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Assessment, characterization and biological control of common bean anthracnose (*Colletotrichum lindemuthianum*) using *Trichoderma* spp. in Gedeo and West Guji Zones, Ethiopia

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Abstract

Background Common bean (*Phaseolus vulgaris* L.) is a vital legume crop in Ethiopia, but its production is severely constrained by anthracnose, caused by the fungus *Colletotrichum lindemuthianum*. The disease is particularly important in southern Ethiopia, where information on its distribution, pathogen characteristics, and biological control options is limited. Therefore, this study was conducted to assess the occurrence, incidence and severity of common bean anthracnose, to characterize the causal pathogen, and to evaluate the antagonistic potential of *Trichoderma* species against *Colletotrichum lindemuthianum* in Gedeo and West Guji Zones.

Results The survey revealed significant variation in anthracnose intensity, with the highest disease incidence (61.23%) and severity (29.95%) recorded in Wonago district. Altitude, cropping system, and weed management significantly influenced disease levels. Morpho-cultural characterization of fifteen *Colletotrichum lindemuthianum* isolates showed considerable variability in growth rate, texture, and colony color. All *Trichoderma* species significantly inhibited the pathogen's mycelial growth. *Trichoderma viride* was the most effective, showing a maximum inhibition percentage of 90.34%.

Conclusion The findings of the present study highlight the widespread and severe nature of common bean anthracnose in Gedeo and West Guji Zones, Ethiopia. The demonstrated efficacy of *Trichoderma* species has potential as biological control agents against *Colletotrichum lindemuthianum*. However, further field-based evaluations are required to validate their effectiveness under natural conditions.

Keywords Anthracnose, Common bean, *Colletotrichum lindemuthianum*, *Trichoderma*, Biological control

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Background

The common bean (*Phaseolus vulgaris* L.) is a crucial legume crop worldwide, serving as a vital source of protein, vitamins, and minerals for millions, particularly in developing nations (FAO, 2020). In Ethiopia, it is not only a staple food but also a key income source for smallholder farmers in regions like Gedeo and West Guji (CSA, 2021). Despite its economic significance and extensive cultivation, the national annual yield remains low, estimated at around 1.79 tons per hectare (CSA, 2021).

Bean production faces significant constraints, chief among them being anthracnose, a destructive disease caused by the fungus *Colletotrichum lindemuthianum*. This pathogen can persist in seeds for up to five years and survive in crop debris, with infected seeds being the primary source of dissemination (Manjunath et al. 2012). Disease symptoms include dark, linear lesions along leaf veins, varying in color from black to brick red. Anthracnose is characterized by sunken lesions on leaves, pods, and seeds, leading to premature leaf drop, pod rot, and seed deterioration (Lima et al. 2019). In severe cases, yield losses can exceed 80%, severely threatening food security and farmer livelihoods (Benítez et al. 2004). In Ethiopia, the disease is particularly devastating, causing substantial yield reductions and posing a major production challenge nationwide (Negera and Dejene 2018; Hussien et al. 2020).

In the Gedeo Zone, farmers primarily rely on traditional practices, while in West Guji's Abbaya district, fungicide application is common. However, these chemicals are often ineffective, environmentally harmful, and costly for smallholders (Harman et al. 2004). Their overuse has also led to the emergence of fungicide-resistant strains of *C. lindemuthianum*, further complicating control (Vinale et al. 2008). This underscores an urgent need for sustainable and cost-effective alternatives, such as biological control agents.

Biological control using beneficial microorganisms like *Trichoderma* species is gaining attention as a sustainable and eco-friendly management strategy. *Trichoderma* species suppress fungal pathogens through mechanisms including antibiosis, competition, and the induction of plant defense responses (Harman et al. 2004). While the use of host resistance and biological control agents represents a promising integrated approach, these strategies have received limited attention in Ethiopia.

Critically, there is a lack of comprehensive information on the geographical distribution and severity of common bean anthracnose in the Gedeo and West Guji zones. Furthermore, the morphological and cultural diversity of *Colletotrichum lindemuthianum* in these areas has not been thoroughly examined, and the efficacy of *Trichoderma* species as biological control agents against this pathogen remains largely unexplored. Therefore, this

study was designed to address the following key questions: What is the distribution and severity of anthracnose in these zones? What are the morphological characteristics of the prevailing *Colletotrichum lindemuthianum* isolates? And how effective are native *Trichoderma* species in suppressing the pathogen?

The objectives of this study were to: (i) assess the distribution and severity of common bean anthracnose, (ii) characterize the associated *Colletotrichum lindemuthianum* isolates, and (iii) evaluate the antagonistic potential of different *Trichoderma* species against the pathogen. The findings will provide critical data for developing targeted management strategies, offering farmers a sustainable alternative to chemical fungicides, and ultimately contributing to improved bean productivity, food security, and livelihoods in the region.

Methods

Description of the study area

The research was carried out in three specific districts—Dilla Zuria, Wonago (Gedeo Zone), and Abbaya (West Guji Zone)—in Southern Ethiopia. Dilla Zuria covers an area of 137 square kilometers (CSA, 2007). The Gedeo Zone has a bi-modal rainfall pattern, with annual precipitation ranging from 1001 to 2000 mm and temperatures fluctuating between 12 °C and 25 °C (CSA, 2007). Abbaya district is about 430 km south of Addis Ababa, with elevations varying from 800 to 2300 m above sea level. It also experiences a bi-modal rainfall pattern, averaging between 800 and 1800 mm each year, along with temperatures from 12.5 °C to 28 °C (CSA, 2007). GPS coordinates were recorded for each survey field to document the geographic distribution of the disease.

Field survey and disease assessment

A field survey was conducted in July and August of 2023/2024, during the peak growing season for common beans, in the purposively selected districts of Wonago, Dilla Zuria, and Abbaya, Ethiopia. These districts were identified by zonal agriculture offices as major common bean production areas. A total of 63 fields (18–24 per district) were randomly selected along major roads, with sampling points spaced 5–6 km apart.

In each field, the severity of common bean anthracnose was assessed using a standard 1 to 9 scale (Schoonhoven and Pastor-Corrales 1987), where: 1 = no symptoms; 3 = 1–5% leaf area affected (small, scattered lesions); 5 = 6–20% leaf area affected (numerous lesions, some coalescing); 7 = 21–50% leaf area affected (large, coalescing lesions, some defoliation); and 9 = 50% leaf area affected (severe defoliation and stem lesions). To ensure consistency, a visual guide with photographs representing each score was used by all assessors, and assessments

were conducted between 8:00 and 10:00 AM to standardize observations.

Each field was divided into five (1 m x 1 m) quadrants in an X pattern. The total number of plants and the number of diseased plants (showing typical anthracnose symptoms) within each quadrat were counted. From each quadrat, leaves with distinct anthracnose symptoms were collected, placed in separate paper bags, and transported to the laboratory in a cool box for pathogen isolation within 24 h of collection. The Percentage of Disease Incidence (PDI) and Percentage Severity Index (PSI) were calculated using standard epidemiological formulas (Sharma et al. 2023) as follows:

$$\text{PDI}(\%) = (\text{Number of infected plants} / \text{Total number of plants assessed}) \times 100$$

$$\text{PSI}(\%) = [\text{Sum of all numerical ratings} / (\text{Number of plants scored} \times \text{Maximum score on the scale})] \times 100$$

Isolation and characterization of *Colletotrichum lindemuthianum*

Infected leaf tissues from the border of lesions were cut into small pieces (0.5 x 0.5 cm), surface-sterilized in 70% ethanol for 30 s, followed by 1% sodium hypochlorite for 2 min, and then rinsed three times in sterile distilled water (Mungalu et al. 2023). After drying on sterile filter paper, the tissues were plated on Potato Dextrose Agar (PDA) and incubated at 25 ± 1 °C for 7–10 days in the dark.

For long-term storage, pure cultures were maintained on PDA slants at 4 °C. Morphological characterization was performed on 15-day-old cultures. Colony characteristics (growth rate, texture, color on upper and lower surfaces) were recorded. Conidial morphology was examined microscopically (at 40x magnification) using lactophenol cotton blue mounts. Conidial dimensions (length and width) of 50 conidia per isolate were measured using an ocular micrometer. While morphological identification is a valuable first step, future work should include molecular characterization (e.g., sequencing of the ITS or TEF1-α regions) to confirm species identity and assess genetic diversity.

In vitro evaluation of *Trichoderma* biological control agents Source and maintenance of biological control agents

Five antagonistic *Trichoderma* species—*Trichoderma harzianum*, *Trichoderma viride*, *Trichoderma atroviride*, *Trichoderma longibrachiatum*, and *Trichoderma asperellum*—were obtained from the Ambo Agricultural Research Center. The cultures were maintained on PDA

slants at 4 °C and sub-cultured onto fresh PDA plates for the experiment.

Dual culture assay

The antagonistic activity of the *Trichoderma* species against *Colletotrichum lindemuthianum* was evaluated using the dual culture technique (Dennis and Webster 1971) on PDA. A 5-mm mycelial disc from a 7-day-old culture of *Colletotrichum lindemuthianum* was placed on one side of a 9-cm Petri dish, and a similar disc of a *Trichoderma* species was placed on the opposite side, 6 cm apart. A control plate contained only the pathogen disc. The experiment was arranged in a Completely Randomized Design (CRD) with three replications per treatment combination. The cultures were incubated at 22 ± 1 °C.

The radial growth (in mm) of the pathogen towards the antagonist was measured in two perpendicular directions after 7 days. The percentage of mycelial growth inhibition was calculated using the formula (Pandey et al. 1982):

$$\text{Inhibition}(\%) = [(C - T) / C] \times 100$$

where: C = radial growth of the pathogen in the control plate (mm), and T = radial growth of the pathogen in the dual culture with the antagonist (mm).

Data analysis

Field data on common bean anthracnose incidence and severity were analyzed using descriptive statistics. Disease incidence and severity were categorized into binary groups (50% and ≤ 50% for incidence; 25% and ≤ 25% for severity) based on field averages (Fininsa and Yuen 2001; Yuen 2006). A logistic regression analysis was performed using SAS software to evaluate the impact of independent variables (district, altitude, variety, etc.) on disease incidence and severity.

For the laboratory data, the inhibition percentages were subjected to analysis of variance (ANOVA) using the General Linear Model (GLM) procedure in SAS software (version 9.3). All statistical tests were considered significant at $p < 0.05$. The assumptions of ANOVA (normality and homogeneity of variances) were checked using residual plots, and means were separated using the Least Significant Difference (LSD) test.

Results

Demographic characteristics of respondents

A total of 63 farmers participated in the survey across the three districts (Table 1). Male respondents (69.8%) outnumbered female respondents (30.2%). The majority of farmers (39.7%) were aged 41–50 years, while only 9.5% were under 30 years. Regarding education, 34.9% of respondents were illiterate, and 30.2% had elementary-level education. Most participants (76.2%) were married.

Table 1 Demographic characteristics of respondents in the common bean anthracnose survey

Characteristics	Wonago (n=22)	Abba- ya (n=20)	Dilla Zuria (n=21)	Total (n=63)
Gender				
Male	15 (68.2)	14 (70.0)	15 (71.4)	44 (69.8)
Female	7 (31.8)	6 (30.0)	6 (28.6)	19 (30.2)
Age groups				
18–30 years	2 (9.1)	2 (10.0)	2 (9.5)	6 (9.5)
31–40 years	4 (18.2)	5 (25.0)	4 (19.0)	13 (20.6)
41–50 years	9 (40.9)	8 (40.0)	8 (38.1)	25 (39.7)
51–60 years	5 (22.7)	4 (20.0)	4 (19.0)	13 (20.6)
Over 60 years	2 (9.1)	1 (5.0)	3 (14.3)	6 (9.5)
Marital status				
Single	3 (13.6)	2 (10.0)	2 (9.5)	7 (11.1)
Married	16 (72.7)	15 (75.0)	17 (81.0)	48 (76.2)
Divorced/Widowed	3 (13.6)	3 (15.0)	2 (9.5)	8 (12.7)
Education				
Illiterate	8 (36.4)	7 (35.0)	7 (33.3)	22 (34.9)
Elementary	7 (31.8)	6 (30.0)	6 (28.6)	19 (30.2)
Secondary	4 (18.2)	4 (20.0)	5 (23.8)	13 (20.6)
Diplom and above	3 (13.6)	3 (15.0)	3 (14.3)	9 (14.3)

Values are number (percentage). Percentages may not sum to 100 due to rounding

Occurrence, Incidence, and severity of common bean anthracnose

Anthracnose was observed in all surveyed districts with varying intensity (Fig. 1). Wonago district showed the highest disease incidence (61.23%) and severity (29.95%), while Abbaya district had the lowest (43.42% incidence, 24.62% severity) (Table 2).

Altitude significantly influenced disease levels, with the highest incidence (64.19%) and severity (32.16%) recorded at elevations above 2000 m a.s.l. Local bean varieties showed higher disease intensity (54.12% incidence, 28.43% severity) compared to improved varieties (38.75%, 21.14%). Agronomic practices including sole cropping, broadcast sowing, absence of fertilizer application, and poor weed management were associated with significantly higher disease levels.

Analysis of variance confirmed that district, altitude, variety type, cropping system, fertilization, weed management, and sowing method significantly affected both disease incidence and severity ($p < 0.05$), while crop growth stage did not show significant effects (Table 3).

Association of common bean anthracnose with biophysical factors (Logistic Regression)

The influence of various biophysical factors on the probability of high anthracnose incidence and severity was quantified using logistic regression (Table 4). The likelihood ratio test confirmed that district, altitude, variety type, cropping system, fertilization, weed management,

and sowing method were significant predictors of disease intensity.

The analysis revealed strong spatial and altitudinal trends. Farms in Wonago district had a significantly higher probability of high disease incidence compared to other districts ($p < 0.001$). Similarly, altitude was a major risk factor, with fields above 2000 m a.s.l. showing a substantially greater likelihood of both high incidence and high severity ($p < 0.001$).

Crop management practices significantly altered disease risk. Sole cropping was associated with a significantly increased probability of higher disease incidence and severity compared to intercropping ($p < 0.001$). The use of local varieties resulted in a higher likelihood of high disease incidence compared to improved varieties ($p = 0.045$). Fields where fertilizer was not applied had a significantly greater probability of high incidence ($p = 0.008$). Poor weed management was a critical risk factor, significantly increasing the probability of high incidence ($p < 0.001$). Furthermore, broadcast sowing was associated with a higher likelihood of high disease incidence compared to row sowing ($p = 0.014$). The crop growth stage was not a consistent significant factor in the model.

LRT = likelihood ratio test; VEF = variable entered first; VEL = variable entered last; DR = deviance reduction; P = probability of an χ^2 value exceeding the deviance reduction; χ^2 = chi-square; and df = degrees of freedom.

Characterization of causal pathogen of common bean anthracnose

Fifteen *Colletotrichum lindemuthianum* isolates were successfully obtained from symptomatic samples. Morphological characterization revealed variability in growth rate (66.7% slow-growing, 33.3% moderate-growing) and colony texture (60% velvety, 40% cottony). Colony colors varied, with gray being most common on the front (26.7%) and dark gray on the reverse (40.0%) (Table 5). It should be noted that identification was based on morphological characteristics only; molecular confirmation would be required for definitive species identification and to assess potential genetic diversity within the population.

Values are mean $\pm$ standard error of three replications for colony growth (mm). Means followed by different superscript letters are significantly different at $p < 0.05$ according to LSD test.

The results revealed that the conidial length and width varied significantly among isolates, with Kara-002 and Sis-002 having the largest conidia, and Hand-001 and Tum-002 having the smallest. The largest conidia length and width may indicate high sporulation potential or adaptability to specific conditions.

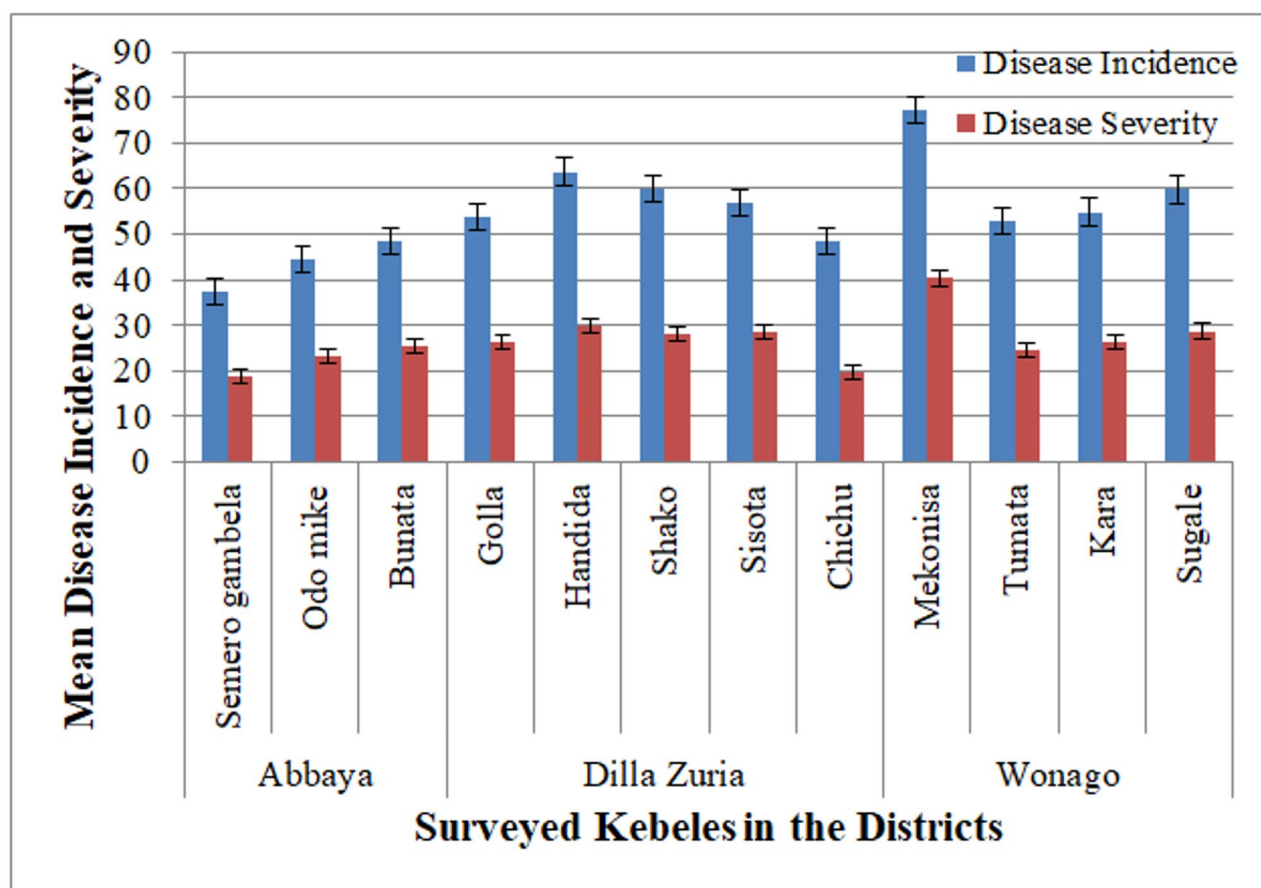


Fig. 1 Disease incidence and severity of common bean anthracnose across the study districts. Error bars represents the 95% confidence intervals. Differences between locations were considered significant at $p < 0.05$ based on the LSD test

Conidial dimensions varied significantly among isolates, with length ranging from 11.9 μm to 18.4 μm and width from 3.7 μm to 5.9 μm (Table 6). Conidia were predominantly cylindrical (66.7%), with the remainder slightly curved.

Values are mean $\pm$ standard error of 50 conidia per isolate for conidial dimensions (μm). Means followed by different superscript letters are significantly different at $p < 0.05$ according to LSD test.

The study further showed that 66.7% of isolates had cylindrical conidia shape, while 33.3% of the isolates had slightly curved conidia. Cylindrical conidia are characteristic of *Colletotrichum lindemuthianum* and are frequently linked to effective dissemination and infection. (Fig. 2).

In vitro antagonistic effect of trichoderma spp. Against *Colletotrichum lindemuthianum*

The dual culture assay revealed that all five *Trichoderma* species significantly inhibited the mycelial growth of *Colletotrichum lindemuthianum*, but their efficacy varied significantly ($p < 0.05$) both among species and in their interaction with different pathogen isolates. *Trichoderma*

viride was the most effective antagonist overall, showing a maximum mycelial inhibition percentage of 90.34%. It was followed by *Trichoderma asperellum*, *Trichoderma atroviride*, *Trichoderma harzianum*, and *Trichoderma longibrachiatum*.

A highly significant ($p < 0.05$) interaction was observed between *Trichoderma* species and *Colletotrichum lindemuthianum* isolates, indicating that the biocontrol efficacy was isolate-specific. The maximum mycelial inhibition (90.34%) was recorded in the interaction between the *Colletotrichum lindemuthianum* isolate Goll-002 and *Trichoderma viride*. In contrast, the minimum inhibition (59.39%) was observed when the isolate Han-002 was paired with *Trichoderma viride*, demonstrating that even the most potent antagonist's performance can be modulated by the specific pathogen strain it encounters (Table 7). It is important to note that these results represent in vitro conditions only; field efficacy may differ due to environmental factors and plant-pathogen-antagonist interactions.

Table 2 Mean disease incidence and severity of common bean anthracnose across different biophysical variables

Variable	Category	Incidence (%)	Severity(%)
Districts	Abbaya	43.42	24.62
	Dilla Zuria	56.92	26.62
	Wonago	61.23	29.95
Fertilizer	Applied	47.25	25.89
	Not applied	56.34	29.47
Cropping system	Sole cropping	52.64	30.12
	Intercropping	49.83	25.67
Altitude (ma.s.l)	< 1500	45.28	23.87
	1500–2000	53.67	27.34
	2000	64.19	32.16
Type of variety	Local	54.12	28.43
	Improved	38.75	21.14
Weed management	Poorly	55.67	29.12
	moderately	50.23	26.45
	Well managed	45.89	17.78
Crop growth stage	Vegetative	51.34	26.78
	Flowering	53.67	27.34
	Podding	52.12	28.43
	Maturity	48.75	25.14
Method of sowing	Broadcast	54.21	28.56
	Row	45.78	21.89

m a.s.l. = meters above sea level

Discussion

Demographic characteristics of respondents and implications for anthracnose management

The demographic profile surveyed by farmers provides the important context for developing anthracnose management strategies in Gedeo and West Guji zones. The observed gender imbalance, with male respondents comprising nearly 70% of participants, reflects broader agricultural decision-making patterns in Ethiopian small-holder systems (Kebede et al. 2022). This disparity suggested that extension programs must ensure both male and female farmers receive information about integrated disease management approaches (Doss 2013).

The age distribution, with the most farmers (39.7%) aged 41–50 years, indicated that experienced individuals dominate bean cultivation. However, the low participation of youth (9.5% under 30 years) raises concerns about future sustainability, a challenge also noted in assessments of agricultural labor dynamics in Ethiopia (White 2012; Bezu and Holden 2014).

High illiteracy rates (34.9%) indicates the inadequacy of text-based extension materials. Visual, participatory methods such as farmer field schools would be more effective for communicating concepts like anthracnose identification, Trichoderma application, and resistant

Table 3 Analysis of variance of the effects of independent factors on common bean anthracnose incidence and severity

Source of variation	Disease incidence				Disease severity			
	df	Ms	F-value	p-value	df	Ms	F-value	p-value
District	2	120.45	12.0	< 0.001***	2	140.	14.23	< 0.001***
Altitude	2	180.23	18.76	< 0.001***	2	0.45	21.45	< 0.001***
Variety	1	50.34	5.34	0.021*	1	0.12	6.12	0.013*
Cropping System	1	95.67	9.87	0.002**	1	110.34	11.34	< 0.001***
Fertilization	1	70.12	7.23	0.008**	1	85.67	0.56	0.004**
weed Manag'n't	2	150.89	0.67	< 0.001***	2	180	18	< 0.001***
Growth Stage	3	14	1.45	0.342NS	3	1234	1.23	0.251NS
Sowing Method	1	65.78	6.78	0.0014**	1	75.89	7.89	0.009*

df: Degree of freedom; MS: Mean Square; NS: Not Significant. *, **, *** imply significance at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively**Table 4** Logistic regression model evaluating the association of biophysical factors with high common bean anthracnose incidence and severity

Variable	Disease incidence LRT					Disease severity LRT			
	df	Type 1 analysis (VEF)		Type 3 analysis (VEL)		Type 1 analysis (VEF)		Type 3 analysis VEL	
		DR	P χ^2	DR	P χ^2	DR	P χ^2	DR	P χ^2
District	1	15.42	<0.0001	18.75	<0.0001	12.86	<0.0001	10.33	0.006**
Altitude	2	8.76	0.01	6.45	0.04	7.89	0.02	5.12	0.08*
Variety	1	6.34	0.01	0.88	0.024*	5.78	0.01	0.65	0.013 *
Cropping System	1	14.28	<0.0001	3.45	0.02	22.15	<0.0001	9.87	<0.001***
Fertilization	1	7.25	0.007	1.12	0.005**	10.33	<0.001	0.45	0.003**
Weed Manag'nt	2	11.47	0.003	5.23	0.07	18.64	<0.0001	4.12	<0.001***
Growth Stage	3	3.45	0.33	4.56	0.03	2.10	0.35	1.23	0.54ns
Sowing Method	1	9.63	<0.001	2.15	0.009**	8.92	<0.001	1.98	0.016*

Table 5 Morphological characterization of *Colletotrichum lindemuthianum*

Isolates	Colony		Colony color		Colony growth
	Growth	Texture	Front	Reverse	Aerial (mm)
Sam-001	Slow	Cottony	Greenish gray	Dark gray	60.7 ^d
Tum-001	Medium	Cottony	White gray	Black gray	48.8 ^{ef}
Sug-001	Slow	Velvety	Dark gray	Dark brown	70.6 ^a
Kara-001	Slow	Cottony	Olivaceous	Purple gray	60.5 ^d
Goll-001	Medium	Cottony	White	White gray	70.8 ^a
Buno-001	Medium	Cottony	White gray	Black gray	45.1 ^g
Tum-002	Slow	Velvety	Olive brown	Gray	70.5 ^{ab}
Mek-001	Slow	Velvety	Olive brown	Dark gray	34.3 ^h
Kara-002	Medium	Velvety	Gray	Black	67.4 ^{bc}
Hand-002	Slow	Velvety	Dark gray	Dark	67.4 ^{bc}
Hand-003	Slow	Cottony	White gray	Dark	46.6 ^{fg}
Sis-001	Slow	Velvety	Dark gray	Dark	59.2 ^d
Sis-002	Slow	Velvety	Gray	Dark gray	51.9 ^e
Hand-001	Medium	Velvety	Greenish gray	Black	66.6 ^c
Goll-002	Slow	Velvety	Dark gray	Dark	51 ^e
Lsd					3.1
Cv					4.4

variety use, an approach validated in extension studies (Quisumbing et al. 2014).

In this study, the predominance of married households (76.2%) suggested that household-level approaches may enhance the adoption of integrated practices requiring collective labor and decision-making. This demographic trend underscores the need to demonstrate that improved bean production with integrated pest management can be economically viable.

Factors influencing the Occurrence, Incidence, and severity of common bean anthracnose

The widespread occurrence of anthracnose across all surveyed districts confirms its status as a major production constraint in southern Ethiopia (Hussien et al. 2020). The pronounced spatial variation, with Wonago District as a disease hotspot, demonstrates how localized agro-ecological and management factors drive epidemics.

The strong positive correlation between disease intensity and altitude aligns with *Colletotrichum lindemuthianum* epidemiology (González et al. 2019; Tesfaye et al. 2020). High elevations (>2000 m a.s.l.) experience cool temperatures and high humidity, conditions that favor conidial germination and disease development.

The superior performance of improved varieties over local landraces emphasizes genetic resistance's critical role in anthracnose management. This finding strongly

supports prioritizing resistant variety dissemination as an integrated management cornerstone, a strategy emphasized in regional breeding programs (Nkal et al. 2018).

Agronomic practices substantially influenced disease levels. The lower disease incidence in intercropped systems supports the “dilution effect” observed in similar legume-based cropping systems (Mwangi et al. 2021). Similarly, row sowing improves air circulation, reduces canopy humidity, and shortens leaf wetness duration, creating less favorable conditions for pathogen development.

The reduction of disease in fertilized plots suggests enhanced plant vigor contributes to disease resistance, while poor weed management increases disease risk, as weeds can serve as alternative reservoirs for *Colletotrichum lindemuthianum* and elevate canopy humidity. The significant role of weed management in disease epidemiology has been highlighted in integrated management studies (Silva et al. 2020).

It is important to note that while various agronomic factors were significantly associated with disease levels, this observational study cannot establish causal relationships. Experimental verification under controlled conditions is needed to confirm these interactions.

Quantifying disease risk through biophysical factors

Logistic regression provided a probabilistic model quantifying the risk associated with key biophysical factors (Table 4). Farms located at higher elevations (>2000 m a.s.l.) showed a significantly greater likelihood of high disease incidence and severity, confirming the pathogen's preference for cool, humid highland conditions (Tesfaye et al. 2020).

Similarly, Wonago District emerged as a high-risk area, likely due to the combined influence of favorable environmental conditions and prevalent local agronomic practices.

Improved crop management significantly reduced disease risk. Intercropping provided protection by disrupting spore dispersal, supporting the “dilution effect” documented in similar cropping systems (Mwangi et al. 2021).

Our results showed that fertilized fields exhibited a substantially lower probability of high disease incidence, underscoring the role of plant vigor in disease resistance through enhanced physical and biochemical defenses, a concept supported by previous research (Niyibigira et al. 2019).

The use of local varieties was associated with a higher probability of high disease incidence compared to improved varieties in our survey, providing statistical support for the deployment of resistant improved varieties, as recommended in regional breeding programs (Nkal et al. 2018).

Table 6 Cultural characterization of *Colletotrichum lindemuthianum*

Isolates	Conidial length (µm)	Conidial width (µm)	Conidia shape
Sam-001	13.4 ^c	4.7 ^{cd}	Cylindrical
Tum-001	13.2 ^c	4.7 ^{cd}	Slightly curved
Sug-001	12.6 ^c	4.9 ^b	Cylindrical
Kara-001	13.3 ^c	4.7 ^{cd}	Cylindrical
Goll-001	13.3 ^c	4.8 ^{bc}	Slightly curved
Buno-001	13.7 ^{bc}	4.9 ^{bc}	Cylindrical
Tum-002	12.4 ^c	3.7 ^e	Cylindrical
Mek-001	14.4 ^b	5.1 ^b	Cylindrical
Kara-002	18.4 ^a	5.9 ^a	Slightly curved
Hand-002	15.1 ^b	5.5 ^{ab}	Cylindrical
Hand-003	14.5 ^b	3.7 ^e	Slightly curved
Sis-001	13.5 ^{bc}	4.1 ^{de}	Cylindrical
Sis-002	18.2 ^a	5.8 ^a	Cylindrical
Hand-001	11.9 ^c	3.9 ^e	Cylindrical
Goll-002	15 ^b	5.4 ^{ab}	Slightly curved
LSD	2.1	0.7	
CV	6.9	7.3	

Poor weed management emerged as one of the strongest risk factors in our analysis, highlighting a manageable intervention point for disease control, consistent

with integrated disease management principles (Silva et al. 2020).

Pathogen diversity and management implications

The morphological and cultural variability among fifteen *Colletotrichum lindemuthianum* isolates indicates a diverse pathogen population in the study areas. The predominance of slow-growing isolates (66.7%) may reflect adaptation to cool highland conditions, a trait observed in fungal populations from similar environments.

Considerable conidial size and shape variation further confirms distinct strains within the local *Colletotrichum lindemuthianum* population, a diversity also reported in *Colletotrichum* species from other bean-growing regions (Silva et al. 2018; Mungalu et al. 2023).

A key limitation of this study is that pathogen characterization relied solely on morphological features; molecular analysis is needed for definitive species confirmation, as is now standard practice in phytopathological research (Alves et al. 2017; Sharma et al. 2015).

The pathogen diversity observed in this study underscores the importance of comprehensive management strategies. Based on our findings, breeding programs should focus on developing varieties with

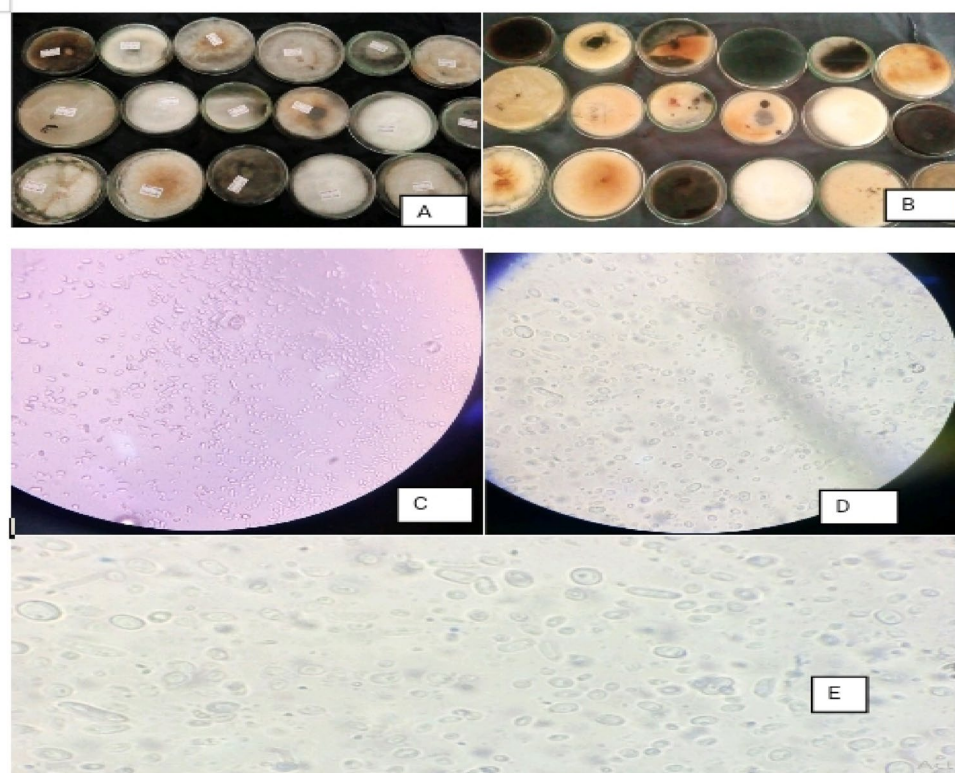


Fig. 2 Cultural and morphological characteristics of *Colletotrichum lindemuthianum*. (a) Front view and (b) reverse view of colony growth of different *Colletotrichum lindemuthianum* isolates on PDA. (c) Conidia morphology of *Colletotrichum lindemuthianum* isolate observed 10x (d and e) conidia morphology of *Colletotrichum lindemuthianum* isolate observed 40x

Table 7 The interaction of *Trichoderma* spp. And *Colletotrichum lindemuthianum* isolates on mycelial growth Inhibition (%)

No.	Treatment interaction	Mean(%)	No.	Treatment interaction	Mean(%)
1	Golla002* <i>Trichoderma viridea</i>	90.34 ^a	31	Han001* <i>Trichoderma harzianum</i>	74.77 ^{c-k}
2	Golla002* <i>Trichoderma harzianum</i>	89.75 ^{ab}	32	Sam001* <i>Trichoderma atroviridea</i>	74.71 ^{c-k}
3	Han001* <i>Trichoderma viridea</i>	89.29 ^{ab}	33	Tuma001* <i>Trichoderma asperellum</i>	74.69 ^{c-k}
4	Golla002* <i>Trichoderma longibrachiatum</i>	84.074 ^{a-c}	34	Tuma001* <i>T. longibrachiatum</i>	73.82 ^{d-l}
5	Sis001* <i>Trichoderma viridea</i>	83.58 ^{a-c}	35	Mek001* <i>Trichoderma asperellum</i>	73.58 ^{d-l}
6	Sis001* <i>Trichoderma asperellum</i>	81.85 ^{b-d}	36	Golla001* <i>Trichoderma atroviridea</i>	73.33 ^{d-m}
7	Sug001* <i>Trichoderma asperellum</i>	81.481 ^{a-e}	37	Mek001* <i>Trichoderma atroviridea</i>	73.27 ^{d-m}
8	Golla001* <i>Trichoderma longibrachiatum</i>	80.648 ^{b-f}	38	Mek001* <i>Trichoderma longibrachiatum</i>	72.84 ^{d-m}
9	Mek001* <i>Trichoderma viridea</i>	80.11 ^{b-g}	39	Sam001* <i>Trichoderma asperellum</i>	72.54 ^{d-m}
10	Sug001* <i>Trichoderma atroviridea</i>	79.03 ^{c-h}	40	Tuma001* <i>Trichoderma harzianum</i>	72.32 ^{d-m}
11	Sis001* <i>Trichoderma atroviridea</i>	78.42 ^{c-i}	41	Sam001* <i>Trichoderma longibrachiatum</i>	72.15 ^{e-m}
12	Golla002* <i>Trichoderma asperellum</i>	78.27 ^{c-i}	42	Han003* <i>Trichoderma longibrachiatum</i>	71.73 ^{f-m}
13	Golla001* <i>Trichoderma harzianum</i>	78.04 ^{c-i}	43	Kara001* <i>Trichoderma harzianum</i>	71.11 ^{f-m}
14	tuma001* <i>Trichoderma viridea</i>	78.03 ^{c-i}	44	Han003* <i>Trichoderma harzianum</i>	71.04 ^{f-m}
15	Kara001* <i>Trichoderma atroviridea</i>	77.16 ^{c-j}	45	Han003* <i>Trichoderma atroviridea</i>	70.95 ^{g-m}
16	Kara001* <i>Trichoderma asperellum</i>	77.11 ^{c-j}	46	Sis002* <i>Trichoderma atroviridea</i>	70.52 ^{g-m}
17	Tuma001* <i>Trichoderma atroviridea</i>	76.42 ^{c-j}	47	Han001* <i>Trichoderma asperellum</i>	70.37 ^{h-m}
18	Sug001* <i>Trichoderma harzianum</i>	76.17 ^{c-j}	48	Sis001* <i>Trichoderma harzianum</i>	69.36 ^{h-m}
19	Sug001* <i>Trichoderma viridea</i>	76.17 ^{c-j}	49	Han003* <i>Trichoderma viridea</i>	69.29 ^{i-m}
20	Golla001* <i>Trichoderma asperellum</i>	76.14 ^{c-j}	50	Sam001* <i>Trichoderma harzianum</i>	69.25 ^{i-m}
21	Sam001* <i>Trichoderma viridea</i>	76.12 ^{c-j}	51	Mek001* <i>Trichoderma harzianum</i>	69.01 ⁱ⁻ⁿ
22	Golla002* <i>Trichoderma atroviridea</i>	76.11 ^{c-j}	52	Han002* <i>Trichoderma atroviridea</i>	68.10 ^{j-n}
23	Sug001* <i>Trichoderma longibrachiatum</i>	76.09 ^{c-j}	53	Sis002* <i>Trichoderma viridea</i>	67.56 ^{j-n}
24	Kara001* <i>Trichoderma viridea</i>	76.05 ^{c-j}	54	Sis002* <i>Trichoderma longibrachiatum</i>	66.22 ^{k-n}
25	Golla001* <i>Trichoderma viridea</i>	76.05 ^{c-j}	55	Han001* <i>Trichoderma longibrachiatum</i>	66.17 ^{k-n}
26	Sis001* <i>Trichoderma longibrachiatum</i>	75.12 ^{c-k}	56	Han002* <i>Trichoderma harzianum</i>	65.55 ^{k-n}
27	Sis002* <i>Trichoderma asperellum</i>	74.98 ^{c-k}	57	Han002* <i>Trichoderma longibrachiatum</i>	64.74 ^{l-n}
28	Sis002* <i>Trichoderma harzianum</i>	74.96 ^{c-k}	58	Han002* <i>Trichoderma asperellum</i>	64.49 ^{l-n}
29	Han003* <i>Trichoderma asperellum</i>	74.95 ^{c-k}	59	Han001* <i>Trichoderma atroviridea</i>	63.84 ^{mn}
30	Kara001* <i>Trichoderma longibrachiatum</i>	74.94 ^{c-k}	60	Han002* <i>Trichoderma viridea</i>	59.39 ⁿ
	Cv	8.05			8.05
	LSD	9.68			9.68

Means followed by the same letter in a column are not significantly different according to the Least Significant Difference (LSD) test at $p < 0.05$. CV = 8.05%, LSD = 9.68
 The antagonistic interaction between *Trichoderma* species and *C. lindemuthianum* on dual culture plates is visually presented in Fig. 3

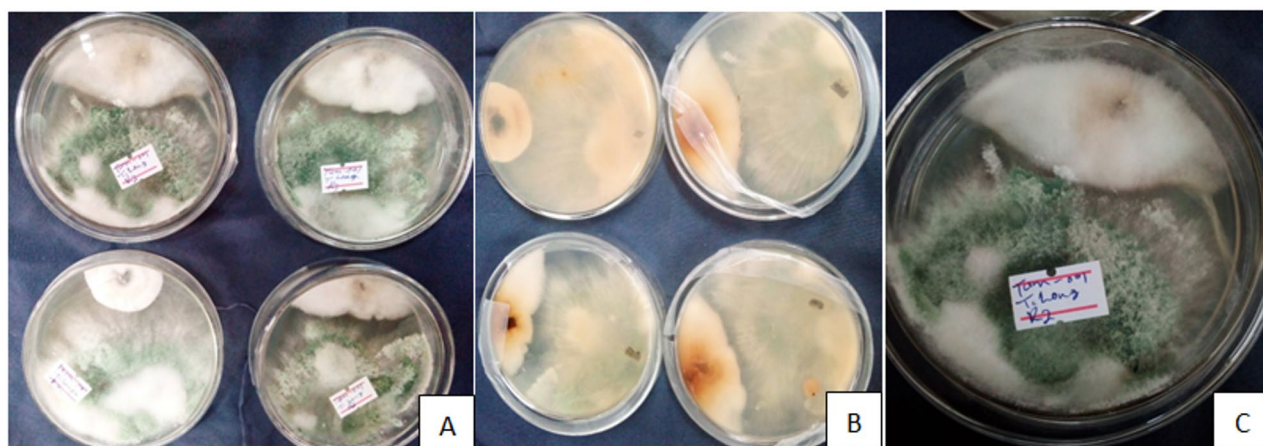


Fig. 3 Dual culture of different *Trichoderma* spp with *Colletotrichum lindemuthianum*. (a) Front view and (b) reverse view of dual culture and (c) *Colletotrichum lindemuthianum* isolate Tuma001 and *Trichoderma longibrachiatum* in PDA

broad-spectrum resistance to manage such a variable pathogen population effectively.

Biocontrol Potential, antagonistic Specificity, and future directions

The results confirm the potential of native *Trichoderma* species as biocontrol agents against *Colletotrichum lindemuthianum*, supporting contemporary research on *Trichoderma* as a sustainable biocontrol agent. The superior performance of *Trichoderma viride* is consistent with recent reports highlighting its strong antagonistic and growth-promoting activities (Kashyap et al. 2021; Mukherjee et al. 2022).

In our in vitro assays, the observed antagonism likely involves multiple mechanisms. Visible overgrowth and colonization indicate mycoparasitism, while clear inhibition zones suggest the production of diffusible antifungal metabolites, which are well-documented modes of action for *Trichoderma* species (Gupta et al. 2022).

Critically, the significant species isolate interaction demonstrates that biocontrol efficacy is highly specific to both antagonist and pathogen strains. This specificity emphasizes the need for screening and selecting *Trichoderma* strains against prevalent local pathogen populations, a principle recognized in biocontrol research (Druzhinina et al. 2011).

A major limitation of this study is that these findings are based solely on in vitro conditions; field efficacy may differ substantially due to environmental factors, formulation stability, and complex plant-pathogen-antagonist interactions (Pandey et al. 2023). Field validation is essential to translate this in vitro potential into practical application methods.

Conclusions

The present study concludes that common bean anthracnose, caused by *Colletotrichum lindemuthianum*, poses a significant threat to bean production in the Gedeo and West Guji zones of Ethiopia. This survey revealed the marked spatial variation in disease intensity was observed, with Wonago District identified as a high-risk area, while Abbaya District recorded low disease pressure.

Logistic regression analysis identified key biophysical and agronomic associated with disease epidemics, including district, altitude, cropping system, fertilization, and weed management. The model demonstrated increased risk associated with practices such as sole cropping and poor weed control. In parallel, morphological characterization revealed considerable diversity among *Colletotrichum lindemuthianum* isolates, suggesting the need for management strategies that account for this variability.

Importantly, in vitro antagonism assays demonstrated strong inhibitory activity of *Trichoderma* species against the pathogen, with *Trichoderma viride* exhibiting the highest inhibition under controlled conditions. These in vitro findings suggest potential for further investigation of biological control within integrated disease management strategies.

To mitigate impact of anthracnose, farmers are recommend to adopt resistant bean varieties, implement intercropping and row sowing, apply balanced fertilization, and improve weed management. Extension services should prioritize farmer training and access to improved seed and pathogen such as *Trichoderma viride*. Future research should emphasize on molecular characterization of local pathogen populations and the development of farmer-friendly biocontrol formulations validated under field conditions. Integrated implementation of these strategies, combining improved varieties, cultural practices and biological control, is essential for sustainable anthracnose management and safeguarding bean productivity in the region.

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Author contributions

corresponding author reviewed.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable. This study involved only field surveys and laboratory experiments with plant materials. No human participants or animals were used in trials beyond anonymous farmer surveys for agronomic data, which did not require ethical approval.

Consent for publication

Not applicable. This manuscript does not contain any individual person's data, images, or videos.

Competing interests

The authors declare no competing interests.

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