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Soil physico-chemical properties and microbial diversity on chilli anthracnose disease severity in Northern Karnataka, India

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ABSTRACT

Chilli anthracnose disease causes a huge commercial loss in the globe. Studying soil physico-chemical properties is crucial to understand chilli anthracnose because these properties significantly affect the efficacy of biocontrol agents and herbicides used to manage the disease. This study aimed to evaluate the relative percentage of disease incidence (% DI) of chilli anthracnose in dominant chilli growing areas of Northern Karnataka in India and its relationship to soil properties. The soil physico-chemical (texture, moisture, density, pH, EC, OC, N, P, K, Ca, Mg, S, Zn, Cu, Fe, and B) properties, microbial (fungi and bacteria) diversity of 17 soil samples were analysed by standard protocols and evaluated their correlation with % DI, using Pearson correlation and cluster analysis method. Highest % DI was found in Shira with more value of pH (8.45), and Mg (14.63 meq 100 g^{-1}), whereas in Nela with more value of EC (0.38%), moisture (46%), and Ca (33.83 meq 100 g^{-1}), and also in the regions where the beneficial microbes were less in number (Tegg, Shira, Agad and Nela). The results obtained from Pearson correlation indicated that % DI was positively correlated to moisture ($r=0.851^{**}$, $P=0.01$), EC ($r=0.488^{*}$, $P=0.05$) and negatively correlated to *Pseudomonas* sp. ($r=-0.322^{*}$, $P=0.05$). The present study provides comprehensive information about the role of physical, chemical and biological properties of soil characteristics responsible for the development of anthracnose disease prevalence and reducing soil quality as well as chilli production under natural conditions.

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1. INTRODUCTION

Olericulture in the horticulture industry dealing with the production of vegetables is one of the most considerable sectors that can improve food security, provide employment and contribute towards economic growth, in which chilli (*Capsicum annuum* L.), the 'wonder spice' is an essential vegetable, cultivated throughout the world, area covering about 1,832 thousand hectares, and the production 2,959 thousand tonnes (Jaskani & Khan, 2021; Yadav et al., 2024). Worldwide, the leading producers and exporters are China, India, Pakistan, Morocco, Mexico, Thailand and Turkey. During 2021, India cultivated chilli on approximately 7.3 million hectares of land, resulting in the production of 1.988 million tonnes (Jalgaonkar et al., 2023). Universally, India was the key producer and exporter of chilli, following a decline in chilli production, India has slipped to the third position in terms of global production hierarchy (FAOSTAT, 2019) Worldwide 400 varieties of chilli are available with different pungency, size, colors, shape, and its usage; among them, 50 varieties from India contribute about 36% to the total world production. Karnataka, Andhra Pradesh, West Bengal,

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Maharashtra, Orissa, Tamil Nadu, Uttar Pradesh, and Rajasthan are the top chilli producing states in India (Rao & Rao, 2014). Driving the country's overall production, Raichur, Bellary, and Byadagi are the major trading centres of chilli and chilli powder in Karnataka (Malathi et al., 2022). Chilli offers numerous culinary and nutritional benefits; it contains a diverse range of bioactive compounds, including volatile oils, capsaicinoids, fatty acids, carotenoids, protein, vitamins, mineral elements, and fibers (Villa-Rivera & Ochoa-Alejo, 2020). Chillies contain less sodium, are cholesterol-free, and are abundant in Vitamins A, C, and E and minerals like potassium, iron, magnesium, and folic acid (Reddy, 2023). Globally plant crop production is principally caused due to biotic stress, despite the fact, that chilli seed production and fruit yield are drastically declined because of various biotic and abiotic constraints (Pandey et al., 2017)(Pandey et al., 2017). Jayaraman et al. (2021)Jayaraman et al. (2021) stated that the key epidemiological factors such as chemical, physical, and biological properties of soil can significantly influence the dynamics of the plant disease occurrence and severity. The pH, nitrogen, and phosphorus content in soil play an important role in the growth, survival and susceptibility of the host, multiplication and infectivity of the pathogen (Elmer & Datnoff, 2014; Razaq et al., 2017). Literature has revealed that indigenous microbial communities present in soil harbor specific subpopulations that exhibit pathogen-suppressive properties, conferring protection to host plants against infectious diseases (Shen et al., 2015). The intricate relation among the properties of soil and the microorganism behavior has been the subject of extensive research; however, a comprehensive understanding of interactions remains elusive (Kabir et al., 2024). Soil is the residence of a large group of microorganisms (Setiawati et al., 2023). Soil functions include plant growth promoting mechanisms, such as, nutrient supply, water retention and conductivity, support of soil food webs, and environmental regulatory functions like nutrient cycling, source of microbial diversity, remediation of pollutants, and sequestration of heavy metals (Elmer & Datnoff, 2014; Razaq et al., 2017). One of the most destructive diseases restricting chilli production is anthracnose, caused by *Colletotrichum* sp. (De Silva et al., 2021).

The transmission of pathogen can occur through seeds, soil, and air, which is prevalent in most of the chilli-growing regions, resulting in losses of 40% to 50% in various parts of India (Rai et al., 2020). 50% of the chili production in Malaysia and 15% yield loss in Korea (Ridzuan et al., 2018) have been recorded. An annual chili production loss of more than 35% in Indonesia and an approximately 80% yield loss (caused by severe epidemics in Thailand, and Brazil, United States were also facing same contest (Ridzuan et al., 2018). Anthracnose, a disease caused by *Colletotrichum* spp., which poses a major threat to chilli crops, leading to significant losses in production. Traditionally, identification of species relied on physical characteristics, are limited by variations within species can be large, making it hard to define a specific species and some species have rare teleomorphic stage, making identification even more challenging. Advanced genomic approaches includes multigene phylogenetic analyses distinguish *Colletotrichum* species. *C. nymphaeae*, *C. karstii*, *C. fructicola*, *C. kahawae*, *C. siamense*, *C. gloeosporioides*, *C. cliviae*, *C. truncatum*, *C. coccodes* and *C. jasminigenum*, *C. brevisporum*, were reported in India, causing chilli anthracnose (Mongkolporn & Taylor, 2018). Typical anthracnose symptoms found on both green and ripe fruits include water soaked sunken necrotic lesions with black acervuli fruiting bodies arranged in concentric rings (Mongkolporn, 2019). Predominantly, orange to pink conidial mass appear on the fruit surface. The pathogen produces destructive dark spots that contain conidia. These conidia can survive in plant debris, seeds, or soil as dormant structures called microsclerotia and mycelium. These survival structures allow the pathogen to endure unfavorable conditions and remain infectious, ready to infect chilli plants when conditions become favorable. The annual yield loss of chilli due to anthracnose has been reported to vary by about 10% (Saxena et al., 2016). Interaction between soil physico-chemical parameters and microbes is essential for the effective disease control in agricultural systems (Naseri & Ansari Hamadani, 2017). Although, before applying fertilizers and fungicides into the field it is very much imperative to analyze the quantity and quality of the nutrients because these not only enhance vegetative growth but also increase yield components, chemical constituents, and overall plant health, by showcasing their essential role in maximizing chilli production and quality. A literature review has revealed that there are very limited studies concentrating on the influence of soil parameter on chill anthracnose disease prevalence. In this perspective, the primary goal of present work is to examine and assess the combination of soil physico-chemical and microbial parameters that affect the severity of chilli anthracnose disease and to identify potential factors that contribute to disease severity.

2. MATERIALS AND METHODS

2.1. Soil sampling locations

A roving survey was supported to collect rhizospheric soil from major chilli cultivating districts of Northern Karnataka, India including, Dharwad, Gadag, Haveri, Raichur, Vijayanagara, and Bellari, during November 2022 to February 2023 across different agro-climatic zones of North Karnataka, (Fig. 1, Table 1). Rhizospheric soil samples were collected from seventeen chill crop field locations. From each sampling location, we collected 5-20 soil samples in a zig-zag pattern to accurately represent the area, depending on the size of the land and its variability; these individual samples were combined into one individual sample to capture the range of soil characteristics within that location. About 100 g of soil samples were taken at depths of 0-30 cm below the soil surface. Initially, samples were sieved to eradicate the plant debris and stones, dehumidified, and crushed into 2 mm constituents for subjecting to physical, chemical, and microbial analysis.

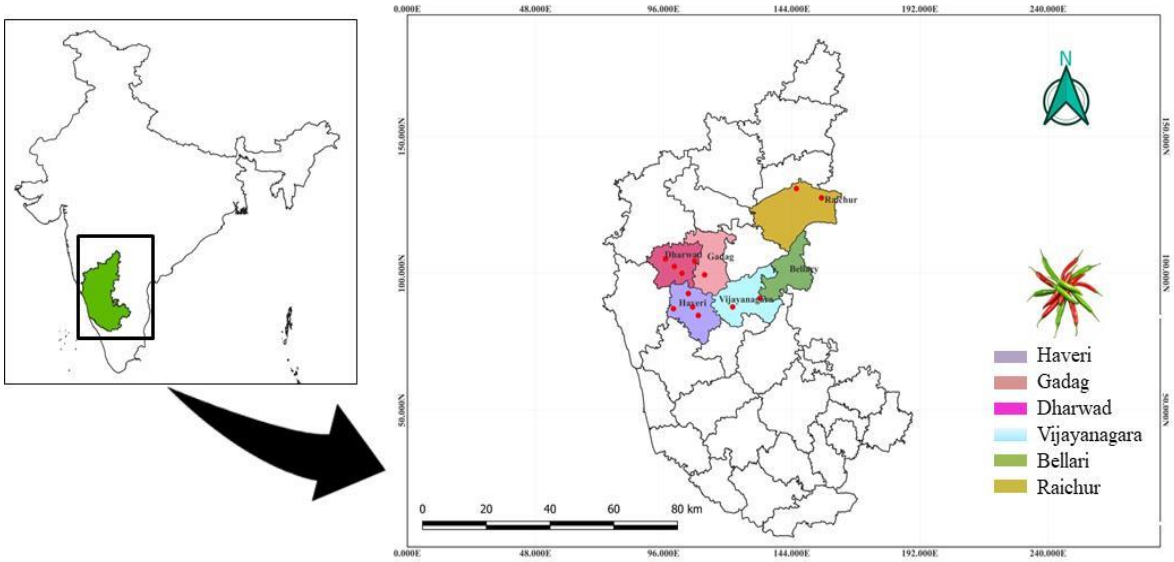

Figure 1. Karnataka map depicting the geographical location of soil samples collected from different areas

Table 1. Soil samples collection location and their coding from different agro-climatic zones of Northern Karnataka

Place of collection			GPS		Altitude above the sea level (m)
District	**Village**	**Code**	**Latitude (°N)**	**Longitude (°E)**	
Haveri	Agadi	Agad	14.829578	75.462950	558
	Aladakatti	Alad	14.780158	75.358172	558
	Maranbeed	Mara	14.827885	75.259091	572
	Krishnapur	Kris	14.950340	75.465135	584
	Teggihalli	Tegg	14.915697	75.457445	584
	Hedigonda	Hedi	14.697422	75.387911	572
	Hombaradi	Homb	14.706508	75.41513	572
Gadag	Shiratti	Shir	15.222889	75.533194	659
	Kurtakoti	Kurt	15.359193	75.557021	655
Dharwad	Nelagudda	Nela	15.137556	75.137556	636
	Kusugal	Kusu	15.371867	75.225694	750
	Annigeri	Anni	15.444263	75.463892	624
	Shiraguppi	Shira	15.331210	75.283816	600
Vijayanagar	Harapanhalli	Harp	14.781224	76.035880	633
	Somalapur	Soml	15.030553	76.486646	508
Bellari	Kudligi	Kudl	14.922726	76.401641	596
Raichur	Kochigudda	Koch	16.316825	77.109799	400

2.2. Evaluation of physico-chemical properties of soil

The physico-chemical properties were analyzed by adopting various standard methodologies. such as texture was analyzed by the Hydrometric method (Das et al., 2020), moisture by Gravimetric method (Das et al., 2020), density by the Core method (Indoria et al., 2020), pH by Potentiometry (Marple & LaCourse, 2019), electrical conductivity (EC) by Conductometry (Smagin et al., 2024), organic carbon (OC) following Wet-oxidation method (Ramamoorthi & Meena, 2018) , nitrogen (N) using Alkaline permanganate method (Zhang et al., 2024)), phosphorous (P) by Olsen's P method (Koralage et al., 2015), potassium (K) by Flame photometry method (Kumari et al., 2024), calcium (Ca), magnesium (Mg) zinc (Zn), copper (Cu), iron (Fe), and manganese (Mn) by Complexometric titration (Kalinowska et al., 2021), sulfur (S) by Turbidometry method (Kundu et al., 2020), and boron (B) by Hot water-soluble extraction method (Devi & Sumathy, 2017).

2.3. Analysis of soil microbiome

The indigenous bacterial and fungal species were analyzed by adopting serial dilution and spread/pour plate techniques (Ruparelia et al., 2022). Potato dextrose agar for fungal and nutrient agar and King's B medium for bacterial isolation were used. About 10 g of the sample was immersed in 90 ml of sterile distilled water, and retained on shaker for 30 min at 200 rpm. 10 ml of aliquot from a 10^{-1} dilution test tube was transferred into 90 ml distilled water to prepare 10^{-2} dilution. Similarly, successive dilutions up to 10^{-7} were prepared from the previous suspensions. 1 ml of sample added to 9 ml sterile distilled water to produce 10 fold dilutions (10^{-1}), 1 ml of the 10 fold dilution is added to other 9 ml sterile distilled water

containing test tube to yield 100 fold dilutions (10^{-2}), same process was followed for remaining test tubes. The arranged samples were inoculated (100 µl) by spread plate technique into the Petri plates containing growth media and incubated at 26 or 28±1 °C up to 7 days for fungal growth and 28±1 °C up to 3 days for bacterial growth in darkness to create an environment favorable growth conditions. Observations were recorded by calculating the colony-forming units (CFU) per sample. Colonies were identified based on the conidial structures, pictorial microscopic observations and using specific keys documented for identification (Sangeetha & Thangadurai, 2013).

2.4. Assessment of chilli anthracnose disease incidence

Pictorial observations in the field showed the typical symptoms of anthracnose disease appeared predominantly on chilli fruits. The most noticeable anthracnose symptoms are black-colored sunken lesions comprising conidial deposition on the infected chilli fruits (Fig. 2). To evaluate the percent incidence, 50 fruits were randomly observed in each field. Evaluation of percent incidence was done using Equation 1, by Heck et al. (2021).

$$\text{Percent DI} = \frac{\text{Number of infected fruits}}{\text{Total Number of observed fruits}} \times 100 \quad \text{..... [1]}$$

2.5. Statistical approach

The entire randomized data was assessed using Principal component analysis (PCA), and ANOVA was performed using 3 replicas at *p-value* <0.05. Pearson's correlation was applied at a significance level of 0.01 and 0.05 to identify potential associations and patterns. IBM SPSS statistics version 20. (SPSS Inc., Chicago, IL, USA) was utilized for statistical data visualization. By taking the first two principal components, scores, k-means clustering, and biplots were drawn.

3. RESULTS

The present study analyzed the effects of soil physicochemical characteristics on chilli anthracnose disease and provided valuable insights. Remarkable differences in the physicochemical properties, availability of macro- and micronutrients and presence of bacterial and fungal species were observed among the soil samples collected. These traits had a profound impact on increasing the susceptibility of the chilli crop to anthracnose disease in the studied area.

3.1. Soil physico-chemical properties

In the present study, clay loamy soil was the prominent type represented at ten locations followed by sandy loam in five locations and loamy texture in two locations. Soil moisture was high in clay loam and loamy soils and low in sandy loamy soils. Soil moisture ranged from 24.40% to 40.46%, with the highest value in the Nela region and the lowest value in the Shir region. The density of the soil samples varied greatly among the studied locations, and it ranged from 1.54 kg cm^{-3} in Homb to 1.19 kg cm^{-3} in Alad.

The chemical composition of soil has a crucial impact on plant-pathogen interaction, as observed in the present study, three major characteristics of soil, such as pH, EC, and OC have been analyzed among the soil samples collected from major chilli growing locations. Results showed that the pH varies from 5.19 in Kris to 8.45 in Shira. The EC content varies from 0.01 (dS m^{-1}) in Homb to 0.38 (dS m^{-1}) in Nela, Anni, and Harp, whereas the soil OC content ranged from 0.11% in Shira to 0.87% in Kris (Table 2).

Figure 2. Infected chilli samples (A, B, C, D and E)

Table 2. Physico-chemical properties of soil collected from different chilli growing regions of Karnataka

Locality (code)	Soil texture	Soil moisture (%)	Soil Density (kg cm^{-3})	pH	EC (dS m^{-1})	OC (%)
Agadi (Agad)	Clay Loam	37.30±0.36^{cd}	1.26±0.05^{de}	6.77±0.04^{d}	0.36±0.03^{ab}	0.37±0.03^{bc}
Aladakatti (Alad)	Clay Loam	35.36 ±0.34^{e}	1.19±0.04^{e}	5.57±0.29^{ef}	0.19±0.10^{ab}	0.37±0.33^{bc}
Maranbeed (Mara)	Loamy	38.50±0.28^{b}	1.35±0.03^{bcd}	6.08±0.04^{e}	0.26±0.03^{ab}	0.17±0.03^{bc}
Krishnapur (Kris)	Loamy	36.40±0.32^{d}	1.34±0.04^{cde}	5.19±0.05^{f}	0.27±0.04^{ab}	**0.87±0.03^{a}**
Teggihalli (Tegg)	Clay Loam	39.40±0.34^{ab}	1.35±0.03^{bcd}	7.35±0.04^{bcd}	0.16±0.05^{ab}	0.58±0.04^{ab}
Hedigonda (Hedi)	Sandy Loam	28.53±0.29^{f}	1.45±0.03^{ab}	5.92±0.05^{e}	0.17±0.04^{ab}	0.13±0.08^{bc}
Hombaradi (Homb)	Sandy Loam	25.26±0.40^{g}	**1.54±0.03^{a}**	6.92±0.05^{cd}	0.01±0.00^{b}	0.18±0.05^{bc}
Shiratti (Shir)	Sandy Loam	24.40±0.32^{g}	1.37±0.05^{bcd}	6.93±0.05^{cd}	0.18±0.04^{ab}	0.55±0.03^{abc}
Kurtakoti (Kurt)	Clay Loam	27.56±0.29^{f}	1.27±0.04^{de}	7.06±0.34^{cd}	0.06±0.02^{ab}	0.35±0.04^{bc}
Nelagudda (Nela)	Clay Loam	**40.46±0.35^{a}**	1.25±0.03^{de}	7.74±0.06^{bc}	**0.38±0.26^{a}**	0.39±0.25^{bc}
Kusugal (Kusu)	Clay Loam	37.33±0.37^{cd}	1.34±0.03^{bcd}	7.84±0.07^{b}	0.19±0.10^{ab}	0.28±0.025^{bc}
Annigeri (Anni)	Clay Loam	38.43±0.31^{b}	1.28±0.04^{cde}	7.53±0.40^{bc}	**0.38±0.26^{a}**	0.23±0.13^{bc}
Shiraguppi (Shira)	Clay Loam	40.36±0.37^{a}	1.25±0.03^{de}	**8.45±0.22^{a}**	0.04±0.02^{ab}	0.11±0.04^{c}
Harapanahalli (Harp)	Sandy Loam	28.40±0.32^{f}	1.45±0.03^{ab}	6.90±0.32^{cd}	0.38±0.05^{a}	0.16±0.04^{bc}
Somalapur (Soml)	Clay Loam	40.30±0.37^{a}	1.47±0.04^{ab}	5.70±0.40^{ef}	0.18±0.06^{ab}	0.26±0.04^{bc}
Kudligi (Kudl)	Clay Loam	38.33±0.35^{bc}	1.46±0.03^{ab}	7.76±0.06^{b}	0.14±0.03^{ab}	0.54±0.04^{abc}
Kochigudda (Koch)	Sandy Loam	39.20±0.46^{b}	1.41±0.05^{abc}	6.96±0.04^{cd}	0.26±0.04^{ab}	0.37±0.26^{bc}
Minimum	-	24.40	1.19	5.19	0.01	0.11
Maximum	-	40.46	1.54	8.45	0.38	0.87

Notes: each value represents the mean ± standard error (SE) of 3 replicas. Probability values of ANOVA and its significant difference denoted by letters (Duncan's multiple range test, P < 0.01).

3.2. Soil macro and micronutrients

The present analysis showed a significant variation in the N content of the soil samples from different locations. The N content ranged from 111.80 kg ac^{-1} in Mara to 185.76 kg ac^{-1} in Kusu. Available P content was found low in the Nela region with an average value of 5.73 kg ac^{-1} and high with an average value of 45.43 kg ac^{-1} in Kudl. A low amount of K was recorded in Mara with an average of 117.50 kg ac^{-1}, whereas a high content of K was detected in Kusu with a quantity of 379 kg ac^{-1}. The amount of Ca ranged from 5.73 meq 100 g^{-1} in Mara to 33.83 meq 100 g^{-1} in Nela. The Mg content varied from 2.80 meq 100 g^{-1} in Hedi to 14.63 meq 100 g^{-1} in Shira. S content was varied from 10.36 ppm in Harp to 19.53 ppm in Anni. Zn content was varied from 0.07 ppm in Kurt to 0.64 ppm in Harp. The Cu content ranged from 0.09 ppm Kudl region to 0.75 ppm in Soml. The content of Fe ranged from 0.68 ppm in Shira to 13.46 ppm in Kris. The Mn content ranged from 0.44 ppm in Kudl to 10.81 ppm in Kris. B content ranged from 0.09 ppm in Harp to 0.66 ppm in Mara (Table 3).

3.3. Soil microbiome

The present work indicated that, the soil microbiome comprises diverse microbial species among seventeen different regions, and it includes fungi, such as *Trichoderma* sp., *Pencillium* sp., *Rhizopus* sp., *Alternaria* sp., *Cladosporium* sp., *Fusarium* sp., *Chaetomium* sp., *Colletotrichum* sp., *Aspergillus* sp., and bacteria including *Bacillus* sp. and *Pseudomonas* sp. (Fig. 3A).

3.4. Disease assessment

The study revealed that the disease is widespread and highly prevalent across all study sites, with a prevalence exceeding 90% in numerous locations, as illustrated in Figure 3B. ANOVA, explored substantial differences between % DI rates ranged from 69% in Kurt genotype, 70.33% in Homb, 80% in Shir, 81% in Harp, 90% in Alad and Kudl, 94% in Kris and Hedi, 95% in Shira and Koch, 96% in Agad, 97% in Kusu and Soml, 98% in Mara, Tegg, and Anni, 100% in Nela region (Fig. 3B).

3.5. Principal Component Analysis of soil properties

Eigenvalues were determined by considering each trait association with the axes. The 21 soil parameters were subjected to PC analysis, which were grouped into different components based on their loadings; the variables with the highest loadings were categorized and placed in descending order under each component. Seven PCs had an eigenvalue >1 and accounted for 84.67% of the total variance in the data set. The first, two components of PC correspond about a total of 41.00% of the variance. The first PC corresponds to 25.29% of the total variance and is represented by four characters, *viz*., pH, K, Ca, and Mg. The second PC corresponded to 15.70 % of the variance and represented density, boron, and *Bacillus* species.

Table 3. Assessment of macro and micro nutrients present in soil collected from different chilli growing regions of Karnataka

Locality (code)	N (Kg ac^{-1})	P (Kg ac^{-1})	K (Kg ac^{-1})	Ca (meq 100 g^{-1})	Mg (meq 100 g^{-1})	S (ppm)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	B (ppm)
Agadi (Agad)	120±0.43^{i}	31.63±0.31^{g}	232.40±0.37^{g}	17.66±0.33^{f}	9.46±0.34^{c}	12.80±0.40f	0.38±0.05^{cd}	0.21±0.03^{cdefgh}	5.53±0.04^{c}	4.16±0.06^{de}	0.35±0.03^{bcdef}
Aladakatti (Alad)	129±0.43^{g}	33.40±0.32^{de}	207.76±0.43^{h}	8.70±0.37^{j}	5.66±0.29f^{g}	15.63±0.34^{d}	0.48±0.04^{bc}	0.26±0.02^{cdef}	6.03±0.06^{c}	5.74±0.03^{c}	0.55±0.03^{ab}
Maranbeed (Mara)	111.80±0.40^{j}	33.36±0.32^{d}	117.50±0.32^{n}	5.73±0.38^{k}	3.16±0.38^{h}	16.83±0.46^{c}	0.58±0.05^{ab}	0.26±0.03^{cdefg}	5.76±0.03^{c}	4.18±0.04^{de}	**0.66±0.03^{a}**
Krishnapur (Kris)	161.53±0.32^{c}	35.61±0.32^{c}	135.76±0.43^{m}	5.76±0.29^{k}	3.10±0.28^{h}	12.80±0.43^{f}	0.18±0.04^{efg}	0.46±0.03^{b}	**13.46±0.05^{a}**	**10.81±0.36^{a}**	0.65±0.03^{a}
Teggihalli (Tegg)	120.76±0.43^{i}	30.60±0.30^{g}	181.53±0.32^{i}	27.53±0.35^{c}	11.09±0.21^{b}	15.12±0.03^{e}	0.28±0.03^{de}	0.18±0.04^{defgh}	4.45±0.03^{d}	6.45±0.03^{b}	0.40±0.04^{bcd}
Hedigonda (Hedi)	125.43±0.31^{h}	32.63±0.31^{ef}	153.46±0.34^{l}	5.76±0.40^{k}	2.80±0.43^{h}	11.42±0.03^{g}	0.16±0.02^{efg}	0.26±0.03^{cdef}	9.53±0.04^{b}	7.01±0.03^{b}	0.47±0.05^{abc}
Hombaradi (Homb)	129.70±0.43^{g}	28.53±0.32^{h}	269.93±0.34^{d}	14.36±0.34^{h}	6.76±0.40^{ef}	12.55±0.03^{f}	0.15±0.03^{efg}	0.34±0.03^{bcde}	5.52±0.04^{b}	3.60±0.45^{ef}	0.28±0.05^{cefgh}
Shiratti (Shir)	125.40±0.34^{h}	26.63±0.32^{i}	160.74±0.05^{k}	11.70±0.30^{i}	4.83±0.46g	10.48±0.04^{h}	0.11±0.04^{fg}	0.10±0.02^{fgh}	5.53±0.04^{c}	5.73±0.32^{c}	0.18±0.10^{defg}
Kurtakoti (Kurt)	138.60±0.45^{e}	14.63±0.04^{k}	251.76±0.46^{f}	26.10±0.40^{d}	8.66±0.37cd	17.56±0.03^{c}	0.07±0.02^{g}	0.09±0.03^{gh}	5.55±0.03^{c}	5.66±0.35^{c}	0.16±0.11^{efg}
Nelagudda (Nela)	138.16±0.32^{e}	5.73±0.38^{n}	256.40±0.04^{a}	**33.83±0.46^{a}**	13.63±0.40^{a}	11.16±0.02^{gh}	0.54±0.04^{ab}	0.21±0.14^{defgh}	3.37±0.04^{ef}	4.46±0.05^{d}	0.37±0.04^{bcde}
Kusugal (Kusu)	**185.76±0.04^{a}**	10.06±0.40^{m}	**379.08±0.04^{a}**	27.10±0.37^{cd}	11.53±0.32^{b}	14.45±0.03e	0.18±0.04^{efg}	0.35±0.03^{bcd}	1.86±0.43^{g}	4.44±0.03^{d}	0.13±0.08^{fg}
Annigeri (Anni)	133.10±0.26^{f}	11.83±0.46^{l}	255.58±0.28^{e}	28.73±0.40^{b}	14.46±0.38^{a}	10.36±3.75^{h}	0.18±0.04^{efg}	0.35±0.03^{bcd}	1.83±0.46^{g}	4.43±0.03^{d}	0.13±0.08^{f}
Shiraguppi (Shira)	142.45±0.05^{d}	19.10±0.37^{j}	325.23±0.37^{b}	32.80±0.46^{a}	**14.63±0.48^{a}**	11.45±0.07^{g}	0.25±0.03^{def}	0.37±0.04^{bc}	0.68±0.36^{h}	3.47±0.04^{f}	0.47±0.05^{abc}
Harapanahalli (Harp)	162.65±0.04^{b}	30.33±0.35^{g}	169.03±0.34^{j}	19.03±0.37^{e}	7.63±0.46^{de}	**19.53±0.04^{a}**	**0.64±0.03^{a}**	0.18±0.03^{efgh}	4.45±0.03^{d}	3.45±0.05^{f}	0.09±0.05^{g}
Somalapur (Soml)	142.57±0.04^{d}	43.63±0.32^{b}	266.46±0.34^{d}	16.50±0.40^{g}	7.50±0.37^{de}	12.80±0.43^{f}	0.12±0.05^{fg}	**0.75±0.03^{a}**	4.47±0.05^{d}	3.03±0.06^{f}	0.16±0.11^{efg}
Kudligi (Kudl)	142.56±o.o4^{d}	**45.43±0.31^{a}**	297.46±0.43^{c}	9.63±0.40^{j}	4.80±0.46^{g}	17.43±0.03^{c}	0.10±0.05^{g}	0.09±0.04^{h}	3.48±0.05^{f}	0.44±0.35^{g}	0.27±0.04^{cdefg}
Kochigudda (Koch)	126.27±0.05^{h}	33.63±0.38^{de}	152.46±0.35^{l}	8.76±0.46^{j}	3.46±0.40^{h}	18.33±0.40^{b}	0.35±0.03^{cd}	0.46±0.05^{b}	4.27±0.27^{de}	5.56±0.35^{c}	0.18±0.04^{defg}
Minimum	111.80	5.73	117.50	5.73	2.80	10.36	0.07	0.09	0.68	0.44	0.09
Maximum	185.76	45.43	379.08	33.83	14.63	19.53	0.64	0.75	13.46	10.81	0.66

Notes: Each value represents the mean ± standard error (SE) of 3 replicas. Probability values of ANOVA and its significant difference denoted by letters (Duncan's multiple range test, P< 0.01).

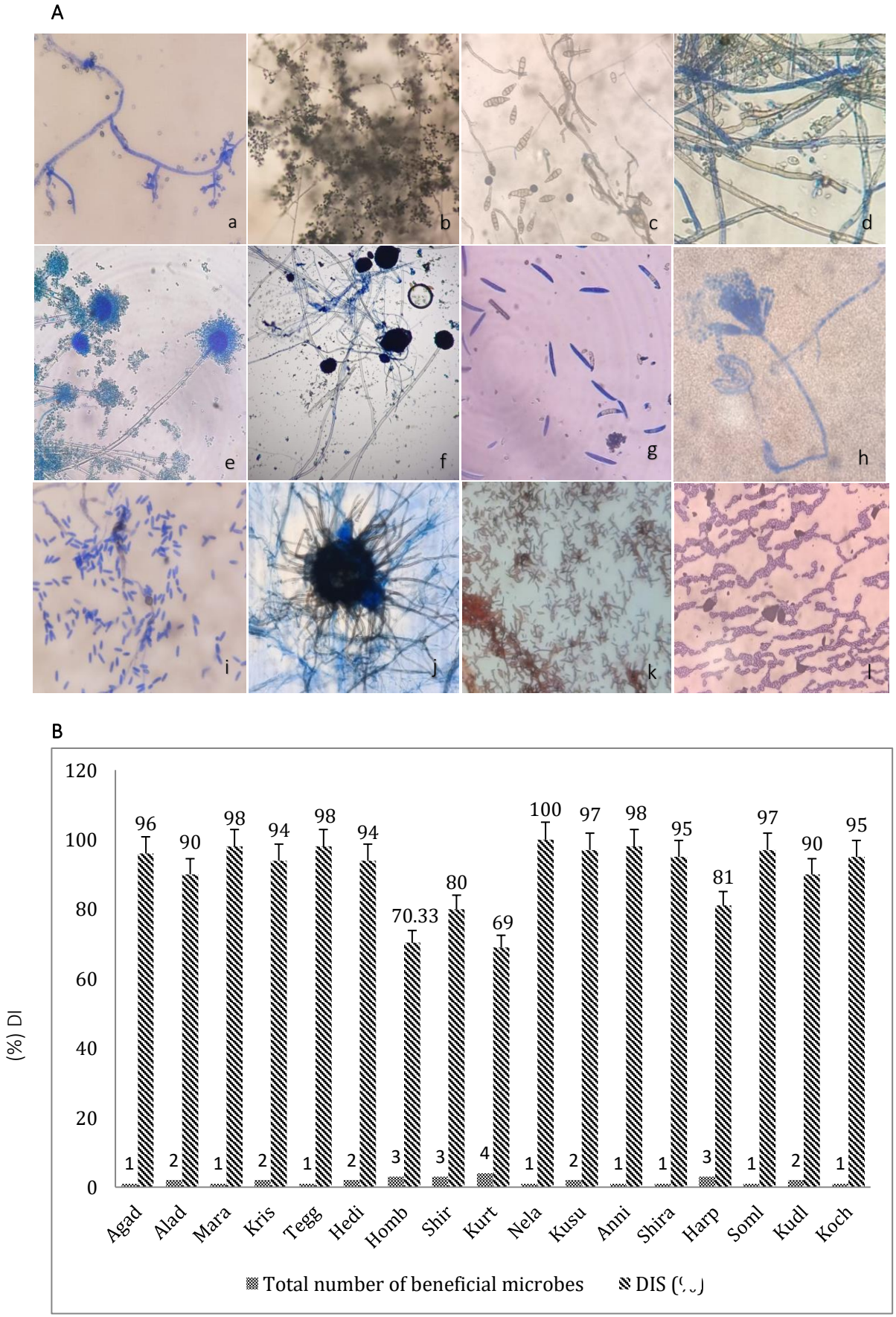

Figure 3. (A). Microbiome of fungi and bacteria associated with soil samples collected from chilli growing areas of Karnataka; (a, b) *Trichoderma* sp.; (c) *Alternaria* sp.; (d) *Cladosporium* sp.; (e) *Aspergillus* sp.; (f) *Rhizopus* sp.; (g) *Fusarium* sp.; (h) *Penicillium* sp.; (i) *Colletotrichum* sp.; (j) *Chaetomium* sp.; (k) *Bacillus* sp.; (l) *Pseudomonas* sp.; (B) Prevalence of anthracnose disease and association of beneficial microbes

Table 4. Results showing the principal component analysis of soil properties

Soil parameters	Rotated component matrix						
	PC1	PC2	PC3	PC4	PC5	PC6	PC7
% of variance	25.299	15.706	12.313	11.644	8.264	6.277	5.169
Cumulative %	25.299	41.006	53.318	64.963	73.227	79.504	84.673
Eigenvalues	5.313	3.298	2.586	2.445	1.735	1.318	1.085
Moisture %	0.193	-0.150	0.055	**0.919**	0.114	0.006	0.049
Density (kg cm^{-3})	-0.327	**0.637**	-0.400	-0.259	0.131	-0.295	0.127
pH	**0.864**	-0.083	-0.107	-0.067	0.174	-0.119	0.001
EC (dS m^{-1})	-0.028	0.064	**0.776**	0.376	0.015	-0.018	-0.003
OC %	-0.430	-0.350	0.133	0.034	-0.103	0.292	**0.295**
Available N (kg ac^{-1})	0.204	-0.042	-0.020	0.025	0.086	-0.005	**0.912**
Available P (kg ac^{-1})	-0.746	0.224	-0.289	0.153	**0.348**	-0.015	-0.087
Available K (kg ac^{-1})	**0.746**	-0.063	-0.450	0.093	0.043	0.082	0.354
Ca (meq 100 g^{-1})	**0.903**	-0.109	0.146	0.050	-0.192	-0.048	0.149
Mg (meq 100 g^{-1})	**0.903**	-0.110	0.144	0.174	-0.235	-0.048	0.090
S (meq 100 g^{-1})	-0.181	0.092	0.188	-0.123	**0.862**	0.097	0.151
Zn (ppm)	0.024	0.138	**0.726**	0.244	0.360	-0.190	-0.247
Cu (ppm)	-0.180	0.347	-0.200	**0.559**	-0.331	0.044	0.353
Fe (ppm)	-0.873	-0.177	**0.148**	-0.183	-0.283	-0.047	0.128
Mn (ppm)	-0.524	-0.283	**0.341**	-0.079	-0.565	0.143	0.176
B (ppm)	-0.038	**0.945**	0.073	-0.023	0.067	0.133	-0.045
Trichoderma sp.	0.028	-0.102	**0.726**	-0.262	-0.065	0.149	0.118
Pseudomonas sp.	-0.228	-0.076	0.501	-0.322	0.030	**0.665**	-0.030
Bacillus sp.	-0.038	**0.945**	0.073	-0.023	0.067	0.133	-0.045
Penicillium sp.	-0.003	0.222	-0.116	0.020	0.040	**0.924**	0.026
% DI	0.026	-0.075	0.125	**0.938**	-0.117	-0.112	-0.071

The third PC was represented by EC, Fe, Mn, and *Trichoderma* sp. corresponding to 12.31% of the total variance. The fourth PC accounted for 11.64% of the total variance, constituted by moisture, Cu content, and % DI. The fifth and sixth PCs accounted for 8.26 and 6.27% of the total variance corresponding to P, S, *Pseudomonas* sp. and *Penicillium* sp. The seventh PC showed a variance of 5.16% and had OC and N content in it. Table 4 shows the detailed results of PCA.

Development of scattered biplot with the aid of scores obtained from the first two principal components representing the total variance of about 41% (Fig. 4A). PCA biplot characterized the seventeen experimental locations that were scattered normally on the bases of quality and quantity into 21 physical, chemical and microbial parameters in relation to anthracnose disease prevalence (Fig. 4A). 1st consecration axis accounted for about 25.29%, and the 2nd axis accounted for 15.70% of the total variance. According to the output of PCA analysis, moisture, Mg, Ca, and DI were grouped together at the right side of the biplot, while density, S, P, Cu. Each cluster represents a distinct category of soil quality characteristics. The soil analysis data from all 17 samples was reduced to PC scores, and were then utilized to group the different geographical regions using k-means clustering (Fig. 4B), where it provides the details of the variables on the distribution patterns. Locations were grouped into 4 clusters closely associated with their soil physico-chemical qualities. Cluster 1 includes 5 locations that have a significant amount of available N (average of 144.20 kg ac^{-1}), K (average 260.71 kg ac^{-1}), and Ca (average 25.83 meq 100 g^{-1}). Cluster 2 consists of 5 locations that are rich in their available P (average of 33.40 kg ac^{-1}), Mg (average 8.26 meq 100 g^{-1}), S (average 14.73 meq 100 g^{-1}), Zn (average 0.252 meq 100 g^{-1}), and Cu (average 0.346 ppm). Cluster 3 contains 5 locations that are superior in their total B content (average 0.486 ppm), and Cluster 4 consists of 2 locations with the highest content of Fe (average 8.86 ppm) and Mn (Average 8.18 ppm). Considering all the clusters, cluster 2 locations, including Homb, Shira, Harp, Soml, and Kudl, have a rich quantity of soil parameters, including P, Mg, S, Zn, and Cu (Fig. 4B).

3.6. Pearson correlation Analysis of soil properties

Pearson correlation assessment showed that the available P is positively correlated to soil density (r=0.538*, *P*=0.01) and negatively correlated to soil pH (r=-0.569*, *P*=0.01), Furthermore, available K was positively correlated to soil pH (r=0.635**, *P*=0.01) and available N (r=0.488*, *P*=0.01). While, the Ca was p correlated positively to soil pH (r=0.739*, *P*=0.01), available K (0.619**, *P*=0.01), and negatively correlated to available P (r=-768**, *P*=0.05). In addition, the Mg was positively correlated to soil pH (r=0.707**, *P*=0.01), K (r=0.653**, *P*=0.01), Ca (r=0.963**, *P*=0.01) and negatively correlated to available P (r=-723**, *P*=0.01). Besides, S was positively correlated to EC (r=0.593*, *P*=0.01). The Fe was correlated negatively to soil pH (r=-0.813**, *P*=0.01), K (r=-0.656**, *P*=0.01) and Ca (r =0.675**, *P*=0.01) and positively correlated with OC (r = 0.490*, *P*=0.05) and Mg (r=-0.700**, *P*=0.01).

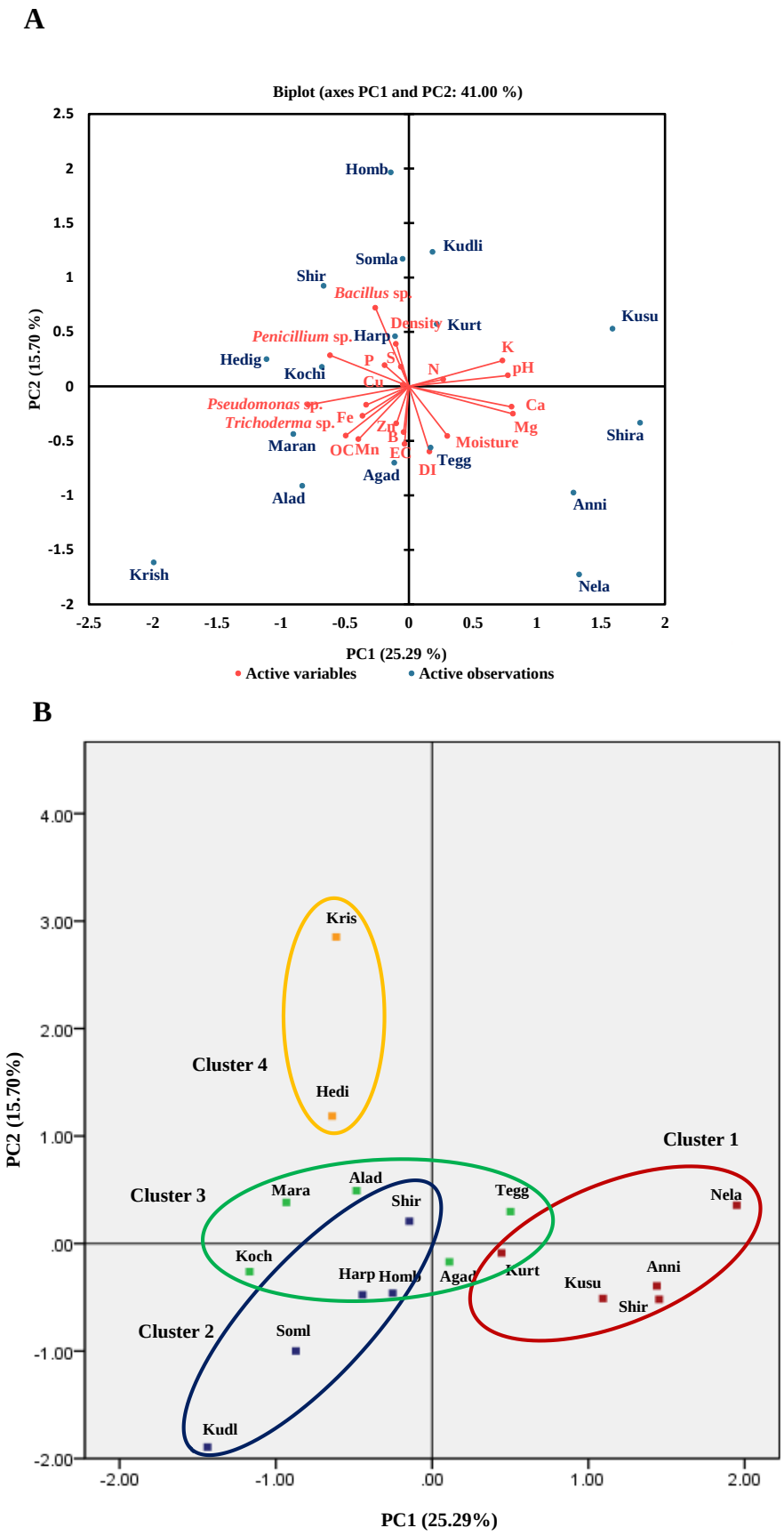

Figure 4. A. Biplot analysis of 17 chilli growing areas: correlations among physicochemical properties (moisture, density, pH, EC, OC, N, P, K, Cu, Fe, Mn, Mg, Zn, S, and B), microbiological characteristics (*Pseudomonas* sp., *Bacillus* sp., *Penicillium* sp., *Trichoderma* sp.) and DI %, PC1 accounted for 25.29% of the variance and PC2 accounted for 15.70%, **B.** Cluster diagram constructed using k-means clustering method, and locations were scattered using the scores of the first two principal component axes.

Table 5. Pearson correlations among physical, chemical and biological properties of soil

Soil properties	Moisture	Density	pH	EC	OC	N	P	K	Ca	Mg	Zn	S	Cu	Fe	Mn	B	*Trichoderma*	*Pseudomonas*	*Bacillus*	*Penicillium*	% DI
Moisture	1																				
Density	-0.382	1																			
pH	0.178	-0.144	1																		
EC	0.302	-0.254	-0.118	1																	
OC	0.11	-0.143	-0.228	0.099	1																
N	0.037	-0.018	0.172	0.045	0.099	1															
P	0.017	**.538***	**-.569***	-0.135	0.231	-0.255	1														
K	0.233	-0.117	**.635****	-0.324	-0.259	**.488***	-0.414	1													
Ca	0.264	-0.428	**.739****	0.036	-0.216	0.261	**-.768****	**.619****	1												
Mg	0.358	-0.475	**.707****	0.11	-0.251	0.219	**-.723****	**.653****	**.963****	1											
Zn	-0.003	0.148	-0.053	0.006	-0.005	0.116	0.325	-0.19	-0.245	-0.353	1										
S	0.224	-0.3	-0.084	**.593***	-0.233	-0.132	-0.055	-0.358	0.004	0.031	0.354	1									
Cu	0.416	0.22	-0.347	0.005	-0.118	0.205	0.219	0.098	-0.087	-0.014	-0.215	-0.142	1								
Fe	-0.329	0.111	**-.813****	0.04	**.490***	-0.075	0.427	**-.656****	**-.675****	**-.700****	-0.036	-0.084	0.062	1							
Mn	-0.153	-0.275	**-.531***	0.099	**.509***	0.019	-0.061	**-.551***	-0.237	-0.278	-0.202	-0.071	0.108	**.749****	1						
B	-0.129	**.516***	-0.07	0.063	-0.147	-0.091	0.246	-0.134	-0.132	-0.148	0.185	0.172	0.173	-0.13	-0.202	1					
Trichoderma	-0.069	-0.245	-0.07	0.363	0.217	-0.086	-0.223	-0.199	0.175	0.163	0.166	0.302	-0.109	0.166	0.297	-0.068	1				
Pseudomonas	-0.316	-0.237	-0.265	0.349	0.308	-0.067	0.025	-0.385	-0.21	-0.207	0.193	0.113	-0.203	0.268	0.344	0.028	**.529***	1			
Bacillus	-0.129	**.516***	-0.07	0.063	-0.147	-0.091	0.246	-0.134	-0.132	-0.148	0.185	0.172	0.173	-0.13	-0.202	**1.000****	-0.068	0.028	1		
Penicillium	-0.061	-0.091	-0.167	-0.068	0.074	0.059	0.015	0.132	-0.108	-0.13	0.134	-0.153	0.157	-0.096	0.028	0.292	-0.017	**.488***	0.292	1	
% DI	**.851****	-0.318	0.009	**.488***	0.065	-0.016	0.019	0	0.104	0.222	-0.231	0.27	0.38	-0.129	0.054	-0.077	-0.228	**-.322***	-0.077	-0.113	1

Notes: *. Correlation is significant at the 0.05 level (2-tailed)
**. Correlation is significant at the 0.01 level (2-tailed)

The Mn was negatively correlated to soil pH (r=-0.531*, *P*=0.01) and K (r=-0.551*, *P*=0.01), positively correlated with OC (r=0.509*, *P*=0.01) and Fe (r=0.749**, *P*=0.01). However, B was positively correlated to density (r=0.516*, *P*=0.01). *Pseudomonas* sp. was positively correlated to *Trichoderma* sp. (r=0.529*, *P*=0.01), whereas *Bacillus* sp. was positively correlated to density (r=-0.516*, *P*=0.01) and B (r=1.000**, *P*=0.01). *Penicillium* sp. was correlated positively to *Pseudomonas* sp. (r=0.488*, *P*=0.05). The % DI was positively correlated to moisture (r=0.851**, *P*=0.01) and EC (r=0.488*, *P*=0.05) and correlated negatively to *Pseudomonas* sp. (r=-0.322*, *P*=0.05) (Table 5).

4. DISCUSSION

The correlation between soil properties and chilli anthracnose disease is significant, as various soil characteristics influence disease severity and plant health. Research indicates that soil amendments, organic matter content, and moisture levels play crucial roles in managing anthracnose in chili plants. Present work conducted to determine the impact of soil's physico-chemical and biological properties on chilli anthracnose in major chilli cultivating areas of Northern Karnataka. During the survey geographical variation was observed in occurrence of anthracnose, with predominance of the symptoms in the areas of investigation. Result showed significant variation in disease prevalence levels in geographical areas, the soil health and subsequently the % DI. Soil texture can either enhance or diminish plant diseases development, as it influences water retention, nutrient uptake and root growth (Anaba et al., 2020). Soil moisture content varied greatly with the soil texture. Simultaneously, in present study high content of moisture occurred in Nela 40.46% resulted in severity of anthracnose disease in chilli of about 100%. In current analysis Alad region has less soil density (1.19 kg m^{-3}) which comprises 90% disease incidence.

Anthracnose disease may be more severe in soils with extreme pH values. In the present study Shira region has high pH 8.45 which supported the pathogen growth and disease incidence of about 95%. Research showed that the optimal pH range for the growth of *C. capsici* is 6.50-7.00 (Akhtar et al., 2018). However, at higher pH levels, such as pH 8.0, the radial growth of the pathogen decreases, with pH 4.0 showing the minimum radial growth (Kommula et al., 2017). Low EC (<2 dS m^{-1}) may reduce disease incidence and limit fungal growth, may lead to nutrient deficiencies, stressing plant and increases susceptibility thus, EC level was 0.01 to 0.38 dS m^{-1}, hence EC may not greatly influence anthracnose disease in all the locations.

High organic matter content in soil directly correlates with reduced anthracnose disease intensity, as observed in various production centers in East Java (Ridzuan et al., 2018), consequently pH between 6 and 8 maximizes the N availability as it favours the growth of soil microbes that mineralize the N in organic matter (Wang & Kuzyakov, 2024). High nitrogen levels can increase disease incidence by promoting the growth of anthracnose fungus, in Kusu region nitrogen level was very high 180.76 kg ac^{-1} hence disease prevalence was also high 97%. Singh et al. (2022) demonstrated that increased doses of P and K significantly reduce disease incidence and increase yield in chilli plants. According to current analysis Nela region has less quantity of P 5.73 kg ac^{-1}, and 100% disease incidence due to the presence of inadequate quantity of P, that reduces plant defence mechanism and increases chilli plant stress, making it more susceptible to anthracnose disease. Optimum P level for chilli crop of about 100-150 ppm. Presence of excess K (>200) level lead increased susceptibility to disease reduced fruiting and yield, excessive P can reduce Ca uptake, in Kusu region 379.08 kg ac^{-1} K comprises 97% disease incidence. Deficiencies in nutrients like potassium, calcium, and magnesium may be more prone to disease.

The presence of K and Ca can affect the uptake of other essential nutrients, such as nitrogen (N) and phosphorus (P), which are critical for plant health and disease resistance (Suntoro et al., 2024). Quantity of Ca was less in Mara (5.73 meq 100 g^{-1}) which comprises 94% disease in both the locations. Less quantity of S 10.36 ppm comprises 98% of disease incidence in Anni region. However, a deficiency of certain macronutrients such as Cu, Mg, and S can trigger physiological diseases and disorders in plants, ultimately leading to reduced quality and yield of vegetable crops (Sharma & Kumar, 2016; Suntoro et al., 2024). In present study Zn content was high in Harp region that possessed 81% DI rate. By applying Zn as a foliar spray, chilli plants can better resist anthracnose disease and maintain their health and productivity by means of producing antioxidant activity, enhancing defence compound production, strengthen cell walls and improves plant nutrition (Shoaib et al., 2021). Shira region has less quantity of Fe (0.68 ppm) which comprises 95% of anthracnose disease. Silva Souza et al. (2020) demonstrated that, anthracnose disease caused by *Colletotrichum* spp., significantly affects the quality of chilli fruits by means of reducing capsaicin content and phenol content due to Fe deficiency. In the present study Kudl region has 0.44 ppm Mn content that contributing 90% of DI. An adequate supply of Mn through organic and liquid manures can significantly benefit the growth, yield, and quality of chilli plants. In current study Mara region has 0.66 ppm amount of B comprises 98% of DI. B plays an essential role in managing chilli anthracnose by improving plant defense mechanisms and overall yield. Soil residents comprise various kinds of microbes that suppress the activity of the phytopathogens without the usage of any chemicals. *Trichoderma* sp., *Pencillium* sp., and *Cladosporium* sp. were some of the well documented plant growth promoting fungi (PGPF) widely distributed in plant rhizosphere soils that augment growth and resistance in plants (Sembiring et al., 2024). In the present analysis *Trichoderma* sp., *Pencillium* sp. and *Cladosporium* sp. influence the chilli plants growth and development, for instance in the locations such as Kurt, Homb and Harp has maximum PGPF number and where the DI was in low concentration. Restoring the natural balance of ecosystems requires a biocontrol approach to disease management, which has shown promising results. In this connection, present results revealed % DI value is decreased when the concentrations of *Trichoderma* sp., *Bacillus* sp., *Pseudomonas* sp. and *Penicillium* sp. were increased in the

soil. DI was significantly high in the locations such as Tegg, Shira, Agad and Nela, where the beneficial microbes are in less number.

PCA and biplot analysis are substantial tools for analyzing soil properties. In the context of soil analysis, PCA helped in reducing the dimensionality of the analyzed data and identified the patterns within the soil properties dataset (Nusyirwan et al., 2022). By combining PCA with biplot demonstration, we explored the interrelationships between various soil properties, identified key factors influencing soil health and visualized, how samples relate to each other based on their properties. This combined approach allowed us for a comprehensive understanding of soil properties and aids in decision-making processes related to soil quality and disease management.

The relationship between environmental factors such as rainfall severity, duration, optimum temperature, humidity, and pathogen spread, can lead to significant pathogenicity, in the relative infection is most common in warm and wet environmental conditions. Negative correlation of Fe with pH, K, Ca, and Mg weaken plant defenses, and making plants more vulnerable to *Colletotrichum* spp. High humidity of around 40% is the ideal for disease development (Salotti et al., 2022). At 100% relative humidity, the mycelial growth and conidial germination was higher (Udhayakumar, 2018). Pearson correlation showed that moisture exhibited a positive correlation with DI (r=.851**). As the content of moisture increases significantly increased in the DI, this was particularly evident in Nela 40.46%, Shira 40.36%, Soml 40.30% and Tegg 39.40% was shown in the Table 2 and where the clay loam soil is available and number of beneficial microbes was in less number. Shekhar and Singh (2021) observed, soil moisture and temperature are directly correlated to incidence of seedling blight in wheat and corn, with higher moisture and temperature levels increasing the probability of blight. In present study P is positively correlated with soil density (r=538*). Similarly, studies from various contexts indicate that higher level of P in the soil is related to density, which can help in managing chilli anthracnose caused by *Colletotrichum gloeosporioides* (Singh et al., 2022).

The analyzed soil data showed that a positive correlation between EC and percentage DI (r=0.488*), consequently, high content of EC observed in Nela and Anni locations (r=0.38) (Table 2). It was possibly because of the favorable ecological conditions for conidial germination and development of mycelial (Salotti et al., 2022). In present work *Pseudomonas* sp. and *Trichoderma* sp. were positively correlated to each other (r=0.529*), the co-occurrence of *Pseudomonas* sp. and *Trichoderma* sp. can create a favorable soil environment, boosting plant immunity and reducing the risk of diseases like anthracnose (Mahapatra et al., 2024), *Penicillium* sp. and *Pseudomonas* sp. were also positively correlated (r=0.488*) this co-existence of microbes contributes less disease incidence in Kurt 69%, Homb 70.33%, Shir 80% and Hap 81%. DI was negatively correlated with *Trichoderma* sp., *Bacillus* sp., *Penicillium* sp., but significantly with *Pseudomonas* sp. (r=-0.322*). Jisha et al. (2019) found that two P solubilizing *Pseudomonas aeruginosa* strains, exhibited potent antagonistic activity against chilli anthracnose disease in both laboratory and field conditions. The results showed after 5 days of incubation in dual culture inhibition test that, 2 isolates of *Pseudomonas aeruginosa* showed remarkable inhibition of about Ps1 93.41 % and Ps2 showed 72.5% against *Colletotrichum capsici*. The treatment of plants with *Pseudomonas aeruginosa* led to a significance lower incidence of anthracnose infection on matured chilli fruits, compared to untreated controls. In the present study, *Pseudomonas* sp. were found to be negatively correlated (r=-0.322*) with % DI and contributed to the suppuration of chilli anthracnose disease while during *in vitro* studies. Similarly, a negative correlation (r =-0.65*) was recorded in *Fusarium* wilt disease between ID-Foc and *Pseudomonas* spp., by Moutassem et al. (2019). Sutin Raj et al. (2014) demonstrated the efficacy of *Pseudomonas fluorescens* in inhibiting the growth of *Colletotrichum capsici* of chilli anthracnose in both laboratory and field conditions.

In this study, soil physical properties such as moisture and texture were found to influence the abundance and severity of anthracnose disease through their soil drainage, compaction, and temperature. The pH concentration is exceptionally high (>7) in several regions. The concentration of essential macronutrients P and K along with micronutrients Zn, Fe, and B were recorded less when contrasted with standard values. Meanwhile, there is a high variation found in all the physical and chemical parameters. Furthermore, soil analysis data was grouped into 4 clusters on the basis of their nutrient composition and quantity. Cluster 1 containing locations Nela, Anni, Shira, Kusu and Kurt. Cluster 2 consisting the locations Homb, Shir, Harp, Soml, and Kudl are having rich quantity of soil parameters including P, Mg, S, Zn, and Cu. Whereas, cluster 3 has very less quantity of soil parameters including the locations such as Mara, Alad, Agad, Koch, and Tegg. Chilli is a relatively user of N, P, K and other nutrients like Zn, Ca Fe, and B. The deficiency of these nutrients in some soils may also limit the chilli production. These are the major reasons to conclude that chilli yield is greatly affected by all these biotic and abiotic factors. These findings highlight the potential of utilizing soil analysis to identify and leverage beneficial microorganisms for effective and sustainable management of chilli anthracnose, offering farmers a natural and eco-friendly alternative to chemical control methods.

5. CONCLUSION

Outcomes of the current study showed that soil available nutrients are correlated with the incidence and severity of chilli anthracnose. The correlations are not exhaustive, and the relationship between chilli anthracnose disease and soil properties may vary depending on the specific environmental conditions and regional factors. There are certain indications which display a complex relationship, with both positive and negative correlations between the soil parameters and prevalence of anthracnose disease. Soil moisture and electrical conductivity were positively correlated with DI% consequently increases the disease prevalence, whereas DI% was negatively correlated with *Pseudomonas* sp. and consequently reduced severity of disease. The effective management of all micro and micro nutrients which play their role on the growth of microbiome and balance with each

nutrient should be considered in an integrated strategy for chilli anthracnose disease management.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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