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Influence of Soil Physicochemical Properties and Microbial Dynamics on Incidence of Major Diseases of Tomato in High Production Regions of Himachal Pradesh

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Abstract

The study was conducted from March to September, 2021–2022 in the Solan and Sirmour districts of Himachal Pradeshwith an aim to assess the influence of soil physicochemical characteristics and microbial communities on the incidence of major tomato diseases in high-production areas of Himachal Pradesh. Soil samples were collected from tomato-growing fields across multiple locations and analyzed for pH, electrical conductivity, organic carbon, and nutrient content. Standard protocols were followed for physicochemical analyses, and microbial populations were quantified using serial dilution and plating methods. Damping-off incidence ranged from 21.33% to 51.00%, while wilt incidence varied between 18.00% to 37.00%. This reflected a high disease pressure influenced by local soil and environmental conditions. Microbial analysis revealed spatial variation. Panwa recorded the highest fungal count (75×10^3 cfu g^{-1} soil), while Kandaghat recorded the highest bacterial count (98×10^6 cfu g^{-1} soil), highlighting heterogeneity in microbial distribution. Soil pH varied across sites, with slightly alkaline in Palashala and Kurgal. A strong positive correlations were observed between soil pH and microbial counts. Moderate positive correlations were found between, nitrogen, phosphorus, and potassium content with microbial populations. These findings demonstrated that variations in soil physicochemical properties directly influenced microbial dynamics and disease incidences. The results highlighted that soil conditions significantly impact microbial dynamics and disease incidence, emphasizing the need of effective soil health management for sustainable tomato cultivation.

Keywords: Damping-off , soil properties, microbial dynamics, wilt

1. Introduction

Crops thrive in environments where soil conditions are optimized for growth, with balanced nutrients and favourable physical properties supporting healthy plant development (Srinivasan et al., 2017; Shah and Wu, 2019). Soil not only serves as a growth medium but also supports a complex microbial community that plays a crucial role in plant health (Biradar et al., 2025; Adedayo et al., 2022; Bordoloi and Sharma, 2022). For crops like tomatoes (*Solanum lycopersicum*), soil characteristics are particularly significant, as they directly influence both the plant's growth and its susceptibility to diseases (Rodrigues and Furlong, 2022; Bhardwaj et al., 2023b). Harmful soil-borne pathogens, such as fungi causing damping-off and wilt diseases, can proliferate under specific soil conditions, leading to significant crop losses (Bhardwaj and Chandel, 2023a; Bhardwaj and Chandel, 2024; Delai et al., 2024). The occurrence and severity of plant diseases are intricately linked to the physicochemical properties of the soil, which influence both microbial community structure and pathogen behaviour (Wang et al., 2017; Jayaraman et al., 2021; Chaudhary et al., 2024). Variables such as pH, organic matter content, nutrient levels, and microbial populations interact in ways that may either suppress or promote the development of plant diseases (Bonanomi et al., 2018; Niu et al., 2020). Several studies have demonstrated that soil parameters like electrical conductivity (EC), nitrogen, phosphorus, and potassium levels can directly or indirectly influence the incidence of fungal and bacterial diseases (Kim et al., 2016; Wang et al., 2018; Bi et al., 2022). Several studies have explored the complex relationship between soil properties and plant diseases (Jayaraman et al., 2021; Akanmu et al., 2021). For instance, Niu et al. (2020) and Bharat (2017) discussed how a balanced microbial community in the soil can suppress soil-borne pathogens through mechanisms like competitive exclusion and antimicrobial activity. Zhang et al. (2021) highlighted the significant role of soil pH, noting that deviations from the optimal range can either limit nutrient uptake in plants or favour the growth of harmful pathogens. In terms of organic matter, Hu et al. (2023) showed that higher organic content can lead to increased microbial diversity, which helps in controlling pathogens such as *Verticillium dahliae*, responsible for wilt in tomatoes. Nutrient management also plays a crucial role, as Martin-Cardoso et al. (2025) found that excessive nitrogen can promote bacterial pathogens like *Pseudomonas syringae*, while balanced fertilization supports healthy crops and reduces disease prevalence. Maywald et al. (2023) examined the effects of soil salinity, measured through electrical conductivity (EC), and found that higher EC levels exacerbate fungal diseases like *Phytophthora infestans* in tomatoes. Pastor et al. (2023) further emphasized the importance of soil microbial communities, showing that beneficial microbes like *Trichoderma* and *Bacillus* can suppress harmful pathogens such as *Rhizoctonia solani*. Likewise, Chalazas et al. (2022) noted the lack of region-specific studies and called for localized data on soil factors to improve disease management in specific agroecosystems. In regions like Himachal Pradesh, India, the diverse agro-climatic zones and soil types offer a unique opportunity to examine how soil characteristics influence tomato disease prevalence, particularly fungal infections. Despite this potential, there is a lack of localized data on how these factors affect major diseases of the area. This study aims to address this gap by investigating the relationship between soil properties, microbial communities, and the prevalence of damping-off and wilt diseases in major tomato-growing districts. By focusing on these interactions, this study sought to provide region-specific insights to help farmers in Himachal Pradesh develop targeted soil management strategies for disease mitigation and improved tomato health.

2. Materials and Methods

2.1. Study area and experimental design

The study was conducted during March to September, 2020–2021 growing season across two major tomato-growing districts of Himachal Pradesh, Solan and Sirmour. A total of twenty-six experimental plots, representative of natural nursery and field conditions, were selected for the study. These plots were randomly assigned to minimize sampling bias. Disease data were systematically recorded based on the proportion of seedlings exhibiting symptoms of damping-off and wilt in both nursery and fields. For damping-off, symptoms including root rot, softening of the stem at the soil line, water-soaked lower stems, and collapsed seedlings were observed and quantified. For wilt diseases, plants were monitored for characteristic symptoms, such as chlorosis (yellowing) of lower leaves, necrosis (browning) and desiccation of leaf tissues, vascular discoloration, stunted growth, and wilting. Percent Disease Incidence (PDI) was calculated using the formula: Disease incidence (%)=(n/N)×100**,** where nwas the number of plants exhibiting symptoms and N was the total number of plants examined. An average of 10 plants from each site were considered to represent the disease incidence of the respective locality.

2.2. Assessment of soil physicochemical properties

2.2.1. Soil sampling and analysis of chemical properties

Soil samples were collected from a depth of 5–10 cm at various investigation sites within the Solan and Sirmour districts. The samples were air-dried, ground, and sieved through a 2 mm mesh before analysis. The chemical properties of the soil were determined as follows: Soil pH was measured using a 1:2.5 soil-water suspension according to the method outlined by Piper (1966), with pH determined potentiometrically using a glass electrode and a digital pH meter. Electrical conductivity (EC) was assessed in a 1:2.5 soil-water extract using a conductivity bridge, following the procedure of Jackson (1973). Organic carbon (OC) content was quantified using the wet oxidation method (Jackson, 1973), where soil was treated with potassium dichromate solution, and the excess potassium dichromate was titrated using ferrous ammonium sulphate in the presence of concentrated phosphoric acid and diphenyl amine indicator.

2.1.2. Estimation of soil nutrient content and bulk density

Available nitrogen (N) in the soil was estimated using the alkaline potassium permanganate method (Subbaiahand Asija, 1956) with Kjeldhal flasks. Available phosphorus (P) was extracted with 0.5M sodium bicarbonate and quantified using the chloromolybdic blue method on a UV spectrophotometer at 660 nm. Available potassium (K) was extracted with neutral normal ammonium acetate (Jackson, 1973) and measured by flame photometry. Soil bulk density was determined using the standard core method (Wilde et al., 1964).

2.2. Assessment of soil microbial density

To determine microbial counts, 1 g of soil was suspended in phosphate buffer and subjected to serial dilution. For bacteria, the suspension was diluted to 10^{-4}, and for fungi, to 10^{-6}. The dilutions were plated on Nutrient Agar (NA) and Potato Dextrose Agar (PDA), respectively. Bacterial plates were incubated at 37°C for 24–48 h, while fungal plates were incubated at 25–30°C for 3–5 days. After incubation, colonies were counted, and microbial counts were calculated as colony-forming units (CFU) g^{-1} of soil by multiplying the colony count by the dilution factor and dividing by the soil weight (Wollum, 1982).

2.4. *Correlation of soil physicochemical properties with microbial count*

Pearson's correlation coefficient was used to assess the relationships between soil properties (pH, EC, OC, N, P, K, Bulk Density) and microbial counts (fungal and bacterial). Data from each site were analyzed to examine how soil characteristics influence microbial populations in the rhizosphere. OP stat software was used to calculate correlation coefficients, and the results were interpreted to understand the correlations between soil properties and microbial counts (Cui and Holden, 2015).

2.5. Statistical analysis

The Percent Disease Incidence (PDI) was calculated for damping-off and wilt diseases as the percentage of plants showing symptoms in each plot. Descriptive statistics (mean) were computed for soil properties (pH, EC, OC, N, P, K, bulk density) and microbial counts (fungal and bacterial) for each district. The data were analyzed using OP stat software. To assess correlations between soil properties and microbial counts, Pearson's correlation was used for normally distributed data. All statistical tests were considered significant at $p \leq 0.05$.

3. Results and Discussion

3.1. Disease incidence and microbial count in major tomato growing districs of Himachal Pradesh

The occurrence of damping-off and wilt diseases varied significantly across the Solan and Sirmourdistricts of Himachal Pradesh (Table 1). Damping-off incidence ranged from 21.33% to 51.00%, while wilt incidence ranged from 18.00% to 37.00%. In Solan, the mean incidence was 29.46% for damping-off and 25.69% for wilt. In Sirmour, the mean incidence was 34.60% for damping-off and 27.32% for wilt. In Solan district, maximum disease incidence of damping-off (38.00%) was recorded at Jadari, followed by Kathar (36.00%), Mathiya (35.33%), and Palashla (35.00%). The minimum disease incidence (21.33%) was observed at Nauni, followed by Dharja (21.66%), Basal (23.00%), and Dolag (25.00%). Similarly, in Sirmour district, maximum disease incidence of damping-off (51.00%) was at Rajgarh followed by Pabiyana (41.33%), Deothal (39%) and Nainatikker (38.33%). Minimum disease incidence (25.00%) was recorded at Dilman followed by Tikkar and Poanta Sahib (28.00%), which recorded equal level of disease incidence. Regarding wilt, the maximum disease incidence in Solan district (37.00%) was recorded at Damrogfollowed by Dolag and Mansar with 33.23, 32.00%, respectively. However, minimum disease incidence (18.00%) was recorded at Dharja followed by Mathiya and Basal with 19.66% and 20.00%. While in Sirmour district, maximum wilt incidence (35.00%) was recorded in Narag followed by Mangarh (34.00%) and Panwa (32.00%) and minimum disease incidence was recorded in Deothal (20.00%), Dilman (20.56%) and followed by Saraha (22.00%) (Table 1).

The present results aligned with Stepniewska et al. (2020), Tahat et al. (2020), Bossou et al. (2022), and Chittarath et al. (2022), who studied damping-off in spruce, pine and pulse crops in Europe, Jordan, and Benin, as well as Fusarium wilt in bananas in Laos and Vietnam. They concluded that regions with higher disease occurrence likely have favourable conditions for pathogens, plant susceptibility, and poor drainage (Pegg et al., 2019). Additionally, pathogen spores persisted in soil, aiding in disease continuity (Bhardwaj et al., 2023; Bhardwaj and Gupta, 2024). In contrast, areas with lower disease incidence were linked to effective crop rotation, which disrupted the life cycle of soil-borne pathogens, and used of presence of beneficial soil microbes (Panth et al., 2020).

Table 1: Incidence of damping-off and wilt and assessment of microbial count in major tomato growing districts of Himachal Pradesh

Districts	Disease incidence (%)		Microbial count (cfu g^{-1} soil)	
Locations	Damping-off	Wilt	Fungal count ($\times 10^{-3}$)	Bacterial count ($\times 10^{-6}$)
District				
Dharja	21.66	18.00	29	49
Deothi	33.33	26.00	55	34
Damrog	25.66	37.00	42	58
Dadhog	28.66	23.00	39	26
Nauni	21.33	24.33	31	35
Kandaghat	32.00	22.60	62	98
Mathiya	35.33	19.66	40	65
Salogra	31.00	29.33	20	15
Sadhupul	26.00	27.33	51	77
Jadari	38.00	23.00	28	24
Dolag	25.00	33.23	43	73
Basal	23.00	20.00	54	27
Mansar	30.00	32.00	31	56
Kathar	36.00	26.00	52	46
Palashla	35.00	24.00	26	30
Mean	29.46	25.69	40.20	47.53
Sirmour district				
Tikkar	28.00	30.00	37	25
Pabiyana	41.33	26.66	45	18
Nainatikker	38.33	22.33	29	49
Panwa	32.66	32.00	75	36
Deothal	39.00	20.00	51	22
Narag	29.00	35.00	46	73
Saraha	33.66	22.00	34	41
Rajgarh	51.00	28.00	38	27
Dilman	25.00	20.56	66	56
Mangarh	34.66	34.00	43	63
Poanta Sahib	28.00	30.00	37	25
Mean	34.60	27.32	45.54	39.54

The microbial count in tomato rhizospheric soils varied with different sites. Among various locations, Panwa had highest fungal count (75×10^{-3} cfu g^{-1} soil), suggested a favorable environment for fungal proliferation, possibly due to higher organic matter content or more stable moisture conditions (Tang et al., 2023). Conversely, Salograshowed lowest fungal count (20×10^{-3} cfu g^{-1} soil), Kandaghat recorded the highest bacterial count (98×10^{-6} cfu g^{-1} soil), followed by Sadhupul (77×10^{-6} cfu g^{-1} soil) of Solan district and Narag (73×10^{-6} cfu g^{-1} soil) of Sirmour district, potentially indicated stressed soil conditions, such as reduced organic content, low pH, or agricultural practices that disrupt fungal growth (Devi et al., 2020). The lowest bacterial counts were from Salogra (Solan) (15×10^{-6} cfu g^{-1} soil) and Pabiyana (Sirmour) (18×10^{-6} cfu g^{-1} soil), revealing the poor condition of soil. The fungal and bacterial counts of both district ranged 40.20 to 47.53 and 45.54 to 39.54, respectively further underscored the inter-district variability. Such differences might stem from variation in soil management practices, crop rotation histories, and environmental parameters like temperature and humidity. Rhizospheric microbial communitiesknown to be shaped by the interaction of plant species, soil type, and climatic factors (Bai et al., 2022). Microbial analysis revealed significant variations in fungal and bacterial counts across tomato fields, highlighting the complex interplay between microbial communities and disease dynamics (Zhou et al., 2021; Dong et al., 2023). Environmental factors, like soil, moisture, temperature, and agronomic practices, influenced microbial composition and abundance, affecting disease development (Chen et al., 2023). Higher microbial counts promoted biologically active soil, potentially suppressing pathogens through competition or antagonism (Zhao et al., 2023).

3.2. Estimation of physicochemical properties of nursery soils collected from different locations of Solan and Sirmour districts

Considering the diversity of the studied regions and the complexity of all locations, a selection of sites with varying disease incidences and microbial characteristics was prioritized for physicochemical analysis. This focused approach allowed for a more detailed investigation of the relationship between soil properties and disease dynamics across a representative range of conditions. Table 2 highlighted notable variations among the soil samples, particularly in terms of pH levels. While the optimum range for soil pH is generally considered to be 6.5–7.3, the analysis revealed that the highest soil pH values were recorded at Palashala (7.86) and Kurgal (7.78), indicating a shift towards slightly alkaline conditions. In contrast, the pH levels at Damrog Balana (6.58), Dharja (6.62), Kandaghat (6.84), and Mansar (6.96) fell within the slightly acidic to neutral range. The highest electrical conductivity (EC) was recorded in Mathiya (0.79 dS m^{-1}), followed by Palashala (0.74 dS m^{-1}) in Solan district, while the lowest EC value (0.22 dS m^{-1}) was observed in Deothal, Sirmour district. The highest organic carbon (OC) level was found in Palashala (2.60%), followed by Kurgal (2.48%), indicated high soil fertility and microbial activity. Other locations like Dharja (2.09%), Damrogbalana (2.13%), and Basal (2.19%), also showed moderately high

Table 2: Estimation of physicochemical properties of nursery soils collected from different locations of Solan and Sirmour districts

Soil samples (district wise)	pH	EC (ds mm^{-1})	OC (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Bulk density (g ml^{-1})	Microbial count (cfu g^{-1} soil)	
Optimum range	6.5–7.3	≤2.00	0.50–1.00	280–560	10–25	137–337	_	Fungal count (×10^3)	Bacterial count (×10^6)
Solan district									
Dharja	6.62	0.23	2.09	452	32	912	1.49	39	59
Damrogbalana	6.58	0.53	2.13	564	39	759	1.15	40	58
Deothi	7.46	0.48	2.29	445	38	865	1.35	62	98
Kandaghat	6.84	0.55	1.76	483	22	725	1.58	34	55
Mathiya	7.05	0.79	1.62	414	50	949	1.29	42	65
Mansar	6.96	0.46	1.98	408	24	628	1.22	31	56
Palashala	7.86	0.74	2.60	452	48	490	1.41	26	30
Basal	7.75	0.37	2.19	464	21	932	1.38	22	51
Kurgal	7.78	0.40	2.48	508	34	706	1.25	34	41
Sirmour district									
Deothal	7.56	0.22	1.55	364	46	273	1.17	29	50
Nainatikker	7.08	0.28	2.00	439	39	460	1.46	39	49

*pH: Potential of hydrogen, EC: Electrical conductivity, OC: organic carbon; N: nitrogen; P: Phosphorus; K: Potassium organic carbon levels, supporting agricultural practices. Mathiya (1.62%) and Mansar (1.98%) had OC near the upper limit of the recommended range, indicated good soil quality. In Sirmour, the highest OC value was at Nainatikker (2.00%), within the optimum range. Deothal had the lowest at 1.55%, suggesting a deficiency in soil quality.

In Solan district, nitrogen levels generally fell within the ideal range. Damrog Balana (564 kg ha^{-1}) and Kurgal (508 kg ha^{-1}) showed higher nitrogen levels.Dharja (452 kg ha^{-1}), Palashala (452 kg ha^{-1}), and Basal (464 kg ha^{-1}) also had sufficient nitrogen content. While, Sirmourdistrict had slightly lower nitrogen levels, with Deothal (364 kg ha^{-1}) falling below the optimum range, which could indicate a deficiency that may affect soil fertility. However, Nainatikker (439 kg ha^{-1}) had nitrogen within the ideal range.The maximum value for potassium (949 kg ha^{-1}) was recorded from Mathiya, followed by Basal (932 kg ha^{-1}), Dharja (912 kg ha^{-1}), Deothi (865 kg ha^{-1}), Damrog Balana (759 kg ha^{-1}), Kandaghat (725 kg ha^{-1}), Kurgal (706 kg ha^{-1}), and Mansar (628 kg ha^{-1}). The minimum potassium value (273 kg ha^{-1}) was recorded from Deothal. On the other hand, the lower potassiumvalues in Mansar and Deothal indicated that either these soils are naturally poorer in potassium, have experienced leaching, or have received less agricultural input to replenish potassium levels. Bulk density also varied significantly, with the highest value (1.58 g ml^{-1}) recorded in Kandaghat, followed by Dharja (1.49 g ml^{-1}), and the lowest bulk density (1.15 g ml^{-1}) recorded in Damrog. In terms of microbial populations, Deothi exhibited the highest fungal (62×10^3 cfu g^{-1} soil) and bacterial (98×10^6 cfu g^{-1} soil) counts, followed by Mathiya with 42×10^3 cfu g^{-1} soil and 65×10^6 cfu g^{-1} soil, respectively. In contrast, the lowest fungal count (22×10^3 cfu g^{-1} soil) was observed in Basal, and the lowest bacterial count (30×10^6 cfu g^{-1} soil) was found in Palashala.

Beneficial soil microbes that suppressed pathogens thrive in slightly acidic to neutral pH (6.5–7.3). When soil became alkaline (above pH 7.3), these microbes turned less active, weakening the plant's defenses. This led to nutrient deficiencies, stressing plants like tomatoes and increasing their susceptibility to fungal pathogens (Yang et al., 2024; Cabral-Miramontes et al., 2022). Elevated EC indicated high soluble salts in the soil, which harmed plant growth and microbial health. The high EC and lower microbial counts in areas like Basal and Palashala suggested that saline conditions hinder the growth of beneficial soil microbes, increased the risk of disease outbreaks (Nikitin et al., 2023). High OC improved soil aggregation, enhanced water infiltration, root growth, and air circulation, which helped managing disease and pathogen spread. In contrast, low OC reduced beneficial microbes that suppressed pathogens, allowed harmful bacteria, fungi, and nematodes to thrive, with increased disease risk. Additionally, low OC weakened the soil's ability to store carbon and nutrients, compromising plant defenses and boosting susceptibility to diseases (Vasundhara et al., 2020). The relationship between nitrogen (N), phosphorus (P), potassium (K), and disease incidence in plants crucial for understanding plant health and pathogen susceptibility (Kalbande and Yadav, 2021). Excessive nitrogen increased vulnerability to pathogens. Low nitrogen weakened plants, impaired cell wall strength and disease resistance (Sharma, 2020). Phosphorus supported energy transfer and root development, with enhanced plant vigor, while its deficiency weakened roots and made plants more prone to infections. Potassium regulated water balance and strengthened cell walls, boosting disease resistance while deficiency weakened cell walls, increased disease susceptibility (Martin-Cardoso and San Segundo, 2025).

3.3. Correlation of soil physicochemical properties with microbial count

The correlation between soil properties and microbial counts (Table 3) showed that pH was positively correlated with both fungal (0.71) and bacterial (0.85) counts, indicating its significant influence on microbial populations.On contrary to pH, all other factors under study of soil had no impact with respect to fungal and bacterial count as all showed non-significant correlation. Similarly, the correlation between electrical conductivity (EC) and fungal count (0.56) was moderate, indicating that increased electrical conductivity could promote fungal growth. However, EC did not significantly affect bacterial counts, as evidenced by the very low correlation (0.02). Organic carbon showed a weak positive correlation with fungal count (0.20) but no significant relationship with bacterial count, pointing that while OC had some influence on fungal populations, its effect on bacteria was minimal. Nitrogen content in the soil appeared to have a moderate positive correlation with both fungal (0.37) and bacterial count (0.24), showcasing that higher nitrogen levels might slightly enhanced microbial growth. Phosphorus and potassium also exhibited moderate positive correlations with both fungal and bacterial counts, with phosphorus-correlations of 0.33 with fungal count and 0.41 with bacterial count, and potassium-correlations of 0.33 with fungal count and 0.49 with bacterial count. Bulk density, however, showed only a weak correlation with fungal count (0.29) and no correlation with bacterial count, revealedthat the physical structure of the soil (as indicated by bulk density) had a minor effect on fungal populations, but not on bacterial communities.

These results were in agreement with other studies suggesting that nitrogen availability influenced microbial abundance and activity. EC reflected the ion concentration in the soil, which affected microbial activity by altering osmotic stress conditions, particularly for fungi (Gupta et al., 2021; Bogati et al., 2022). Also, phosphorus and potassium with their availability counteracted the composition of soil microbial communities. Similarly, the weak positive correlation between organic carbon and fungal count (0.20), along with no significant relationship with bacterial count suggested that organic matter had slight influence on fungal growth, meaning it had a minimal impact on bacterial populations. This finding

Table 3: Correlation of soil physicochemical properties with microbial count

	pH	EC	OC	N	P	K	Bulk density	Fungal count	Bacterial count
pH	1.00*	0.05*	0.44*	0.23*	0.18*	0.27*	0.11*	0.71**	0.85**
EC		1.00*	0.12*	0.17*	0.33*	0.26*	0.07*	0.56*	0.02*
OC			1.00	0.50*	0.06*	0.12*	0.08*	0.03*	0.20*
N				1.00	0.24*	0.37*	0.02*	0.14*	0.08*
P					1.00	0.32*	0.33*	0.21*	0.41*
K						1.00	0.20*	0.33*	0.49*
Bulk density							1.00	0.00*	0.29*
Fungal count								1.00	0.28*
Bacterial count									1.00

**: Positive correlation; *: Non-significant correlation

contrasted with earlier research by Soares and Rousk (2019), who found a stronger relationship between organic carbon and microbial activity. The differences might arose from the specific microbial communities present in the study areas, as some bacteria relied more on other organic compounds or nutrients not measured in this study (Gralka et al., 2020; Siedt et al., 2021).

4. Conclusion

The study showed geographic disease variation, with highest damping-off observed at Jadari, Rajgarh, and wilt at Damrog and Narag. Soil fertility varied, with highest organic carbon in Palashala (2.60%), potassium (949 kg ha^{-1}) in Mathiya, and lowest in both (1.55% OC, 273 kg ha^{-1}) in Deothal. Microbial counts correlated moderately with conductivity (0.56), nitrogen (0.37 fungi, 0.24 bacteria), while organic carbon had minimal impact, especially on bacteria. These findings highlighted the influence of environmental and edaphic factors on disease prevalence and soil health.

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