study area

TARI Selian is found at a medium–high altitude of 1407 m 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 [15,16]. The soils are moderately suitable for bean cultivation and contain 0.53% organic carbon, 0.92% organic matter, 0.079% total nitrogen, 0.17 cmol (+)/kg exchangeable potassium and 8.0 mg/kg phosphorus). Seasonal rainfall, temperature and relative humidity in trial locations are shown in Fig. 1a, b, c & d 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 °C/23.7 °C) and mean relative humidity (78.7%/72.7%).

2.3. Experimental design

Disease screening trials were planted in anthracnose hotspots fields (TARI Selian, Arusha region and at the Tanzania Coffee Research Institute (TACRI), Lyamungo) during March to August 2022 cropping season. The same CBVs were planted in a screen house (TARI Selian site) to validate their resistance to anthracnose.

The 22 common bean varieties (CBVs) were planted 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. Two rows of differential cultivar - G2333 to anthracnose were planted as the spreader for anthracnose disease at the border on both four sides of the trial and on each trial (treated trial and untreated trial). The four central rows of each plot 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 each trial spaced by 5 m. The first trial was sprayed with Chlorothalonil (tetrachloroisophthalonitrile) at the rate of 30 ml/15L of water during 14, 28 and 42 DAG to control anthracnose disease (treated trial) and the second trial without fungicide sprays (untreated). Canvas/plastic covering was aliened at the 5 m to demarcate the boundary between the two trials during fungicide spraying, with the goal of preventing the chemical mist from reaching the untreated trial.

Table 2
Data collection details.

Phenotypic traits	Details on the way data were collected	Period of collection	Tools	Reference
Anthracnose score	Rating anthracnose seviarity on bean leaves, stem, pod and seeds	21, 35 and 49 days afrter germination (DAG)	Disease scoring scale of 1–9, where the scale of 1 = immunity (no visible symptoms) and 9 = very severe symptoms	[14])
Leaf length	Three center trifoliate leaves were measured from the base of the leaf to the apex	54 DAG	30 cm ruler	
Leaf width	Three center trifoliate leaves measured throughout the leaf veins and midrib.	54 DAG	30 cm ruler	
Length of fifth internode	Measure the main stem from the ground soil up to the 5th internode	54 DAG	30 cm ruler	
Length of petiole	Measure the main stem holding the three trifoliate leaves	54 DAG	30 cm ruler	
Canopy width	Measured throughout bean plant surface covering leaf circumference	54 DAG	30 cm ruler	
Canopy height	Measured the plant length from the ground soil to the apex of the plant	54 DAG	100 cm ruler	
Plant vigour	Bean plants evaluated by observing the stems, leaves and flowers wheather they are many, few or scattered. The presence or absence of dead bunches.	54 DAG	Visual observation using a scale 1–5, 5 = excellent; 4very good; 3 Good; 2 Poor and 1 = very poor	[14]
Number of plant stand emerge	Count number of plant per plot	14 DAG	Count number	
Number of days to 75% flowering	Irregular visit to the trial from 35 DAG, visual observation and counting	35, 40 and 45 DAG	Visual observation and counting	
Number of days to 75% maturity	Irregular visit to the trial from 60 DAG, visual observation and counting	60, 65, 70, 75 and 80 DAG	Visual observation and counting	
Number of plant stand at harvest	Count number of plant per 3 pot during harvesting	During harvesting	Count number	
Number of pod per plant	Count number of pod from 5 randomly selected plant/3 pot during harvesting	During harvesting	Count number	
Number of grain per pod	Count number of grain/pod from 5 randomly selected plant/3pot during harvesting	During harvesting	Count number	
100 grain weight	Count 50 grain each breeding material after harvest and dying, the counted grain were weighed using weighing balance	After harvest and drying	Count grain and weighing balance	
Grain yield per plot	Measure all grain from 3pot/breeding material after harvest and dying using weighing balance	After harvest and drying	Weighing balance	

Table 3
Combined analysis of variance for phenotypic traits associated with anthracnose resistance – Untreated -field study.

Traits		Plant stand emerge			Anthracnose score			Leaf length			Leaf width			Length of fifth internode		
Sources	Df	SS	MSS	Pr(>F)	SS	MSS	Pr(>F)	SS	MSS	Pr(>F)	SS	MSS	Pr(>F)	SS	MSS	Pr(>F)
Env (E)	1	104.4	104.4	1.2***	44.2	44.2	2.1***	34.2	34.2	1.3***	48	48.4	4.2***	23	23	3.9***
Rep (Env)	4	22.4	5.6	0.3*	1.4	0.3	0.5**	2.7	0.7	0.5**	2.2	0.6	0.8***	4	1	0.2*
Gen (G)	21	1750.3	83.3	1.6***	197.3	9.4	4.9***	162.3	7.7	4.6***	143	6.8	3***	153	7.3	1.6***
G X E	21	98.1	4.7	0.3*	23.3	1.1	0.8***	7.2	0.3	0.9***	6.9	0.3	0.9***	1	0	0.9***
Error	216	902.6	4.2		85	0.4		183.5	0.8		323	1.5		153	0.7	
CV(%)			1.2			33.7			7.2			12.3			6.8	
MSR+/MSR-			8.2			4.8			2.6			2.1			2.2	
OVmean			176			1.9			12.8			9.9			12.3	
Traits		**Length of petiole**			**Canopy height**			**Canopy width**			**Plant vigour**			**Days to 75% flowering**		
Sources	**Df**	**SS**	**MSS**	**Pr(>F)**	**SS**	**MSS**	**Pr(>F)**	**SS**	**MSS**	**Pr(>F)**	**SS**	**MSS**	**Pr(>F)**	**SS**	**MSS**	**Pr(>F)**
Env (E)	1	14.1	14.1	1.6***	87.5	87.5	3.2***	47.5	47.5	5.9***	11	11.1	1.00***	53.6	53.6	5.2***
Rep (Env)	4	3.1	0.8	1.2***	2.2	0.6	0.9***	13.6	3.4	0.01 ns	0.8	0.19	0.40**	7.4	1.8	0.1 ns
Gen (G)	21	105.3	5	6.5***	15866	755.5	8.7***	1058.7	50.4	6.1***	33	1.56	7.20***	1274	60.6	3.9***
G X E	21	3.5	0.2	0.9***	5.7	0.3	1***	18.3	0.9	0.2*	1.5	0.07	0.90***	8.9	0.4	0.9***
Error	216	103.8	0.5		573.8	2.7		145.4	0.7		42	0.19		179	0.8	
CV(%)			6.6			3.7			5.2			10			2	
MSR+/MSR-			1.4			2.4			1.2			1.4			1.5	
OVmean			10.5			44.6			15.8			4.4			44.7	
Traits		**Days to 75% Maturity**			**Plant stand at harvest**			**Number of pod per plant**			**Number of grain per pod**			**100 grain weight (gm)**		
Sources	**Df**	**SS**	**MSS**	**Pr(>F)**	**SS**	**MSS**	**Pr(>F)**	**SS**	**MSS**	**Pr(>F)**	**SS**	**MSS**	**Pr(>F)**	**SS**	**MSS**	**Pr(>F)**
Env (E)	1	314.2	314.2	1***	5947	5947	9.4***	3795.5	3795.5	2.4***	20	20.2	5.6***	1671	1671	1.1***
Rep (Env)	4	0.5	0.1	0.9***	119.7	29.9	0.9***	18	4.5	0.9***	3.2	0.8	0.04**	2.8	0.7	0.6***
Gen (G)	21	3626.4	172.7	2.9***	28340	1349.5	4.1***	8078.1	384.7	4.5***	75	3.6	7.3***	5068	241	6**
G X E	21	2.3	0.1	1***	106.7	5.1	1***	82	3.9	0.9***	6.1	0.3	0.6**	6.4	0.3	0.9***
Error	216	448.5	2.1		42093	194.9		4534.5	21		67	0.3		250	1.2	
CV(%)			2			9.2			13.7			13			2.5	
MSR+/MSR-			3.3			2.1			3			1.2			2.5	
OVmean						151.2			33.4			4.3			43.3	
Traits		**Grain yield (kg/ha)**														
Sources	**Df**	**SS**	**MSS**	**Pr(>F)**												
Env (E)	1	5849105.4	5849105.4	6.4***												
Rep (Env)	4	548.2	137.1	0.9***												
Gen (G)	21	14986961	713664.8	5.5***												
G X E	21	310173.6	14770.2	0.9***												
Error	216	5710607.1	26438													
CV(%)			18.4													
MSR+/MSR-			3.3													
OVmean			883													

Significant (*, ***, ns) at ($P \leq 0.05$, $P \leq 0.001$), ns = not significant. DF = Degree of freedom; SS=Sum of squares; MSS = Mean sum of squares; F=F-statistic; CV= Coefficient of variation and MSR = Mean Square Regression.

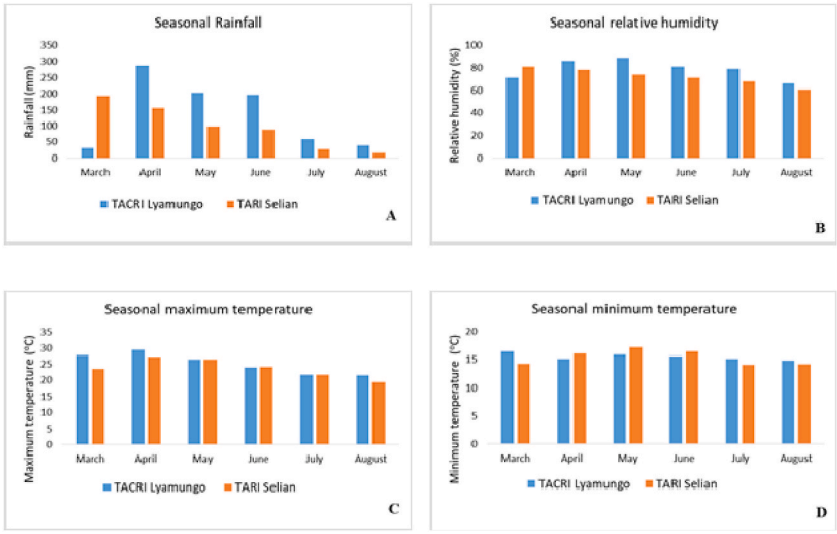

Fig. 1. Weather variables during the 2022 common bean cropping season at a meteorological station located at Arusha airport and TACRI Lyamungo.

The same experiment was conducted in the screen house under control environment using Complete Randomized Design (CRD) with three replications. The same 22 varieties were arranged in 10-L 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 each trial spaced by 5 m. The first trial was sprayed with Chlorothalonil (tetra-chloroisophthalonitrile) at the rate of 30 ml/15L of water during 14, 28 and 42 DAG to control anthracnose disease (treated trial) and the second trial was not sprayed with fungicide (untreated). Canvas/plastic covering was aliened at the 5 m to demarcate the boundary between the two trials during fungicide spraying, with the goal of preventing the chemical mist from reaching the untreated trial.

Symptomatic common bean leave sample were taken from farmers field in Lyamungo (Area with highly virulent race of anthracnose disease [7,17]. The samples were collected to TARI Selian laboratory, stored under normal room temperatureat 24 °C for further analysis to an isolate level. The fungal isolates were grown in the petri plates at 24 °C, on V8 medium composed of V8 juice (200 mls), $CaCO_3$(3.0 g), Bato Agar (15g), streptomycin (10 mg) and distilled autoclaved H_2O (1000 ml). Single spore isolates were established by employing a standard procedure with modification according to Ref. [10] and culture were prepared as prescribed by Ref. [12]. 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 h to maintain relative humidity of approximately >92%, followed by other management practices like irrigation at an interval of five days and hand weeding at 21 and 49 DAG.

2.4. Data collection

Phenotypic and agronomic parameters were collected on five randomly selected plants in both the treated and untreated field experiments as described in Table 2.

2.5. Statistical analysis

All data were subjected to an analysis of variance using R statistical software, R package, version 4.2.2 [18] with the mean separation using Tukey's test at 5% level of significance. AMMI Model and Biplot analysis on anthracnose score and grain yield were conducted to understand the influence of anthracnose infection on grain yield between G, E and GE. In view of our study's objective, we also conducted a correlation analysis on phenotypic traits associated with anthracnose resistance. Correlation coefficients are valuable for quantifying the strength and direction of linear relationships between variables, which can help identify associations between components or traits [19]. However, they do not provide information about the relative importance of direct and indirect effects of these components on the determination of main traits. Therefore path analysis was used to explore and represent the direct and indirect effects of variables on each other [20].

3. Results

3.1. Variation in phenotypic traits among treated trial and untreated trial

The combined analysis of variance shows that, all phenotypic and agronomic variables were significant difference ($P \leq 0.05$)

between G, E & GE (Table 3). Phenotypic and agronomic variables differed significantly among genotype and particularly between treated and untreated trials (Table 4,5& Fig. 2), 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% flowering for the treated trials was 45 while it was 44 for untreated trials. The mean number of days to 75% 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% and 82% for susceptible genotypes. The mean number of days to 75% maturity for resistant genotypes was 73 compared with 68.6 for susceptible genotypes, and the mean percent of plant stands at harvest was 90 and 55 for resistant and susceptible genotypes, respectively.

High rainfall, temperature and relative humidity resulted in a significant increase in anthracnose severity in TACRI Lyamungo compared to TARI Selian (Fig. 1a, b, c &d).The fungicide-treated trial had low anthracnose severity (1.4) compared with the untreated trial (2.5) (Table 4). 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). AMMI analysis indicated that, anthracnose infection were highly influenced by environment main effect (58.9%), while genotype main effect contributed 32.7% (Fig. 3.) 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 (Table 5). Average grain yield was therefore significantly higher in treated trials (1035 kg/ha) compared to untreated trials (739 kg/ha). AMMI analysis showed that the environment was the dominant factor affecting common bean grain yield, explaining 84.9% of the variability, while genotype factors accounted for 15.7% (Fig. 4).

3.2. *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 (Fig. 5a), 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 =

Table 4
Anthracnose severity and phenotypic trait means by trial, genotype and two environment (TARI Selian and TACRI Lyamungo) – Field study.

	Treated trial								Untreated trial							
Breeding material	Anth. Sc.	LL	LW	L 5th I	LP	CH	CW	PV	Anth. Sc.	LL	LW	L 5th I	LP	CH	CW	PV
Glori	2	12	9	12	10	44	13	4	3	11	9	12	9	43	12	4
Kipapi	2	12	9	12	9	44	18	4	3	11	8	12	9	43	17	4
NUA 48	1	14	11	14	11	46	13	5	2	13	10	14	12	45	13	5
NUA 64	1	14	12	14	11	38	14	5	2	13	10	14	12	37	13	5
Sweet Violet	1	13	10	12	11	46	13	5	2	12	9	12	10	46	12	5
VTT 923 -23-10	1	13	10	13	10	59	17	4	2	13	9	13	10	57	17	4
COD MLB 0033	1	12	10	12	10	51	18	4	2	12	9	12	9	50	18	4
KAB 36	1	14	10	14	11	49	16	4	2	13	10	13	11	48	15	4
RCB 593	1	14	10	13	11	42	17	4	2	13	10	13	10	41	16	4
RWR 2154	1	14	11	14	11	40	16	5	2	13	10	13	11	39	15	5
SCR 61	1	14	12	13	11	33	18	4	2	13	11	13	11	32	18	4
SMC 18	1	14	10	13	11	39	17	4	2	13	10	12	11	38	16	4
Selian 12	2	13	10	12	11	36	20	5	4	12	9	11	10	34	18	5
Selian 13	3	14	10	13	12	36	16	5	5	13	8	10	11	34	15	4
Uyole 18	2	13	10	13	11	64	16	5	3	13	9	12	10	62	15	4
Calima Uyole	2	12	10	12	11	56	20	5	3	11	9	12	11	55	20	5
Uyole 03	2	13	10	12	10	42	17	5	2	12	10	12	10	40	16	4
Lyamungo 90	3	14	10	13	11	44	16	4	6	13	9	11	10	42	14	3
Boroto	2	14	11	13	11	42	14	4	4	13	9	11	10	41	12	4
Njano Gololi	3	12	10	12	10	43	17	4	6	11	8	10	9	42	16	3
Rosecoco	3	14	10	13	11	45	15	4	5	13	9	10	10	44	13	3
Soya Kijivu	3	13	10	12	10	57	16	4	5	13	8	11	9	56	14	4
Mean	**1.4**	**13**	**10**	**13.6**	**11**	**46**	**16**	**5**	**2.5**	**13**	**9.4**	**12.1**	**10**	**44**	**16**	**4**

Anth.Sc. = Anthracnose Score; LL = Leaf length; LW = Leaf width; L5thI = Length of fifth internode and LP = Length of petiole; CH= Canopy height; CW=Canopy width; PV= Plant vigour.

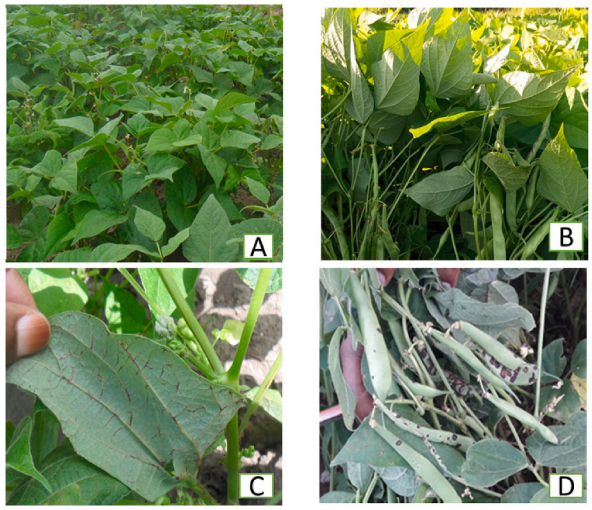

Fig. 2. Bean plant observation on treated and untreated trial. A&B, Healthy bean plant on treated bean plants C& D, Symptoms of anthracnose on untreated bean plants.

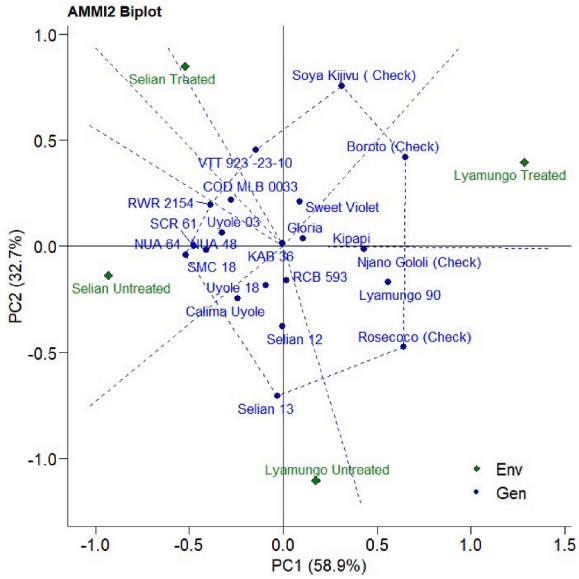

Fig. 3. AMMI Biplot anthracnose severity by genotype by trial and environment (TARI Selian and TACRI Lyamungo).

highly strong [21]. To optimize results, the mean of untreated trials was used to calculate phenotypic traits associated with anthracnose resistance.

3.2.1. Traits highly-strongly correlated with anthracnose resistance

The number of days to 75% maturity and number of plants stand at harvest were very strongly ($P \leq 0.001$) correlated to anthracnose resistance (Fig. 5a). Path analysis revealed that, the number of days to maturity and the number of plants stand at harvest has high strong direct effect association with anthracnose resistance (Supplementary Information Table 8). Common bean varieties needing more days to maturity were resistant to anthracnose compared to genotypes needing fewer days to maturity (Tables 5 and 7). 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 severely affected by anthracnose (Table 5). 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 (Table 5).

Table 5
Anthracnose severity and agronomic trait means by trial and genotype and two environment (TARI Selian and TACRI Lyamungo) – Field study.

	Treated trial						Untreated trial					
Breeding material	Anth. Sc.	PSE	DF	DM	PSH	GY (kg/ha)	Anth. Sc.	PSE	DF	DM	PSH	GY (kg/ha)
Gloria	2	178	44	74	164	1051	3	176	43	72	156	714
Kipapi	2	176	43	71	155	1041	3	175	42	69	147	705
NUA 48	1	179	47	77	166	1528	2	177	46	75	157	1102
NUA 64	1	178	48	78	167	1464	2	178	47	76	157	1040
Sweet Violet	1	178	46	78	160	1231	2	177	45	76	151	895
VTT 923 -23-10	1	178	44	72	166	1189	2	178	43	70	159	864
COD MLB 0033	1	177	46	78	166	1262	2	176	46	75	155	932
KAB 36	1	177	44	73	160	1264	2	177	43	71	152	909
RCB 593	1	176	47	77	158	1158	2	176	47	75	150	848
RWR 2154	1	178	45	78	162	1303	2	178	44	75	152	944
SCR 61	1	177	44	74	161	1143	2	176	42	72	152	842
SMC 18	1	178	48	78	165	1179	2	177	47	76	155	864
Selian 12	2	177	42	69	155	961	4	177	41	67	145	710
Selian 13	3	177	42	68	146	873	5	175	40	65	136	512
Uyole 18	2	178	46	72	159	955	3	177	45	69	150	698
Calima Uyole	2	178	47	79	157	942	3	176	46	77	147	687
Uyole 03	2	178	46	76	162	944	2	176	45	74	153	710
Lyamungo 90	3	178	48	79	140	575	6	173	47	71	128	381
Boroto	2	172	42	69	144	704	4	174	40	69	135	509
Njano Gololi	3	173	42	69	145	608	6	168	41	67	135	396
Rosecoco	3	175	48	80	130	730	5	170	48	72	118	476
Soya Kijivu	3	170	46	74	142	533	5	167	44	71	132	360
Mean	**1.4**	**176**	**45**	**75**	**157**	**1032**	**2.5**	**176**	**44**	**72**	**147**	**734**

Anth.Sc. = Anthracnose Score, PSE = Plant stands emerging; DF = Days to flowering; DM = Days to maturity; PSH= Plant stands at harvest; and GY = Grain yield.

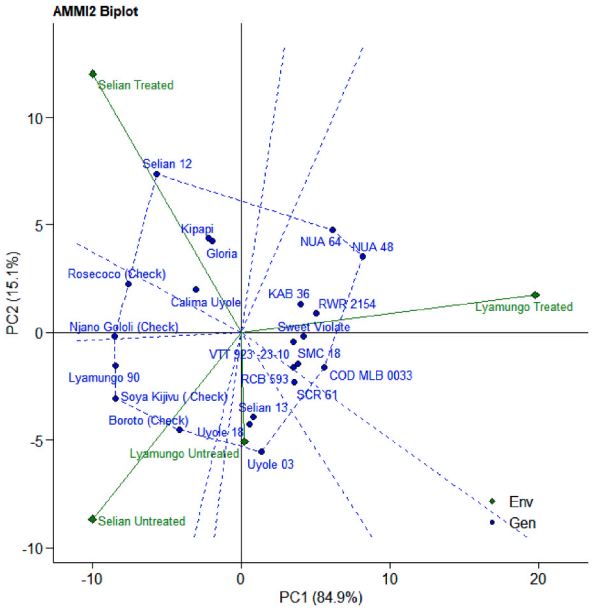

Fig. 4. AMMI model Biplot presenting the mean grain yield of 22 genotypes by trial and environment (TARI Selian and TACRI Lyamungo).

3.2.2. Traits strongly correlated with anthracnose resistance

The number of plants stands emerging, length of fifth internode and grain yield were the traits that were strongly ($P \leq 0.01$) correlated to anthracnose resistance (Fig. 5a). Tested CBVs with a higher germination percentage were significantly resistant to anthracnose compared to varieties with a lower 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**.** 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 (1102 kg/ha), NUA 64 (1040 kg/ha) and RWR 2154

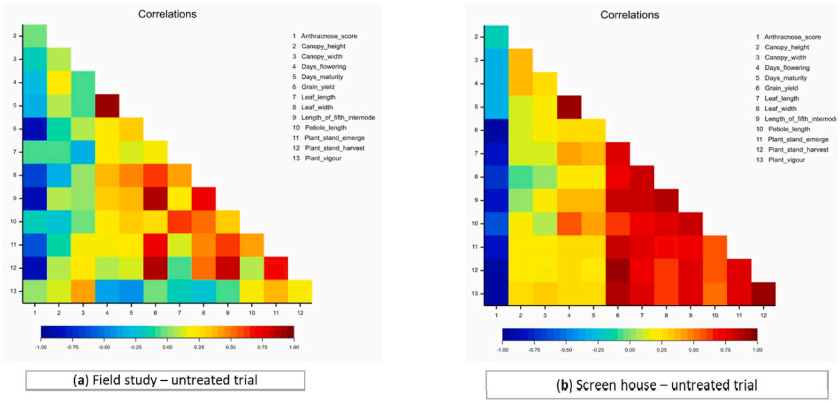

Fig. 5. Correlation analysis – red = positive correlations and blue = negative correlations, the intense the color the stronger the correlation. The legend color below shows the correlation coefficient and the corresponding colors. Correlation ranges: 0.0–0.19 = very mild, ˙0.20–0.39 = mild, ˙0.40–0.69 = moderate, ˙0.70–0.89 = strong and ˙0.90–1.00 = very strong [21].

(944 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 5).

3.2.3. Traits moderately correlated with anthracnose resistance

Leaf width, petiole length and plant vigour were moderately ($P \leq 0.05$) correlated with anthracnose resistance (Fig. 5a). 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 (Table 4). Significance of variation was also 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. 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.

3.3. 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 (Tables 6 and 7). Regarding validation of phenotypic traits associated with anthracnose resistance, positive correlation was revealed among the phenotypic traits evaluated. The magnitude of correlation ranged from negative 0.10 to positive 0.92 (Fig. 5b) with significant difference for most of the phenotypic traits evaluated. Of 12 phenotypic traits evaluated, 33.3% (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% were strongly ($P \leq 0.01$) correlated to anthracnose resistance (Fig. 5b). Additionally; path analysis shows that the length of fifth internode, length of petiole, plant vigour number of days to maturity, number of plant stand at harvest and grain yield traits exhibited substantial direct effect estimates, characterized by their high magnitudes and positive values, which serves as evidence of high strong association with anthracnose resistance (Supplementary Information Table 9)

4. Discussion

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

TACRI Lyamungo site recorded high rainfall, temperature and relative humidity in contrast to TARI Selian site (Fig. 1a, b, c &d). 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. [13] and Masunga et al. [7] 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 [22,23] among common bean genotypes. AMMI analysis indicated that environmental main effect as the primary factor influencing anthracnose infection (58.9%) while genotype factor accounted for 32.7% anthracnose infection rate (Fig. 3). This imply that, production of bean seeds in free regions to anthracnose pathogen and the use of host plant resistance stands out as the optimal approach for disease control. Contrary [24] on evaluation of

Table 6
Anthracnose severity and phenotypic trait means by trial and genotype - Screenhouse study.

	Treated trial								Untreated trial							
Breeding material	Anth. S.	LL	LW	L5th I	LP	CH	CW	PV	Anth. S.	LL	LW	L5th I	LP	CH	CW	PV
Gloria	3	12	11	12	10	45	13	4	3	11	10	11	10	44	13	4
Kipapi	3	12	10	12	10	44	18	4	4	11	9	11	9	43	17	4
NUA 48	1	14	13	15	11	46	15	5	2	14	12	14	12	45	14	5
NUA 64	1	14	13	15	11	46	15	5	2	13	12	14	12	45	14	5
Sweet Violet	2	14	12	11	11	47	13	5	3	13	10	11	10	46	12	5
VTT 923 -23-10	2	13	11	11	10	57	17	4	3	12	10	12	11	56	17	5
COD MLB 0033	2	12	12	12	10	56	18	4	3	12	10	11	10	54	17	5
KAB 36	2	14	12	13	11	50	15	4	3	13	11	12	10	49	14	5
RCB 593	2	14	11	13	11	44	16	4	3	14	10	12	11	43	15	5
RWR 2154	2	14	13	14	11	44	16	5	2	13	12	13	11	44	15	5
SCR 61	2	14	13	13	11	38	17	4	2	13	12	13	11	37	16	5
SMC 18	1	14	11	12	11	43	17	4	2	13	10	12	11	42	16	4
Selian 12	3	11	11	11	11	40	15	5	4	10	9	10	10	39	14	4
Selian 13	4	11	10	10	12	40	15	4	7	10	9	9	9	39	14	2
Uyole 18	3	13	12	12	11	63	16	5	4	12	10	11	11	60	15	4
Calima Uyole	3	12	10	12	11	56	19	5	3	11	9	11	10	55	17	5
Uyole 03	3	13	12	12	10	44	17	5	3	12	10	11	10	43	16	5
Lyamungo 90 (CK)	4	14	10	12	11	44	15	4	8	10	9	10	10	43	14	2
Boroto (CK)	2	14	12	13	11	42	14	4	5	12	11	11	10	41	14	4
Njano Gololi (CK)	4	12	9	11	10	41	14	4	7	9	8	9	9	40	13	3
Rosecoco (CK)	4	14	12	11	11	45	15	4	7	10	9	10	10	44	14	3
Soya Kijivu (CK)	3	12	10	10	10	53	16	4	7	11	9	9	10	51	15	3
Mean	**2.4**	**13**	**12**	**13**	**11**	**47**	**16**	**4.7**	**4.6**	**12**	**10**	**12**	**10**	**45**	**15**	**4**

Anth.Sc. = Anthracnose Score; LL = Leaf length; LW = Leaf width; L5thI = Length of fifth internode and LP = Length of petiole; CH= Canopy height; CW=Canopy width; PV= Plant vigou

Table 7
Anthracnose severity and agronomic trait means by trial and genotype- Field study.

	Treated trial						Untreated trial					
Breeding material	Anth. S.	PSE	DF	DM	PSH	GY (gm/pot)	Anth. S.	PSE	DF	DM	PSH	GY (gm/pot)
Gloria	3	9	44	74	8	109	3	9	43	74	8	102
Kipapi	3	8	43	71	8	108	4	8	41	69	8	101
NUA 48	1	9	47	77	9	128	2	9	46	75	9	124
NUA 64	1	9	48	78	8	126	2	9	46	75	9	121
Sweet Violet	2	9	46	78	9	117	3	9	44	75	9	111
VTT 923 -23-10	2	9	44	72	9	115	3	9	43	69	8	107
COD MLB 0033	2	9	46	78	9	120	3	9	46	77	8	113
KAB 36	2	9	44	73	9	118	3	9	42	70	8	109
RCB 593	2	9	47	77	9	108	3	9	46	75	8	102
RWR 2154	2	9	45	78	9	122	2	9	45	76	8	116
SCR 61	2	9	44	74	8	106	2	9	43	72	8	101
SMC 18	1	9	48	78	8	114	2	9	47	77	8	107
Selian 12	3	9	42	69	8	106	4	8	40	68	8	101
Selian 13	4	8	42	68	7	94	7	8	40	67	5	72
Uyole 18	3	9	46	72	8	102	4	9	45	70	8	95
Calima Uyole	3	9	47	79	9	105	3	9	47	76	8	98
Uyole 03	3	8	46	76	8	107	3	9	46	76	8	100
Lyamungo 90 (CK)	4	7	48	77	7	92	8	8	46	71	4	70
Boroto (CK)	2	9	42	70	8	105	5	9	40	67	7	93
Njano Gololi (CK)	4	7	42	68	7	87	7	7	39	65	5	64
Rosecoco (CK)	4	8	48	78	7	88	7	7	47	72	6	68
Soya Kijivu (CK)	3	7	46	72	7	71	7	7	44	68	5	60
Mean	**2.4**	**8.9**	**45**	**74**	**8.1**	**107**	**4.6**	**8.5**	**44**	**73**	**7.4**	**98**

Anth.Sc. = Anthracnose Score, PSE = Plant stands emerging; DF = Days to flowering; DM = Days to maturity; PSH= Plant stands at harvest; and GY = Grain yield.

water yam to anthracnose severity indicated genotype to be the main factor influencing anthracnose infection (48%) compared to environmental effects (26%). Treatment with fungicide spray reduced the severity of anthracnose disease across locations. Similar findings were reported by Mohammed [25], Gillard and Ranatunga [26], Polanco et al. [27], and Hirpa and Selvaraj [28]. 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.

4.2. Variation in phenotypic traits among treated and untreated trials

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.

4.3. Correlation of phenotypic traits associated with anthracnose resistance

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

4.3.1. Phenotypic traits highly-strong correlated with anthracnose resistance

The number of days to 75% 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 [29]. 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 xylem and phloem, interrupting translocation of water and nutrients, which often reduce plant growth and eventually cause plant death [30]. 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 [30,31]. 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. Regarding grain 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 [31]. Healthy grain is of good quality, with enough weight compared to poor-quality grain, resulting in high productivity compared with the susceptible cultivars [29].

4.3.2. Phenotypic traits strongly correlated with anthracnose resistance

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* [30]. The longer the leaf, the larger the outermost layer of the leaf (cuticle) responsibly protects the common bean plant against anthracnose [29]. The longer the leaf length the higher the density of hairs on the leaves, which physically impede the penetration and spread of anthracnose [21]. 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 [30]. 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 [29]. 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. [32] 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 [30]. 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 [29,33]. 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 [25] and Masunga et al. [7] reported significant anthracnose invasion, stunted growth and bean plant death on cultivars susceptible to anthracnose disease.

4.4. Grain yield and yield component

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 [34] documented that the existence of various mega environments was inferred when significant variation in genotypes was found by environmental interaction [35]. AMMI analysis demonstrated environmental main effect as dominant factor influencing grain yield (84.9%), while genotype factor accounted for 15.7% common bean grain (Fig. 4). This observation implies that the experimental sites and genotypes utilized in the research demonstrated a range of variations, rendering them suitable for assessing genotype adaptability in both specific and broader contexts. Similarly; Tadesse et al. [36] revealed large contribution of environment (78.2%) on grain yield as compared to genotype main effect (6.5%). From this study, the crossover of genotype by environment was obtained (Figs. 3 and 4), 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 (Fig. 4). The most ideal genotype should be highly significant in mean performance and show great stability [37].

5. Conclusions

Based on the results and discussion, the number of days to 75% 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. Study limitations include; a limited number of anthracnose susceptible varieties used for evaluation, which could affect the findings to broader bean populations. The selected common bean varieties (CBVs) may not represent the full genetic diversity of common bean, potentially limiting the applicability of the findings to other bean varieties or populations. The evaluation of phenotypic traits could be influenced by environmental factors such as rainfall temperature, humidity and disease pressure, which may vary across different growing locations and seasons. The study's findings may be influenced by the prevalence and severity of anthracnose in the specific area or growing conditions where the evaluation took place. The methods used to assess phenotypic traits associated with anthracnose resistance (visual rating scales), may have limitations in terms of accuracy and reproducibility. To reduce some of these limitations; many CBVs should be used in evaluations. Evaluation should be done in hotspot areas to anthracnose with good weather conditions. Phenotypic traits evaluated under field condition need to be reconfirmed under screen house condition hence some factors could be hindering or favouring its resistance.

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Data availability statement

Data included in article has been published in Mendely Data online at https://data.mendeley.com/datasets/d3w8s3zcnd/1.

Additional information

The content related to this article is available as preprint at https://www.researchsquare.com/article/rs-3044363/v1, with the following DOI: https://doi.org/10.21203/rs.3.rs-3044363/v1. A preprint is a preliminary version of a manuscript that has not completed peer review at a journal. Research Square does not conduct peer review prior to posting preprints. The posting of a preprint on this server should not be interpreted as an endorsement of its validity or suitability for dissemination as established information or for guiding clinical practice. Research Square lets you share your work early, gain feedback from the community, and start making changes to your manuscript prior to peer review in a journal. A preprint is an author's early version of their manuscript**.** Therefore, publication of the final paper in a journal is **not considered plagiarism or self-plagiarism**.

CRediT authorship contribution statement

Edith L. Kadege: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Pavithravani B. Venkataramana:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Teshale Assefa:** Validation, Supervision, Resources, Methodology, Investigation. **Joseph C. Ndunguru:** Validation, Resources, Investigation. **Jean Claude Rubyogo:** Resources, Funding acquisition. **Ernest R. Mbega:** Visualization, Validation, Supervision, Investigation.

Declaration of competing interest

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Appendix A. Supplementary data

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