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Soil quality and microbial diversity in relation to the severity of coffee leaf rust disease in Karnataka, India

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ABSTRACT

Soil physico-chemical properties significantly influence the quality, growth, productivity, and flavor of coffee. The current study estimates the soil nutritional properties and microbial diversity with the severity of coffee leaf rust disease. A total of twenty-nine localities were surveyed in the major coffee-growing district of Karnataka, mainly Chikkamagaluru, Kodagu, and Hassan, covering the canopies of arabica and robusta coffee plantations. The study on soil quality evaluation determines the sustainability and practices of land management in this region. The physico-chemical properties and microbial diversity of the soil were analyzed. Twenty-nine soil parameters were analyzed using principal component analysis, which accounts for five principal components with eigenvalues>1 explaining 9 % of the total variance. The nine principal components together explain 82.24 % of the total variance. According to K-means clustering, soil analysis can be classified into four clusters. Soil microbial communities primarily control the complex ecosystems of soil, including root- and rhizosphere-associated beneficial microbes, and play a vital role as key components in crop production and sustainable agriculture. The present study revealed that the fertility level of the soil and the diverse taxa of rhizospheric microflora from various soil samples, characterized by an abundant diversity of beneficial microbes, such as *Trichoderma* sp., *Bacillus* sp., *Penicillium* sp., and *Pseudomonas* sp. Furthermore, this work gives insights into the sustainable soil quality and disease management practices that can help farmers to adopt better soil management practices for improving the quality and quantity of coffee production in Karnataka, India.

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1. INTRODUCTION

In the modern world, coffee has gained immense popularity and become the second most popular beverage throughout the world. Subsequently, coffee has emerged as a major cash crop in more than 80 countries. In 2020-2021, global coffee production was assessed to be about 5.5 million kg more than in the previous year, reaching a total of 176.1 million kg. Brazil is the world's leading coffee exporter, accounting for one-third of the global production. Mainly, coffee is grown in southern America, Kenya, Africa, and Asia, primarily by smallholder farmers. Arabica and Robusta coffee are two known types of coffee that are economically and commercially traded.

Globally, India is the seventh largest producer of coffee, with production of 363,500 metric tons (MTs), of which 105,700 MTs of Arabica variety and 257,800 MTs of Robusta variety as per 2024-2025 (Coffee Board Statistics of India). Coffee is mainly grown in southern states of India, such as Karnataka, Tamil Nadu, Kerala, and a small stretch in other non-traditional and nonconventional regions like Andhra Pradesh, Odisha, and the northeastern regions (Vidya & Ravindranath, 2018). Both *C. arabica* and *C. robusta* have

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commercial trade and economic value that require different geographical conditions for growth. *Coffea arabica* requires a maximum altitude of 1000-2000 AMSL (Above Mean Sea Level) with a rainfall of 1200-2000 mm/year. The ideal temperature for the cultivation of *C. robusta* is 24-30 °C with an altitude of 400-800 m AMSL and 2000-3000 mm/year rainfall. In Karnataka, major parts of coffee production are from Chikkamagaluru, Kodagu, and Hassan districts, which account for about 70 % of coffee production in Karnataka. Coffee growers face many problems throughout tropical countries. Climate change alters coffee production, from declining crop yield and quality to increasing fungal disease and invasive pests, as it is a climate-sensitive plant, as well as from the soil fertility management and high-cost production (Pham et al., 2019). Over the last two decades, coffee production has been declining globally as compared to consumption, mainly attributed to the coffee leaf rust (CLR), caused by *Hemileia vastatrix* (Nair, 2010; Silva et al., 2006; Talhinhas et al., 2017). The loss due to this disease exceeds 75 % in severe outbreaks, causing loss of foliage and berries up to 80 % (McCook, 2006; Rutherford & Phiri, 2006).

The *Hemileia vastatrix* is an obligate and host-specific parasite that causes CLR disease, leading to major economic loss. This disease is reported in Arabica coffee from over fifty coffee-growing regions across the globe. In India, this fungus was first observed in 1869 and infects only the leaves and frequently the young branches. Naturally, the soil has a high degree of degradation, with slow renewable resources and a low percentage of regeneration (Chen et al., 2014). Plant-associated soil microbes play a vital role in promoting plant growth and development, including enhanced crop productivity and nutrient cycling (Yan et al., 2015). Soil microorganisms serve as key (Jacoby et al., 2017; Sembiring et al., 2024).

Each crop species requires optimal environmental conditions as well as nutrient, mineral, and organic matter composition, which influences the health of the crop and the quality of the yield. Additionally, soil can influence and assist the entire ecosystem through interaction between the composition of micro-macro-nutrients within the soil and the diversity of flora and fauna that occurs within and around it. Soil microflora in coffee fields can play a crucial role in decreasing CLR by acting as a biocontrol agent against *H. vastatrix* (da Silva Aragão et al., 2020; Medina-Sauza et al., 2022; Ndolo et al., 2019). Soil nutrients can affect tolerance or disease resistance. Adequate nutrient supply influences plant cell structure and composition, leading to improved defense against pathogens. The precise concentration of nitrogen and potassium, graded as the top among macronutrients, greatly affects the coffee plants against pathogens, like *Phoma tarda* and *Cercospora coffeicola*. Potassium allows the recovery of tissues after infection ends when colonized by biotrophic pathogens, including rust. Insufficient nitrogen, phosphorus, and potassium in soil, or excessive nitrogen, disrupts N/P and N/K balances, reducing plant productivity and increasing susceptibility to leaf rust disease (Pérez et al., 2019). For successful crop production, the composition of nutrients and minerals within the soil plays a vital role, but it may not positively influence the sustainability of the soil (Pereira et al., 2021). The present study was undertaken to explore the relationship between soil nutrients and microbial diversity against CLR incidence, which shows the novelty and correlation between CLR disease and soil properties with microbial diversity.

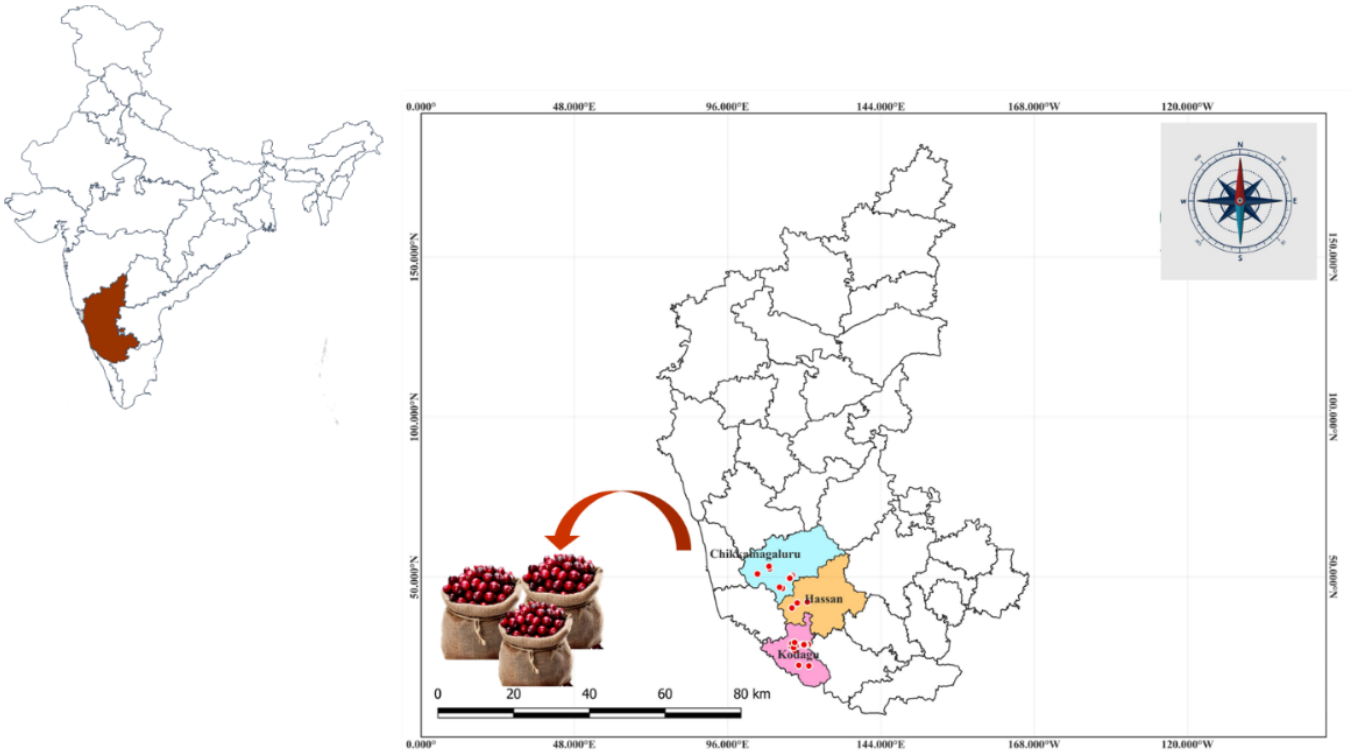

Figure 1. Field survey and soil sampling sites in major coffee growing regions of Karnataka, India

Table 1. Collection of coffee rhizospheric soil samples from different localities of Karnataka, India

District	Taluk	Place of collection	Code	Latitude °N	Longitude °W
Chikkamagaluru	Sringeri	Sringeri	CHK1	13.236334	75.686944
	Narasimharajapura	B. Kanubur	CHK2	13.357673	75.452636
		Balehonnur	CHK3	13.385532	75.444453
		Aladagudde	CHK4	13.274682	75.727617
	Chikmagalur	Chikmagalur	CHK5	13.29513	75.304258
		Mahaji	CHK6	13.256656	75.703555
		Chithavalli	CHK7	13.242651	75.695693
	Mudigeri	Mudigeri	CHK8	13.120486	75.607877
		Baggasagodu	CHK9	13.134043	75.571826
Hassan	Hassan	Hassan	HSN1	12.884167	75.721451
	Arkalgud	Bychanahalli	HSN2	12. 44701	75.934424
	Sakleshpura	Heggadde	HSN3	12.883622	75.721204
	Alur	Rangenahalli	HSN4	12.956416	75.907055
		Sakleshpura	HSN5	12.944697	75.785541
Kodagu	Madikeri	Madikeri	KDG1	12.441384	75.733006
		Katakeri	KDG2	12.414817	75.714479
		Hebbettageri	KDG3	12.458687	75.718896
		Hakathur	KDG4	12.367763	75.757731
		Ibnivalvadi Rural	KDG5	12.429238	75.772203
	Virajpet	Virajpet	KDG6	12.404717	75.742152
	Somwarpet	Basavanahalli	KDG7	12.440995	75.912226
		Kodagarahalli	KDG8	12.443753	75.848023
		Guddehosur	KDG9	12.443205	75.920415
		Andagove	KDG10	12.442461	75.857734
	Ponnampet	Ponnampet	KDG11	12.191769	75.804661
		Gonikoppal	KDG12	12.184935	75.926312
	Kushalnagar	Kushalnagar	KDG13	12.467407	75.754524
		7th Hosakote	KDG14	12.436607	75.882861
		Suntikoppa	KDG15	12.441036	75.867547

2. MATERIALS AND METHODS

2.1. Study locations

In India, Karnataka is the seventh largest state lying between longitudes 74°12'00'' to 78°41'00'' E and latitude 11°31'00'' to 18°45'00'' N. It has an elevation range of 460 AMSL. In the present study, soil samples were collected from Chikkamagaluru, Hassan, and Kodagu districts of Karnataka from January to December 2022 during three different seasons. These regions lie between 75°28'00'' to 75°45'00'' E longitudes and 12°30'00'' to 13°22'00'' N latitudes, and elevation between 920 to 1000 AMSL. The physiography forms a transition zone between the Deccan Plateau and the Western Ghats (Fig. 1), and the codes of the collection sites are mentioned in Table 1.

2.2. Soil sampling and analysis

Coffee rhizospheric soil samples of about 200 g were collected from a depth of 15 cm using a sterile hand trowel in labelled sterile zip-lock polythene bags. The whole-field management through soil sampling, as subsamples were distributed across the entire area, the soil samples were collected in a zig-zag pattern. Collected samples were air-dried, crushed, and passed through a 2 mm sieve for studying the physico-chemical properties of the soil. The texture of soil was determined by the hydrometer method, and soil moisture was studied by the gravimetric method by Das et al. (2020). Density by core method, described by Indoria et al. (2020), pH of soil was estimated by potentiometry method as in Marple and LaCourse (2019), conductometry method was adopted to detect electrical conductivity in soil samples (EC) by following Smagin et al. (2024), organic carbon (OC) was studied by the wet-oxidation method, total nitrogen (N) of soil by alkaline permanganate method, available phosphorus of soil following the procedure of Olsen's P method, available potassium (K) was determined by flame photometry method as in Moutassem et al. (2019), exchangeable calcium (Ca) and magnesium (Mg) was determined by versenate titration method, total sulphur (S) in soil was determined by turbidometry method, available zinc (Zn), total copper (Cu), available iron (Fe), total manganese (Mn) was determined by following Ganapathi et al. (2019), total boron (B) determined by hot water-soluble extraction method mentioned by Devi and Sumathy (2017).

2.3. Analysis of soil microflora

To isolate bacteria and fungi from the soil samples of different locations, a series of test tubes was prepared for serial dilution. About 1 g of soil sample was mixed in 10 ml of sterile distilled water to get a 10^{-1} dilution. According to Al-Dhabaan and Bakhali (2017), 1 ml of a 10^{-1} suspension of soil was diluted serially to get a 10^{-7} dilution. About 0.1 ml from 10^{-4}, 10^{-5}, 10^{-6}, and 10^{-7} dilutions were spread on potato dextrose agar and nutrient agar medium, for fungal and bacterial isolation, respectively. Plates were incubated upside

down at 28 ± 2 °C for about 24 hours for bacteria and 96 hours for fungi. Bacterial identification was done based on the colony characteristics as mentioned in Bergey's manual of determinative bacteriology (Afrin et al., 2024). For fungal isolation, potato dextrose agar medium was used, to which 0.05 mg of streptomycin was added to inhibit the growth of bacteria, and fungal colonies were identified based on morphological characteristics using a compound microscope (40X) (Ezeonuegbu et al., 2022).

2.4. Visual detection of leaf rust disease in coffee

Visual detection of CLR disease was observed by the appearance of disease symptoms on the lower surface of the coffee plant (colors, lesions, and spots) as an indicator of disease (Martinelli et al., 2015). Chlorotic spots or orange dust on the leaf are considered CLR. With the presence of chlorotic spots on the leaves, a visual inspection was carried out to measure the severity and incidence of the disease. The occurrence of CLR infection was evaluated according to Velásquez et al. (2020) in specific lots, where the number of diseased leaves in 60 random trees was divided by the total number of leaves in those trees and multiplied by 100. The urediniospores of *Hemileia vastatrix* are dislocated primarily by rain and wind. The primary effect of CLRs is defoliation of leaves, which decreases the plant's photosynthetic activity. CLR incidence was quantified based on the number and diameter of rust spots on infected leaves using Equation 1 by Velásquez et al. (2020) (Fig. 2).

$$\text{Average infection \% in lot} = \frac{\text{Number of diseased leaves in 60 trees}}{\text{Total number of leaves in 60 trees}} \text{X100} \ldots\ldots [1]$$

2.5. Statistical analysis

The characteristics of soil collected from different locations were subjected to descriptive statistical analysis, including maximum, minimum, mean, and analysis of the abundance of microflora using MS Excel 2019. One-way ANOVA, Pearson correlation analysis, principal component analysis, Duncan's multiple range test (DMRT), and k-means cluster analysis were carried out using IBM SPSS software version 20. Principal component biplot analysis was carried out using XLSTAT software 2024.

3. RESULTS

The current work aimed to examine how soil physicochemical and microbiological traits influence CLR disease, yielding vital insights. Significant variations in soil properties, nutrient levels, and microbial presence were noted across collected samples. These factors remarkably impacted the severity of leaf rust disease in coffee.

3.1. Physical properties of soil

The present study revealed the physical properties, which include soil texture, density, and moisture, of soil samples collected from coffee-growing locations in Karnataka, India. The process of soil formation primarily depends on soil texture, which represents the size distribution. Conversely, the bulk density of soil structure has a significant effect on soil layers. Three types of soil texture, viz., clay loam, loamy, and sandy loam, were found in the studied locations. Among them, clay loam was prominent, represented in 16 locations, followed by sandy loam present in 11 locations. Loamy soil was very rare and found only in two locations. Soil density plays a crucial role in coffee plant growth. Different soil management practices impact soil physical parameters, affecting crop development. Besides, the use of organic compost and coffee husk as soil conditioners has been found to influence soil chemical parameters, potentially affecting soil density and providing essential nutrients for coffee plants to grow effectively (Silvero et al., 2018; Tinuntun et al., 2025). Managing soil density via suitable preparation and amendments is crucial for successful coffee cultivation. The present results showed that the range of soil density varied from 1.43 g cm^{-3} in CHK6 to 0.92 g cm^{-3} in KDG8. In crop production, soil moisture plays a key role by serving as a solvent for other nutrients such as nitrogen, carbon, sodium, and potassium, along with making a substantial impact on the growth of the plant, organic matter decomposition by microbes, evaporation, and heat exchange (Mari et al., 2009). The soil moisture content varied between 27.92 % (CHK9) to 47.93 % (KDG11). The results indicate that clay loamy soil samples from numerous locations exhibited moisture levels, whereas sandy soils from certain areas also displayed high moisture content.

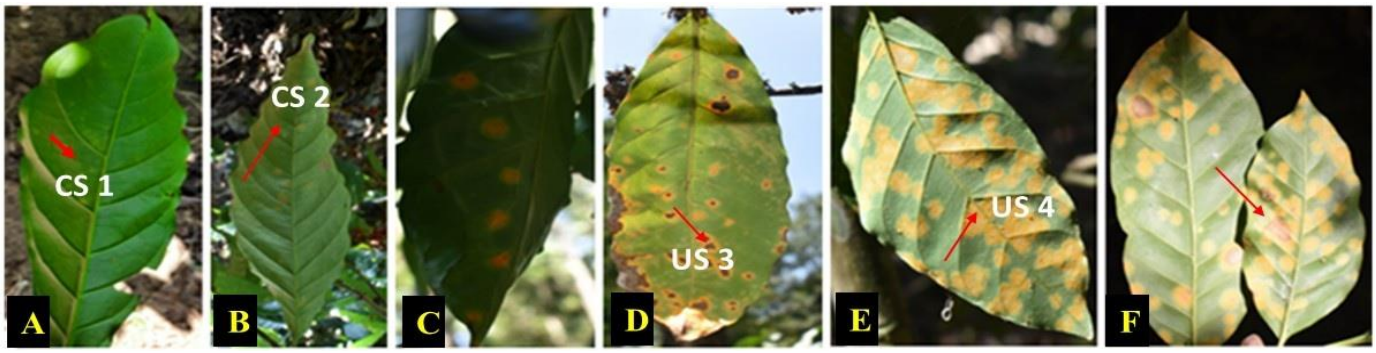

Figure 2. Visual detection of coffee leaf rust disease (A) CS 1 (Chlorotic spot) Appearance of chlorotic spots on the leaf, (B-C) CS 2 Initiation of chlorotic spots and deposition of urediospores on the leaf lamina, (D) US 3 (Uredospores) Spreading of uredospores towards the centre of the leaf, (E-F) US 4 Complete spread of uredospores on the lower surface of the leaf

Table 2. Physico-chemical characteristics of coffee rhizospheric soil samples in Karnataka, India

Collection sites	Texture	Density g cm^{-3}	Moisture %	pH	EC dS m^{-1}	OC %
CHK1	Clay Loam	1.18 ± 0.10ab	38.86 ± 0.10h	4.16 ± 0.23ihj	0.13 ± 0.02fgh	0.71 ± 0.02hij
CHK2	Clay Loam	1.12 ± 0.08ab	35.82 ± 0.13k	4.18 ± 0.04ihj	0.08 ± 0.03ghi	1.22 ± 0.05abcd
CHK3	Loamy	1.30 ± 0.06ab	38.86 ± 0.07h	4.38 ± 0.04fgh	**0.44 ± 0.04a**	1.10 ± 0.03bcdefg
CHK4	Loamy	1.22±0.08ab	36.79 ± 0.10j	4.28 ± 0.04gh	0.18 ± 0.02ef	0.83 ± 0.03fghij
CHK5	Clay Loam	1.31 ± 0.06ab	39.93 ± 0.04g	4.34 ± 0.05fgh	0.05 ± 0.02hi	0.85 ± 0.06fghij
CHK6	Sandy Loam	**1.43 ± 0.12a**	38.88 ± 0.06h	3.75 ± 0.03kl	0.05 ± 0.01hi	0.88 ± 0.03efghij
CHK7	Sandy Loam	1.37 ± 0.11ab	36.92 ± 0.07j	4.65 ± 0.06de	0.08 ± 0.01ghi	0.61 ± 0.08ijh
CHK8	Sandy Loam	1.38 ± 1.15ab	34.93 ± 0.04l	4.78 ± 0.15cde	0.04 ± 0.01hi	1.22 ± 0.04abcd
CHK9	Clay Loam	1.21 ± 0.72ab	**27.92 ± 0.04n**	4.36 ± 0.02fgh	0.03 ± 0.00i	0.36 ± 0.32h
HSN1	Clay Loam	1.20 ± 0.60ab	40.94 ± 0.03f	4.20 ± 0.02hi	0.03 ± 0.00i	0.90 ± 0.05defghi
HSN2	Clay Loam	1.23 ± 0.08ab	37.94 ± 0.04i	**3.63 ± 0.04l**	0.05 ± 0.00hi	0.56 ± 0.06jh
HSN3	Clay Loam	1.22 ± 0.07ab	38.95 ± 0.02h	4.65 ± 0.03de	0.03 ± 0.00i	**0.37 ± 0.32h**
HSN4	Clay Loam	1.20 ± 0.60ab	40.95 ± 0.02f	**5.54 ± 0.04a**	0.03 ± 0.00i	1.39 ± 0.02ab
HSN5	Sandy Loam	1.33 ± 10.09ab	28.95 ± 0.02m	3.92 ± 0.04jk	0.21 ± 0.03cdef	0.77 ± 0.03hij
KDG1	Clay Loam	1.28 ± 0.13ab	40.93 ± 0.04f	4.26 ± 0.13gh	0.28 ± 0.04bc	1.14 ± 0.04acefb
KDG2	Clay Loam	1.27 ± 0.12ab	38.94 ± 0.03h	3.67 ± 0.22l	0.13 ± 0.04fgh	0.72 ± 0.07hi
KDG3	Sandy Loam	1.30 ± 0.11ab	39.93 ± 0.03g	5.19 ± 0.09b	0.04 ± 0.01hi	1.12 ± 0.04abcdefg
KDG4	Clay Loam	1.17 ± 0.12ab	39.93 ± 0.04g	4.36 ± 0.04fgh	0.06 ± 0.02hi	0.84 ± 0.06fghij
KDG5	Sandy Loam	1.25 ± 0.11ab	36.93 ± 0.06j	4.74 ± 0.05cde	0.07 ± 0.01i	1.20 ± 0.03abcde
KDG6	Clay Loam	1.29 ± 0.14ab	39.95 ± 0.05g	3.97 ± 0.04ijk	0.31 ± 0.03b	0.73 ± 0.04hij
KDG7	Sandy Loam	1.25 ± 0.10ab	34.95 ± 0.02l	4.93 ± 0.03bc	0.15 ± 0.02fg	1.10 ± 0.02bcdefg
KDG8	Clay Loam	**0.92 ± 0.43b**	44.95 ± 0.51c	5.46 ± 0.03a	**0.02 ± 0.01i**	0.89 ± 0.04efghij
KDG9	Sandy Loam	1.22 ± 0.13ab	44.93 ± 0.65c	4.34 ± 0.05fgh	0.20 ± 0.03cdef	0.99 ± 0.08cdefgh
KDG10	Sandy Loam	1.23 ± 0.13ab	46.91 ± 0.76b	4.56 ± 0.04ef	0.04 ± 0.02hi	0.56 ± 0.04jh
KDG11	Sandy Loam	1.24 ± 0.09ab	**47.93 ± 0.56a**	4.54 ± 0.03efg	0.07 ± 0.00i	**1.44 ± 0.03abdf**
KDG12	Sandy Loam	1.21 ± 0.11ab	44.93 ± 0.70c	4.23 ± 0.02h	0.28 ± 0.03bcd	1.19 ± 0.04abcde
KDG13	Clay Loam	1.33 ± 0.14ab	36.94 ± 0.55j	4.27 ± 0.06gh	0.24 ± 0.03bcde	0.75 ± 0.03hij
KDG14	Clay Loam	1.29 ± 0.14ab	43.95 ± 0.28d	4.28 ± 0.04gh	0.19 ± 0.03def	0.81 ± 0.03ghij
KDG15	Clay Loam	1.22 ± 0.11ab	41.94 ± 0.31c	4.87 ± 0.04cd	0.05 ± 0.01hi	1.28 ± 0.04abc
Minimum	-	0.92	27.92	3.63	0.02	0.37
Maximum	-	1.43	47.93	5.54	0.44	1.44

Notes: Each value represents the mean ± standard error of three replicates

3.2. Chemical properties of soil

The present study showed an analysis of chemical properties that contain macro and micronutrients of soil collected from CLR-infected locations and their influence on leaf rust disease. Macronutrients are the main elements that are required in huge quantities to produce carbohydrates, proteins, and lipids in plant cells, while micronutrients are required in smaller amounts and generally take part in the enzyme activation process. The present study analyzed three major characteristics, viz., soil pH, EC, and OC, among the soil samples collected from coffee growing locations. A change in pH of the soil effectively influenced leaf rust diseases in crop plants. The pH of soil samples varies from one location to another, ranging from highly acidic 3.63 in HSN2 to less acidic 5.62 in HSN4 locations. EC values varied from 0.44 dS m^{-1} in CHK3 to 0.02 dS m^{-1} found in KDG8. The maximum and minimum value of OC ranges from 1.44 g Kg^{-1} in KDG11 to 0.37 g Kg^{-1} in HSN3. The available nitrogen ranges from 245.94 Kg ac^{-1} in KDG15 to 107.94 Kg ac^{-1} in HSN3. The available phosphorus content ranges from 29.63 Kg ac^{-1} in KDG5 to 11.06 Kg ac^{-1} in KDG4, whereas available potassium ranges from 598.65 Kg ac^{-1} in KDG9 to 97.53 Kg ac^{-1} in KDG10. The exchangeable calcium content varies from 6.06 meq $100g^{-1}$ in KDG3 to 0.97 meq $100g^{-1}$ in KDG10, whereas exchangeable magnesium content varies from 3.33 meq $100g^{-1}$ in KDG3 to 0.39 meq $100g^{-1}$ in KDG8. The total sulphur content varied from 21.41 ppm in KDG4 to 11.45 ppm in CHK5. The available Fe content varies from 22.49 ppm in KDG8 to 13.45 ppm in KDG9. The total Mn content ranges from 17.44 ppm in KDG12 to 11.05 ppm in HSN5. The available Zn ranges from 0.84 ppm in KDG9 to 0.08 ppm in HSN4. The available Cu ranges from 0.91 ppm in CHK2 to 0.08 ppm in KDG7. The available B ranges from 0.73 ppm in KDG1 to 0.15 ppm in KDG3 (Table 2, 3, & 4).

3.3. Principal component analysis (PCA)

Principal component analysis plays a critical role in soil analysis by reducing the dimensionality of datasets and recognizing key variables related to soil properties (Grazia Bonelli & Manni, 2019). PCA effectively summarized the sensitivity patterns of soil parameters by analyzing factor loadings across principal components. Additionally, the principal component biplot is presented to visually represent the data (Fig. 3).

Table 3. Evaluation of total macronutrients in coffee rhizospheric soil samples in Karnataka, India

Collection sites	N Kg ac^{-1}	P Kg ac^{-1}	K Kg ac^{-1}	Ca meq $100g^{-1}$	Mg meq $100g^{-1}$	S ppm
CHK1	160.94 ± 0.03n	13.93 ± 0.31jk	297.69 ± 0.16m	4.14±0.02f	1.67±0.01hi	13.47±0.01lm
CHK2	135.00 ± 0.57rs	14.96 ± 0.24g	258.70 ± 0.35t	4.35±0.02e	2.14±0.03g	15.51±0.04j
CHK3	180.00 ± 0.57k	11.53 ± 0.29n	517.70 ± 0.04c	3.34±0.03i	1.45±0.02ijk	18.54±0.03fg
CHK4	147.80 ± 0.43p	16.01 ± 0.05f	395.73 ± 0.04g	2.16±0.02no	1.15±0.02lm	14.43±0.03k
CHK5	200.00 ± 0.57g	12.96 ± 0.29m	218.40 ± 0.05u	2.13±0.03no	1.54±0.03hij	**11.45±0.06n**
CHK6	230.00 ± 0.57c	14.13 ± 0.18ij	382.23 ± 0.07j	2.35±0.02lm	0.82±0.04no	13.20±0.03m
CHK7	120.70 ± 0.46u	17.03 ± 0.51e	412.11 ± 0.07f	2.11±0.06no	1.31±0.11jkl	19.13±0.07bcd
CHK8	195.66 ± 0.57i	18.16 ± 0.16d	266.81 ± 0.19q	3.62±0.04h	2.33±0.04fg	19.05±0.52de
CHK9	211.00 ± 0.57e	13.43 ± 0.03kl	274.84 ± 0.10o	2.53±0.02j	1.15±0.02lm	18.53±0.04fg
HSN1	134.85 ± 0.10s	17.45 ± 0.02e	273.54 ± 0.03p	2.25±0.02mn	1.74±0.03h	18.08±0.02f
HSN2	112.12 ± 0.19v	11.42 ± 0.04n	116.15 ± 0.02x	1.65±0.02r	0.64±0.03o	18.53±0.04fg
HSN3	**107.94 ± 0.04r**	14.45 ± 0.02i	110.61 ± 0.08y	2.34±0.03m	1.44±0.03ijk	17.44±0.03h
HSN4	179.93 ± 0.04k	13.45 ± 0.02jk	297.18 ± 0.10n	5.05±0.02c	2.35±0.02fg	19.93±0.04b
HSN5	191.00 ± 0.07i	15.55 ± 0.13f	392.66 ± 0.02i	2.47±0.04jk	1.66±0.02hi	16.44±0.29i
KDG1	179.86 ± 0.07k	15.76 ± 0.13f	311.15 ± 0.22l	5.10±0.05c	3.25±0.12ab	13.96±0.48kl
KDG2	175. 77 ± 0.16l	17.44 ± 0.29e	417.64 ± 0.41e	2.21±0.06n	1.26±0.10kl	16.45±0.29i
KDG3	140.00 ± 0.57q	14.55 ± 0.03gh	**97.53 ± 0.04z**	**6.06±0.02a**	**3.33±0.04a**	13.52±0.28lm
KDG4	235.50 ± 0.32b	**11.06 ± 0.23n**	260.52 ± 0.26s	2.15±0.08no	1.44±0.03ijk	**21.41±0.05a**
KDG5	195.66 ± 0.24hi	**29.63 ± 0.04a**	376.63 ±0.07k	2.21±0.06n	1.05±0.02lmn	19.59±0.30bc
KDG6	235.86 ± 0.08b	14.41 ± 0.05ij	136.45 ± 0.33w	3.74±0.03h	1.23±0.03kl	19.43±0.04bcd
KDG7	215.96 ± 0.20d	17.41 ± 0.06e	383.54 ± 0.04	5.61±0.05b	2.52±0.04ef	14.42±0.05k
KDG8	135.93 ± 0.03w	28.74 ± 0.03b	151.36 ± 0.04v	2.44±0.03jkl	**0.39±0.35p**	14.43±0.04k
KDG9	163.91± 0.07m	18.53±0.04d	**598.65±0.05a**	5.05±0.02c	3.05±0.02be	19.53±0.04bcd
KDG10	156.60±0.03o	19.53±0.04c	102.16±0.03z	**0.97±0.10q**	0.97±0.10mn	14.45±0.03k
KDG11	209.94±0.03f	13.44±0.03jk	311.14±0.05l	4.02±0.04g	2.25±0.03g	15.53±0.05j
KDG12	148.12±0.18p	11.14±0.03n	516.94±0.05d	5.05±0.02c	2.93±0.04c	18.55±0.03fg
KDG13	196.51±0.26h	11.15±0.03n	556.04±0.02b	4.85±0.02d	2.85±0.03cd	14.44±0.03k
KDG14	179.94±0.03k	17.45±0.02e	394.40±0.02 h	2.06±0.01o	1.65±0.03hi	16.46±0.03i
KDG15	**245.94±0.03a**	11.55±0.03n	262.86±0.04r	3.35±0.03i	2.64±0.03de	14.46±0.03k
Minimum	107.94	11.06	97.53	0.97	0.39	11.45
Maximum	245.94	29.63	598.65	6.06	3.33	21.41

Notes: Each value represents the mean ± standard error of three replicates

Table 4. Analysis of micronutrients (ppm) in rhizospheric soil from coffee growing regions in Karnataka, India

Collection sites	Zn	Cu	Fe	Mn	B
CHK1	0.36±0.02efg	0.76±0.02abc	18.56±0.02g	11.15±0.03l	0.37±0.23defgh
CHK2	0.53±0.03bcdf	**0.91±0.03a**	22.45±0.03a	13.75±0.03fg	0.40±0.11cdef
CHK3	0.65±0.03b	0.80±0.02abc	20.48±0.04e	14.16±0.02ef	0.50±0.03bcde
CHK4	0.55±0.02bc	0.75±0.55abc	18.61±0.03g	13.45±0.03gh	0.26±0.12hij
CHK5	0.35±0.04efgh	0.83±0.04ab	19.53±0.04f	13.43±0.04gh	0.40±0.02cdefgh
CHK6	0.36±0.04efg	0.75±0.03abc	16.15±0.03j	12.78±0.04ij	0.30±0.04fghij
CHK7	0.40±0.11def	0.63±0.04cd	19.75±0.06f	13.44±0.03gh	0.34±0.03efghi
CHK8	0.63±0.04b	0.34±0.06fg	15.37±0.18k	11.13±0.18l	0.63±0.04ab
CHK9	0.53±0.04bcd	0.26±0.03g	17.43±0.04h	14.55±0.03e	0.35±0.05efhi
HSN1	0.25±0.03fghi	0.35±0.03fg	18.54± 0.03g	15.15±0.03d	0.23±0.04h,i
HSN2	0.20±0.03ijk	0.65±0.03cd	**12.11±0.19n**	14.45±0.03e	0.55±0.03bc
HSN3	0.35±0.07efgh	0.46±0.17ef	19.52±0.04f	16.13±0.18c	0.36±0.05efhi
HSN4	**0.08±0.02k**	0.80±0.47abc	21.93±0.48b	13.46±0.03gh	0.27±0.06ghIj
HSN5	0.35±0.03efgh	0.57±0.03de	19.38±0.19f	**11.05±0.10l**	0.35±0.05efhi
KDG1	0.25±0.03fghi	0.44±0.30ef	16.90±0.10i	13.12±0.08hi	**0.73±0.03a**
KDG2	0.23±0.04ghij	0.54±0.04de	18.58±0.22g	12.60±0.49jk	0.34±0.04efghi
KDG3	0.43±0.09cde	0.24±0.04g	14.40±0.07l	12.82±0.46ij	**0.15±0.06j**
KDG4	0.53±0.04bcd	0.33±0.04fg	18.52±0.05g	12.23±0.07k	0.22±0.04hIj
KDG5	0.64±0.03b	0.35±0.06fg	14.44±0.03l	13.42±0.05gh	0.63±0.05ab
KDG6	0.44±0.03cde	0.27±0.04g	17.43±0.03h	13.53±0.04gh	0.63±0.04ab
KDG7	0.21±0.03hijk	**0.08±0.02h**	19.43±0.03f	13.44±0.03gh	0.40±0.02cdefgh
KDG8	0.37±0.04efg	0.26±0.05g	**22.49± 0.09a**	18.53±0.04a	0.45±0.05cdefg
KDG9	**0.84±0.04a**	0.78±0.04abc	13.45±0.03m	11.44±0.03l	0.54±0.03bcd
KDG10	0.47±0.04cde	0.36±0.03fg	14.53±0.04l	10.04±0.02m	0.46±0.06bcdef
KDG11	0.10±0.03jk	0.77±0.04abc	14.15±0.03l	13.13±0.18hi	0.27±0.05ghij
KDG12	0.15±0.03ijk	0.69±0.04b,d	21.55± 0.03c	**17.44±0.03b**	0.23±0.03hij
KDG13	0.38±0.01efg	0.29±0.03fg	19.55± 0.02f	17.18±0.01b	0.18±0.02ij
KDG14	0.19±0.03ijk	0.67±0.03abc	21.13± 0.23d	13.46±0.03gh	0.37±0.04dgefh
KDG15	0.39±0.02ef	0.67±0.02bd	18.55± 0.03g	13.48±0.05gh	0.36±0.03efhi
Minimum	0.08	0.08	12.11	11.05	0.15
Maximum	0.84	0.91	22.49	17.44	0.73

Notes: Each value represents the mean ± standard error of three replicates

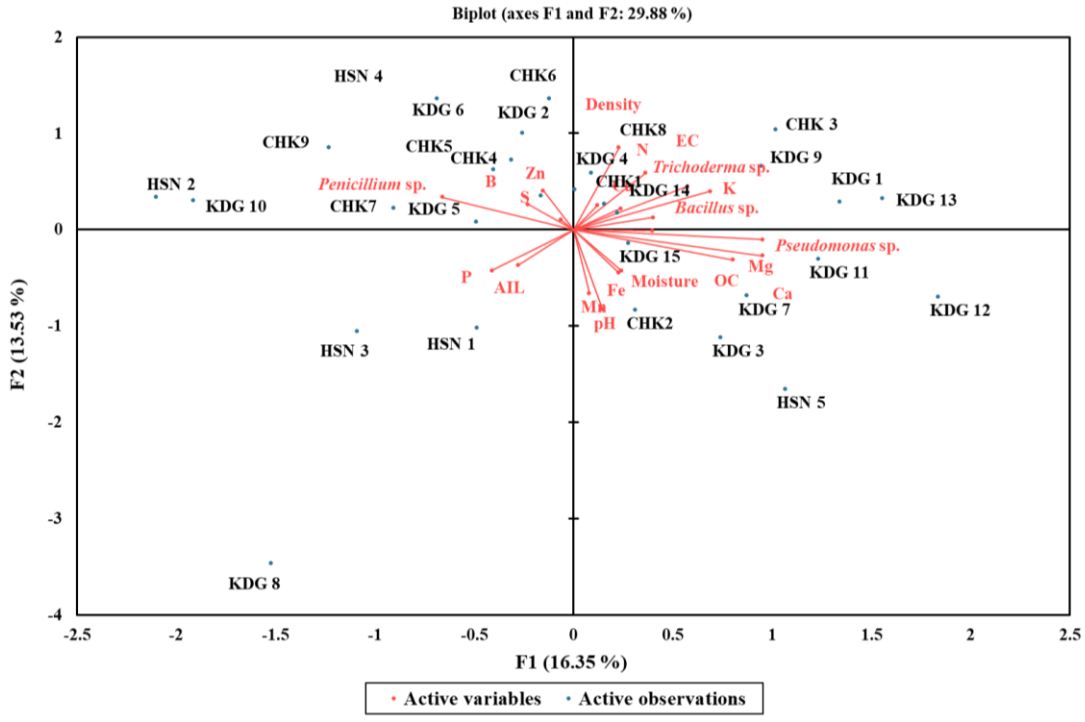

Figure 3. Biplot analysis among soil parameters and Average infection % in lot (AIL)

The PCA yielded nine principal components (PCs) with eigenvalues>1, explaining 82.24 % of the dataset's total variance. According to the rotated factor loading, PC1 explains 16.33 % of the total variance and denotes the N, OC, Ca, and Mg. Furthermore, PC2 explains 13.54 % of the total variance, exhibits the highest positive correlation with *Trichoderma* sp., *Penicillium* sp., *Pseudomonas* sp., and density. PC3 explains about 11.12 % of the total variance, which represents pH and phosphorus. PC4 explains 9.46 % of the total variance, represented by EC and Fe. PC5 explains 8.79 % of the total variance, which represents Mn and AIL. PC6 explains about 7.02 % of the total variance, which represents B and Zn. PC7 explains 6.13 % of the total variance, which represents *Bacillus* sp. and K., while PC8 explains 5.06 % of the total variance, which represents Cu and moisture. Finally, PC9 explains about 4.48 % of the total variance, which is represented in Table 5.

3.4. Pearson coefficient of correlation analysis

The correlation matrix between soil parameters and Average infection % in the lot (AIL) is shown in Table 6. The pH of the soil was positively correlated with OC ($r=0.406^{*}$, $p<0.05$). EC was positively correlated ($p<0.05$) with K ($r=0.499^{**}$), OC was positively correlated ($p< 0.05$) with Ca ($r=0.579^{**}$), and Mg ($r=0.565^{**}$), and negatively correlated with *Penicillium* sp. ($r=-0.376^{*}$). Although available N is positively correlated with AIL ($r=0.456^{*}$) and density ($r=0.386^{*}$).

3.5. Analysis of beneficial microbes from coffee leaf rust affected field soil

The present study illustrates the analysis of beneficial microbes from the coffee leaf rust field and found various taxa of microflora, including fungi, such as *Penicillium* sp., and *Trichoderma* sp., bacterial species, such as *Pseudomonas* sp. and *Bacillus* sp. (Fig. 4), and their effect on the severity of CLR. Among all the sampling sites, HSN4 exhibited the highest severity of coffee leaf rust, that is up to 94 % and has fewer beneficial microbes, whereas CHK2 has less severity of disease with more beneficial microbes. Hence, the presence of beneficial microbes depends on the severity of CLR disease (Fig. 5).

3.6 Clustering of the soil samples

Clustering is an effective data analysis approach that categorizes numerous variables into distinct groups based on specific characteristics. Additionally, cluster analysis helps in grouping soil parameters based on factors controlling soil variation, enabling the development of soil maps and understanding relationships among soil properties. The resulting data of soil parameters were grouped using the k-means clustering method, and a scatter plot was developed using the scores of the first two principal components, which represent 29.89 % of the total variance. The grouping of soil samples resulted in the formation of 4 clusters that were related to their soil parameters.

Table 5. Principal component analysis (PCA) of soil parameters

Soil parameters	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9
pH	.381	.158	**.785**	.053	.036	-.116	-.285	-.094	.079
EC (dSm^{-1})	.264	.193	-.550	**.529**	.077	.347	.128	.056	.022
OC (%)	**.733**	-.136	.306	.064	-.218	.025	.145	.325	.045
N (Kg ac^{-1})	**.156**	.068	-.122	.096	-.794	-.063	.115	-.220	-.002
P (Kg ac^{-1})	-.227	.142	**.662**	-.082	.183	.452	.292	-.135	.001
K (Kg ac^{-1})	.281	.265	-.374	.352	-.012	.011	**.577**	.149	.307
Ca (meq 100^{-1})	**.920**	.038	-.018	.094	.036	-.026	.014	-.073	-.051
Mg (meq $100g^{-1}$)	**.920**	.019	-.113	-.041	-.050	-.086	.074	.020	-.053
S (ppm)	-.041	-.007	.022	-.035	.042	.104	-.013	-.028	**.894**
Zn (ppm)	-.110	.158	-.002	-.023	-.184	**.583**	.098	-.095	.396
Cu (ppm)	-.008	-.092	-.310	.129	-.032	-.095	-.050	**.840**	.083
Fe (ppm)	-.003	-.037	.103	**.855**	.176	-.316	-.087	-.004	.018
Mn (ppm)	.074	-.051	.102	.326	**.746**	-.279	.020	-.210	.005
B (ppm)	-.012	-.049	.003	-.099	-.030	**.897**	-.112	-.024	-.001
Density (g cm^3)	.108	**.292**	-.631	-.321	-.390	-.040	.031	-.092	.022
Moisture (%)	.145	.088	.368	-.094	.170	-.016	.152	**.650**	-.265
T. sp.	-.121	**.938**	.011	.038	-.069	.033	-.035	.111	.069
Pe. sp.	.003	**.919**	.071	.111	-.153	.024	.061	-.111	-.022
P. sp.	.347	**.587**	-.215	-.149	.235	.034	-.295	-.127	-.058
B. sp.	.086	-.119	-.019	-.051	-.097	-.039	**.930**	-.003	-.062
AIL	-.069	-.329	.003	-.580	**.397**	-.224	-.238	-.174	.278
Eigen values	3.430	2.843	2.336	1.987	1.846	1.475	1.288	1.063	1.003
% Variance	16.33	13.537	11.124	9.462	8.789	7.022	6.132	5.064	4.778
% Cumulative variance	16.335	29.872	40.996	50.458	59.247	66.269	72.401	77.464	82.242

Notes: Average infection % in lot (AIL), *T*. sp. - *Trichoderma* sp., *Pe*. sp. - *Penicillium* sp., *P*. sp. - *Pseudomonas* sp., *B*. sp. - *Bacillus* sp.

Table 6. Pearson correlation coefficient (r) between soil parameters

Soil parameters	pH	EC	OC	N	P	K	Ca	Mg	S	Zn	Cu	Fe	Mn	B	Density	Moisture	*T.* sp.	*Pe.* sp.	*P.* sp.	*B.* sp.	AIL
pH	1																				
EC	-0.349	1																			
OC	**.406***	0.05	1																		
N	-0.096	0.117	0.225	1																	
P	0.352	-0.279	0.049	-0.266	1																
K	-0.226	**.550****	0.228	0.162	-0.078	1															
Ca	0.316	0.313	**.579****	0.101	-0.234	0.26	1														
Mg	0.239	0.253	**.565****	0.139	-0.322	0.313	**.850****	1													
S	0.001	0.076	-0.018	0.007	0.021	0.153	-0.097	-0.103	1												
Zn	-0.039	0.12	-0.114	0.067	0.263	0.18	-0.111	-0.095	0.231	1											
Cu	-0.267	0.126	0.236	-0.125	-0.336	0.302	-0.045	0.01	-0.09	-0.055	1										
Fe	0.205	0.237	0.048	-0.107	-0.075	0.191	0.07	-0.014	-0.063	-0.255	0.161	1									
Mn	0.179	0.076	-0.052	-0.311	0.028	0.044	0.083	-0.049	0.014	-0.299	-0.155	**.468***	1								
B	-0.093	0.221	0.036	0.05	**.392***	-0.119	-0.073	-0.132	0.165	0.326	-0.084	-0.317	-0.231	1							
Density	-0.358	0.23	-0.04	**.386***	-0.335	0.289	0.012	0.178	-0.029	0.041	0.073	-0.318	**-.411***	0.039	1						
Moisture	0.206	-0.017	0.308	-0.149	0.103	-0.072	0.07	0.143	-0.106	-0.237	0.211	-0.09	0.098	-0.025	-0.288	1					
***T.* sp.**	0.061	-0.195	-0.111	-0.161	-0.115	-0.144	-0.049	-0.038	0.006	0.04	0.236	0.26	-0.211	0.002	-0.099	-0.149	1				
***Pe.* sp.**	-0.276	-0.075	**-.376***	0.072	-0.076	0.101	0.065	-0.09	-0.117	0.157	0.053	0.038	-0.204	-0.057	-0.062	**-.476****	0.169	1			
***P.* sp.**	0.143	0.083	0.041	-0.04	-0.117	0.099	0.244	0.275	-0.059	0.053	-0.041	-0.093	0.165	0.042	0.279	-0.115	0.121	0.008	1		
***B.* sp.**	-0.271	0.051	0.229	0.192	0.157	**.433***	0.083	0.155	-0.064	0.045	0.005	-0.086	-0.053	-0.087	0.043	0.101	-0.106	0.008	-0.255	1	
AIL	0.028	0.201	0.116	**.456***	-0.103	0.146	-0.004	0.009	-0.029	0.013	-0.064	-0.177	-0.346	0.025	0.262	0.07	-0.172	-0.012	-0.062	-0.17	1

Notes: Average infection % in lot (AIL), *T.* sp. - *Trichoderma* sp., *Pe.* sp. - *Penicillium* sp., *P.* sp. - *Pseudomonas* sp., *B.* sp. - *Bacillus* sp.

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

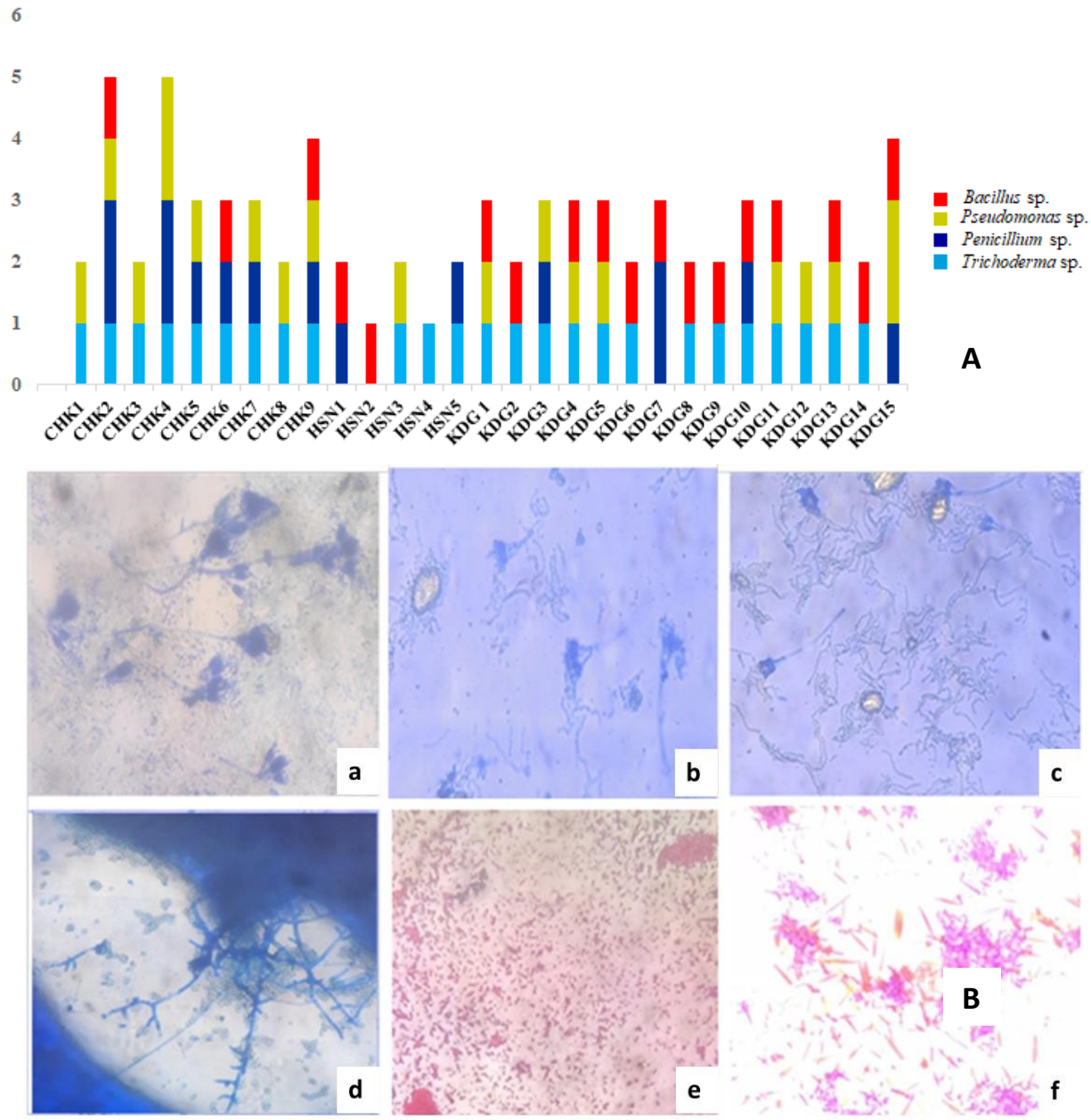

Figure 4. A: Abundance of beneficial microbes in soil; B: Three different *Penicillium* sp. (a-c), *Trichoderma* sp. (d), *Pseudomonas* sp. (e), *Bacillus* sp. (f)

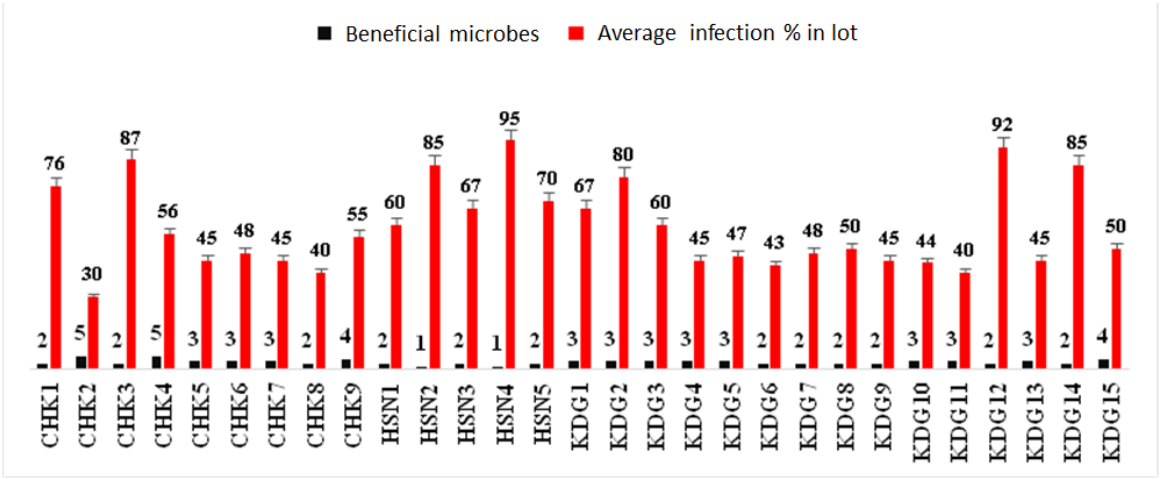

Figure 5. Correlation between AIL % and abundance of beneficial microflora

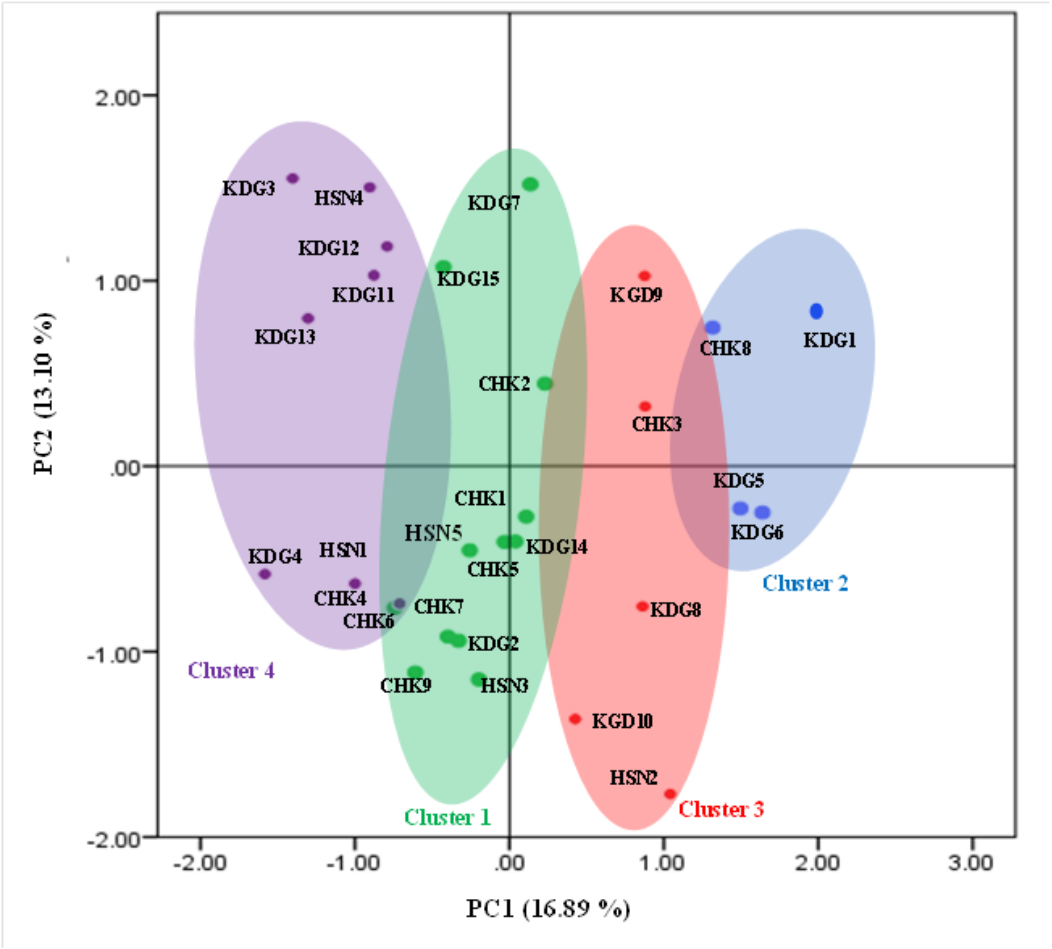

Figure 6. K-means clustering of soil parameters expressed by two principal components

Cluster 1 consists of 12 locations that have the mean values of N 183.51 Kg ac^{-1}, Cu 0.59 ppm, and Fe 19.20 ppm. Cluster 2 consists of 4 locations and has the highest EC 0.16 dS m^{-1}, OC 1.07 %, N 201.76 Kg ac^{-1}, P 19.49 Kg ac^{-1}, S 18.00 ppm, and B 0.65 ppm. Cluster 3 includes 5 locations that have the highest Zn and moisture, with the values of 0.50 ppm and 42.33 %. Cluster 4 is grouped by 9 locations which are characterized by having the highest mean values of pH 4.57, K 338.57 Kg ac^{-1}, Ca 3.94 meq $100g^{-1}$, Mg 2.25 meq $100g^{-1}$, Mn 14.35 meq $100g^{-1}$, and moisture 43.13 % (Fig. 6, Table 7). Considering the all four cluster values (1, 2, 3 and 4) as the class label for the samples, K- means results in the analysis of physico-chemical elements like pH, moisture, density, N, Cu, Fe, EC, OC, K, P, S, B, Zn, K, Ca, Mg, and Mn.

4. DISCUSSION

This study examines the impact of physico-chemical and microbial properties of soils on coffee leaf rust disease. The soil physical properties, such as texture, density, and moisture, are vital assets of the soil that differ greatly in diverse regions. The obtained results represent the variation in coffee leaf rust disease in different geographical regions of coffee growing in Karnataka, and determine the soil physico-chemical and microbial diversity that influences the rust disease. The texture of soil varies from region to region, including clay loam, loamy, and sandy loam. Subsequently, the highest moisture content is found in CHK6. Daivasikamani and Rajanaika (2009) assessed urediospore germination percentages at various temperatures (18, 20, 22, 24, and 26 °C) and relative humidity levels (50, 60, 70, 80, and 90 %). The highest urediospore germination was observed at 24 °C (48.60 %) and 70 % relative humidity (40.80 %). Germination was negatively affected when temperatures deviated from the optimum, decreasing to 33.00 % at 18 °C and 36.20 % at 26 °C. Spore germination was also reduced at extreme relative humidity levels, dropping to 31.60 % at 50 % RH and 26.40 % at 90 % RH. As the moisture content of soil increases, the severity of disease incidence increases; the highest moisture was found in KDG 11, that is 47.93 % which favours the germination of urediospores. Singh and Gupta (2019) studied the role of temperature, rainfall, and humidity in causing French bean rust. Optimum disease development was found at higher relative humidity (> 85 %) with moderate temperature of 20-25 °C. A similar study was reported by Niranjana et al. (2019), which demonstrated seven PCAs with eigenvalues>1 explaining 77.89 % of the total variance from twenty-four soil samples. The relative disease severity of chickpea wilt and its relationship to soil properties and biological parameters showed positive correlation with total N, EC, and ID-Foc, whereas negatively correlated with Olsen-P, TrPn, and *Pseudomonas* (Moutassem et al., 2019). In response to N, the obligate fungal parasites change the anatomy and physiology of the host plant. Due to the presence of high nitrogen, the vegetative stage of young leaves is more susceptible to rust disease.

Table 7. Descriptive statistics for k-means cluster analysis for soil parameters

Soil parameters	Cluster 1					Cluster 2					Cluster 3					Cluster 4				
	Mean	Min	Max	Sd	CV %	Mean	Min	Max	Sd	CV %	Mean	Min	Max	Sd	CV %	Mean	Min	Max	Sd	CV %
pH	4.31	3.67	4.93	0.40	9.20	4.43	3.97	4.78	0.39	8.80	4.47	3.63	5.46	0.65	14.54	4.57	4.20	5.54	0.17	3.71
EC	0.09	0.03	0.21	0.14	155.00	0.16	0.02	0.31	0.15	93.75	0.15	0.02	0.44	0.17	113.3	0.10	0.02	0.28	0.03	30.00
OC	0.80	0.36	1.28	0.29	36.25	1.07	0.73	1.22	0.23	31.50	0.82	0.56	1.10	0.24	29.26	1.05	0.75	1.44	0.26	24.76
N	183.51	120.70	245.90	39.70	21.63	201.76	179.8	235.86	11.96	5.92	144.1	107.9	180.00	32.27	22.39	174.08	134.8	235.50	37.14	21.33
P	15.20	11.55	17.45	1.97	12.96	19.49	14.41	29.63	3.46	17.75	17.95	11.42	28.74	7.12	39.66	13.53	11.06	17.45	2.39	17.66
K	317.14	110.61	417.60	95.52	30.11	272.76	136.4	376.63	50.72	18.59	297.2	102.1	598.6	240.60	80.95	338.57	97.53	556.0	147.96	43.70
Ca	2.97	2.06	5.61	1.14	38.38	3.66	2.21	5.10	1.18	32.24	2.69	0.97	5.05	1.58	58.73	3.94	2.15	6.06	1.55	39.34
Mg	1.65	0.82	2.64	0.54	32.72	1.96	1.05	3.25	1.02	52.04	1.30	0.39	3.05	0.47	36.15	2.25	1.15	3.33	0.76	33.77
S	15.58	11.45	19.13	2.27	14.56	18.00	13.96	19.59	2.70	15.00	17.09	14.43	19.53	2.45	14.33	16.98	13.52	21.41	2.90	17.07
Zn	0.36	0.19	0.53	0.10	27.77	0.49	0.25	0.64	0.18	36.73	0.50	0.20	0.84	0.24	48.00	0.30	0.08	0.55	0.18	60.00
Cu	0.59	0.08	0.91	0.23	41.07	0.35	0.27	0.44	0.06	22.22	0.57	0.26	0.80	0.24	42.10	0.52	0.24	0.80	0.24	46.15
Fe	19.20	16.15	22.49	1.61	8.38	16.03	14.44	17.43	1.37	8.54	16.61	12.11	22.45	4.58	27.57	18.40	14.15	21.93	2.87	15.59
Mn	13.27	11.05	16.13	1.35	10.17	12.80	11.13	13.53	1.12	8.75	13.72	10.04	18.53	3.26	23.76	14.35	12.23	17.44	2.00	13.93
B	0.36	0.30	0.40	0.02	5.55	0.65	0.63	0.73	0.05	7.93	0.50	0.45	0.55	0.04	8.00	0.22	0.15	0.27	0.04	18.18
Density	1.26	1.12	1.43	0.08	6.34	1.30	1.25	1.38	0.05	3.84	1.18	0.92	1.30	0.14	11.86	1.22	1.17	1.33	0.05	4.09
Moisture	37.22	27.92	40.94	3.39	9.10	38.93	36.93	39.93	1.41	3.62	42.33	34.95	46.91	4.86	11.48	43.13	36.94	47.93	4.08	9.45

Notes: Min – minimum value; Max – maximum value; SD – Standard deviation; CV – Coefficient of variation

Metabolism of the plant changes, such as rapid cell growth, cell wall thinning, and induce cuticle at a high rate of N: as a few key enzymes of phenol metabolism have lower activity, this leads to a decrease in phenolics and lowers the lignin content that is part of the defence system against infection in plants and also increases the accumulation of short-chain carbohydrates. These sugars are utilized by rust pathogens as a source of energy for direct entry through the leaf cuticle (Dordas, 2008). Subsequently, in the present study, nitrogen is positively correlated with AIL, and the highest nitrogen content was found in KDG 15. Additionally, total P is positively correlated ($p < 0.05$) with boron ($r=0.392$). K is positively correlated ($p < 0.05$) with *Bacillus* sp. ($r=0.433^{*}$). Subsequently, Ca is positively correlated ($p < 0.05$) with Mg ($r = 0.85^{**}$). Moisture is negatively correlated ($p < 0.05$) with *Penicillium* sp. ($r =-0.47^{**}$). Kiani et al. (2021) screened 16 endophytic bacteria isolated from a strip rust-resistant cultivar of wheat; a total of five bacterial strains, *Bacillus megaterium* 6A, *Serratia marcescens* 3A, *Paneibacillus xylanexedens* 7A, *Staphylococcus agentis* 15A, and *Bacillus subtilis* 11A showed significantly inhibited *Puccinia striiformis* urediniospores germination. The most common genera used mainly as plant growth promoters in coffee production are *Pseudomonas*, *Klebsiella*, *Azotobacter*, *Azospirillum*, *Rhizobium*, and *Serratia*, which may enhance nutrient absorption in shoot and root formation, phosphorus solubilization, environmental stress tolerance, and control phytopathogens. *B. lentimorbus*, *B. thuringiensis*, *Brevibacillus choshinensis*, *P. fluorescens*, *B. cereus*, and *B. subtilis* have been reported as antagonists to the CLR agent (Santiago-Santiago et al., 2023). Abdel-Fattah et al. (2021) determined the quality of soil using PCA and classified it into three clusters: cluster I represents about 13.89 % of the soil samples, cluster II represents about 16.6 % of the samples, and cluster III represents 69.44 %. Soil shows a large variability, with the greatest variation. The PCA explained 65 % variability and three clusters. Cluster I includes the highest loading of PC1, which includes Zn, Cu, pH, Fe, P, and Mn. Cluster II has the highest loading in OC and N. Cluster III comprises only K. Maione et al. (2022) demonstrated the data mining techniques applied to study the elemental fingerprints of soil. Cluster analysis was performed using the k-means clustering algorithm, showing the chemical patterns in three different clusters. Cluster I represents a higher mean value of Ce and a lower concentration value for Cr, Ni, As, and Zn than those of other clusters. Cluster II shows a higher level of Fe, Mn, Ni, Sc, Sr, V, Co, and Cu, compared to samples from other clusters. Cluster III showed higher levels of Cr, Mo, As, Ba, and Th. In the present study, all soil samples are grouped into four different clusters. Cluster IV was grouped by nine locations, which were characterized by the highest mean values of pH, K, Ca, Mg, Mn, and moisture. Sopialena et al. (2022) identified the causes of leaf rust attacking maize plants in two particular regions. Analysis of the relation between ecological factors and the infection rate of maize leaf rust. The development of leaf rust was directly proportional to ecological conditions, particularly temperature, increased humidity, and soil quality. Chaubey et al. (2019) reported that the effect of nitrogen and phosphorus on white rust disease of the mustard plant, where the minimum percentage of disease incidence was found in 17.03 %, and the maximum disease percentage in the control was 67.66 %. The higher concentrations of nitrogen decrease the phenolic compounds like lignin, which stimulates the accumulation of starch in leaves, from which rust pathogens utilize and invade through the cuticle (Marschner, 2012). Devadas et al. (2014) found that increased nitrogen affects the stripe rust infection in wheat. In two repeated planting seasons, the incidence and disease index of powdery mildew and stripe rust increased, whereas the disease index was more affected by nitrogen levels than their incidence (Luo et al., 2021; Panigatti et al., 2025). Pinheiro et al. (2011) reported that potassium (K) and calcium (Ca) supply in nutrient solution impacted Asian coffee leaf rust (CLR) severity, with reduced disease progress observed when Ca was supplied across all K doses, particularly at combined K and Ca doses of 8 and 11 mmol L^{-1}. Pérez et al. (2019) studied the effect of five doses of boron (B), zinc (Zn), and manganese (Mn) (0.05, 0.25, 0.50, 1.0, 2.0, and 4.0 mg L^{-1}) on the severity of rust on the coffee plant. A significant interaction between nitrogen and potassium was concerning the AUDPCS and the dried plant mass. Disease severity was found to be negatively correlated with the dry mass of coffee seedlings, indicating a significant relationship.

5. CONCLUSION

The overview of the study revealed a significant correlation between the severity of coffee leaf rust disease and soil parameters. Correlation analysis revealed that nitrogen, potassium, and density were the most prominent soil parameters influencing coffee leaf rust disease. *Trichoderma* sp., *Penicillium* sp., *Pseudomonas* sp., and *Bacillus* sp. are different taxa of microorganisms found in the coffee rhizosphere. These microbiomes are negatively correlated with rust disease. The soil parameters in different locations are distributed among five different clusters based on the availability of nutrients. Proper management of soil macro- and micro-nutrients helps maintain soil quality and diverse microbiomes, leading to a significant decrease in coffee leaf rust.

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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