Assessment of Soil Quality Using Rhizosphere Fungal Communities Across Tribal Agroecosystems of North-Western Maharashtra, India

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Abstract
Soil quality is a key determinant of agricultural productivity and ecosystem sustainability, with rhizosphere fungi serving as important biological indicators of soil health. This study investigated the relationship between soil physicochemical properties and rhizosphere fungal communities associated with banana, sugarcane, groundnut, and chilli cultivated in different agroecosystems of Nandurbar District, Maharashtra, India. Rhizosphere soil samples were collected during winter, summer, and rainy seasons and analysed for pH, soil moisture, temperature, organic carbon, available nitrogen, phosphorus, potassium, calcium, magnesium, and alkalinity using standard analytical procedures. Fungal isolates were recovered using the serial dilution plate technique and identified through morphological characteristics. Marked seasonal and crop-specific variations were observed in both soil properties and fungal communities. The rainy season supported the highest fungal abundance and diversity, whereas comparatively lower populations were recorded during summer. Dominant fungal genera included Aspergillus, Penicillium, Fusarium, Trichoderma, and Mucor, with their distribution closely associated with soil moisture, organic carbon, and nutrient availability. The findings indicate that soil physicochemical characteristics are closely associated with rhizosphere fungal dynamics and support the suitability of fungal communities as biological indicators of soil quality. Integrating microbial and soil fertility assessments provides an effective approach for monitoring ecosystem health and developing sustainable soil management strategies for improving agricultural productivity in semi-arid regions.

Keywords: Soil Quality Assessment; Rhizosphere Fungi; Biological Indicators; Soil Health; Agroecosystem Ecology; Soil Fertility; Sustainable Agriculture; Microbial Diversity; Nandurbar District; Semi-Arid Ecosystems

1. Introduction

The rhizosphere, the narrow zone of soil directly influenced by plant roots, represents one of the most biologically active ecosystems, harbouring diverse microbial communities that establish complex interactions with plant roots. Among these microorganisms, fungi constitute an essential component of the rhizosphere microbiome and perform vital ecological functions, including decomposition of organic matter, nutrient mineralization, soil aggregation, suppression of soil-borne pathogens, and promotion of plant growth (Choudhary et al., 2022; Chauhan et al., 2023; Dighton, 2018). These functions significantly contribute to soil fertility, ecosystem stability, and sustainable agricultural productivity. Furthermore, fungal-mediated soil aggregation plays an important role in carbon stabilization and the maintenance of soil structure (De Goede et al., 2025).

Agricultural soils support highly dynamic fungal communities whose composition is influenced by crop species, root exudates, soil physicochemical characteristics, and seasonal environmental variations. Soil pH, moisture, temperature, texture, and nutrient availability directly affect fungal abundance, diversity, enzymatic activity, and ecological succession (Dandwate & Gasparyan, 2020; Das et al., 2021). Seasonal fluctuations further regulate microbial populations by altering soil environmental conditions, resulting in significant changes in fungal community composition throughout the cropping cycle (Chaudhary et al., 2016). Understanding these interactions is essential for improving soil health, nutrient cycling, and sustainable crop production.

Banana (Musa spp.), sugarcane (Saccharum officinarum L.), groundnut (Arachis hypogaea L.), and chilli (Capsicum annuum L.) are economically important agricultural crops cultivated extensively in Nandurbar District of Maharashtra. These crops contribute substantially to regional agricultural productivity while supporting diverse rhizosphere microbial populations. Each crop possesses a distinct rhizosphere environment that selects specific fungal communities through root exudates and soil interactions. Previous investigations have reported considerable fungal diversity in banana (Gnanasekaran et al., 2015; Gaikwad, 2019), chilli (Beatrice Florence Febronia, 2016), and sugarcane rhizospheres (Hartoyo & Trisilawati, 2021), demonstrating the ecological significance of fungal communities in enhancing nutrient availability and plant health.

Rhizosphere fungi contribute significantly to sustainable agriculture by facilitating nutrient cycling, phosphate solubilization, decomposition of organic residues, biological control of plant pathogens, and production of plant growth-promoting metabolites (Elias et al., 2016; Adedayo & Babalola, 2023). Beneficial fungal genera such as Aspergillus, Penicillium, Trichoderma, Chaetomium, Mucor, and Fusarium play indispensable roles in improving soil

fertility, increasing nutrient uptake, and protecting plants against various biotic and abiotic stresses (Hariharan et al., 2022; Chaithra et al., 2020). Consequently, assessment of rhizosphere fungal diversity has become increasingly important for the development of environmentally sustainable agricultural practices.

The diversity and distribution of soil fungi are closely associated with soil physicochemical properties. Soil pH, moisture content, temperature, available nitrogen, phosphorus, potassium, calcium, magnesium, soil texture, and organic matter collectively determine fungal colonization, survival, and ecological succession (Dandwate & Gasparyan, 2020; Gasparyan, 2023). Several studies have reported that soil nutrient status and environmental conditions significantly influence fungal diversity and microbial activity in agricultural ecosystems (Fulpagare et al., 2023; Angmo et al., 2024). Understanding these relationships is essential for identifying soil conditions that favour beneficial fungal communities and enhance crop productivity.

Despite increasing research on rhizosphere microorganisms, comparative information regarding fungal diversity associated with multiple agricultural crops cultivated under the agro-climatic conditions of Nandurbar District remains limited. Most previous investigations have focused on individual crops or single growing seasons, while comprehensive studies integrating seasonal fungal diversity with detailed soil physicochemical characteristics across different crop species are scarce. Such investigations are particularly important for tribal agricultural regions where crop productivity largely depends on sustainable soil management practices.

Therefore, the present investigation was undertaken to evaluate the rhizosphere fungal diversity associated with banana, sugarcane, groundnut, and chilli cultivated in different regions of Nandurbar District, Maharashtra. The study also aimed to examine the influence of major soil physicochemical characteristics on fungal abundance and diversity across different cropping systems and seasons. The findings are expected to provide valuable baseline information on soil fungal ecology, improve understanding of soil–plant–microbe interactions, and contribute to the development of sustainable agricultural practices through effective management of beneficial rhizosphere fungal communities.

2. Materials and Methods

2.1 Study Area

The present investigation was conducted in selected agricultural fields of Nandurbar District, Maharashtra, India, where banana (Musa spp.), sugarcane (Saccharum officinarum L.), groundnut (Arachis hypogaea L.), and chilli (Capsicum annuum L.) are extensively cultivated. The district lies between 21°00′–22°03′ N latitude and 73°31′–74°32′ E longitude and experiences a tropical climate with distinct winter, summer, and rainy seasons. The soils are predominantly black to sandy clay loam and are suitable for agricultural cultivation (Shelke & Borse, 2025).

2.2 Collection of Rhizosphere Soil Samples

Rhizosphere soil samples were collected from healthy crop plants during winter, summer, and rainy seasons. Soil adhering to the root zone (10–20 cm depth) was collected using sterile tools, transferred into sterile polyethylene bags, labelled, and transported to the laboratory for microbiological and physicochemical analyses (Shelke & Borse, 2025).

2.3 Isolation and Identification of Rhizosphere Fungi

Rhizosphere fungi were isolated using the serial dilution plate technique. One gram of soil was serially diluted up to 10^{-5}, and 1 mL of the 10^{-3} dilution was inoculated onto Potato Dextrose Agar (PDA) supplemented with streptomycin. Plates were incubated at 25 ± 2°C for 5–7 days, and fungal colonies were expressed as CFU g^{-1} of soil. Representative colonies were purified and identified based on colony morphology, microscopic characteristics using lactophenol cotton blue staining, and standard taxonomic keys. Fungal nomenclature was confirmed using MycoBank and Index Fungorum databases (Bensch, 2023; Gnanasekaran et al., 2015).

2.4 Analysis of Soil Physicochemical Properties

Rhizosphere soil samples were analysed using standard laboratory procedures. Soil pH was determined using a digital pH meter (Jackson, 1973). Soil moisture was estimated by the sun-drying method, while soil temperature was recorded using a digital soil thermometer. Organic carbon was determined by the Walkley and Black wet oxidation method (Walkley & Black, 1934). Soil alkalinity was estimated by the titration method (Dandwate & Gasparyan, 2020). Available nitrogen was determined by the alkaline potassium permanganate method (Subbiah & Asija, 1956), available phosphorus by the Olsen sodium bicarbonate extraction method (Olsen et al., 1954), and available potassium by the neutral ammonium acetate extraction method followed by flame photometry (Jackson, 1973). Exchangeable calcium (Ca) and magnesium (Mg) were estimated by the EDTA titration method (Jackson, 1973). Soil texture was determined using the Bouyoucos hydrometer method and confirmed by the feel method (Bouyoucos, 1962), while soil colour was identified using the Munsell Soil Color Chart (Munsell Color, 2013). The analysed soil properties were correlated with rhizosphere fungal diversity and abundance (Shelke & Borse, 2025).

2.5 Data Analysis

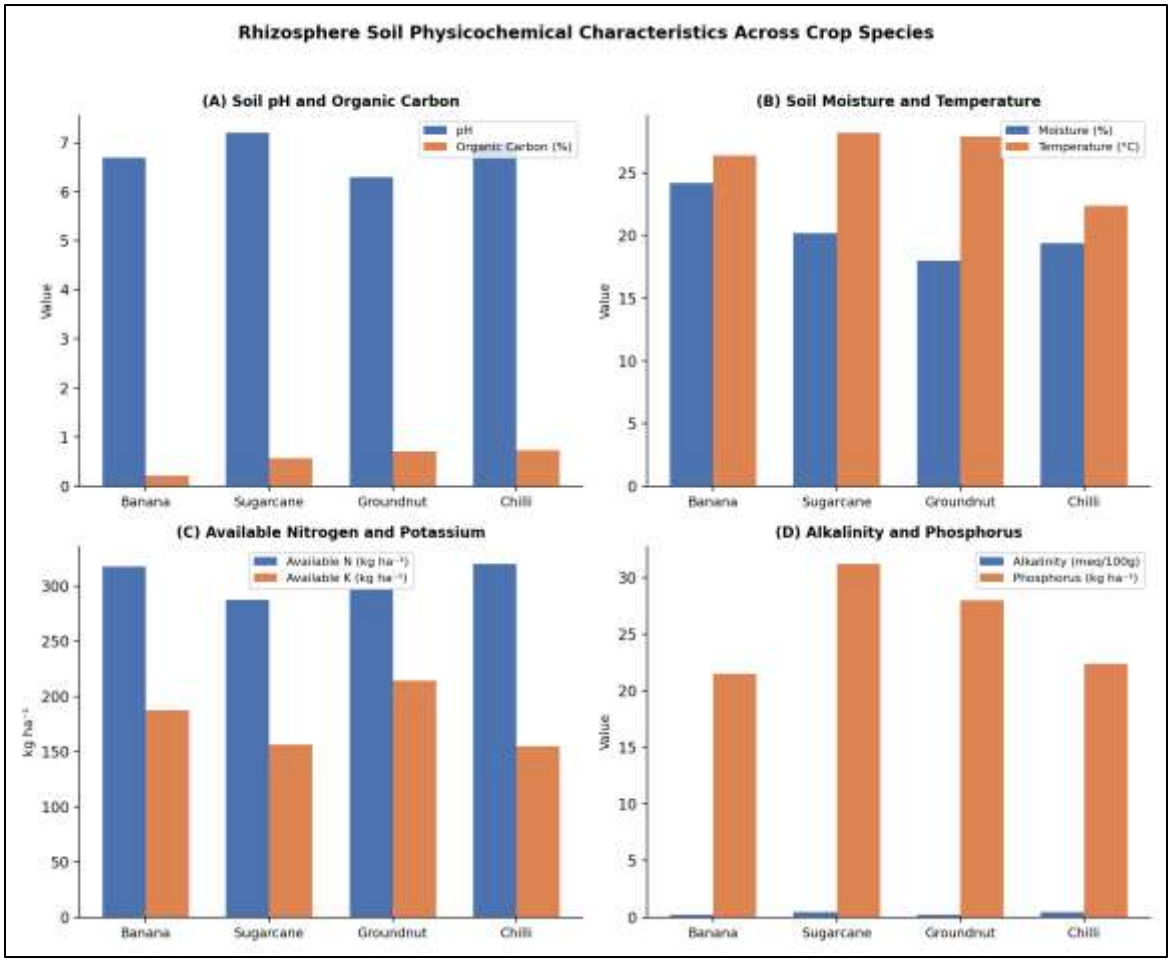
Fungal populations were expressed as colony-forming units per gram of soil (CFU g^{-1}), and the percentage contribution of each fungal species was calculated for different crops and seasons. The influence of soil physicochemical properties on fungal diversity was evaluated using descriptive statistical analysis (means).

3. Results

3.1 Soil Physicochemical Characteristics

S.N.	Ecological Parameter	Banana (Musa paradisiaca L.)	Sugarcane (Saccharum officinarum L.)	Groundnut (Arachis hypogaea L.)	Chilli (Capsicum annuum L.)
1	pH	6.7	7.2	6.3	7.0
2	Moisture (%)	24.2	20.2	18.0	19.4
3	Temperature (°C)	26.4	28.2	27.9	22.4
4	Organic Carbon (%)	0.21	0.57	0.71	0.73
5	Available Nitrogen (kg ha^{-1})	317.5	287.7	297.1	320.0
6	Alkalinity (meq/100g)	0.20	0.43	0.23	0.46
7	Available Phosphorus (kg ha^{-1})	21.5	31.2	28.0	22.4
8	Available Potassium (kg ha^{-1})	187.4	156.2	214.3	154.8
9	Exchangeable Calcium (meq L^{-1})	5.13	8.71	23.2	12.3
10	Exchangeable Magnesium (meq L^{-1})	12.0	14.5	20.2	22.3

Table 1. Average Mean Values of Rhizosphere Soil Physicochemical Characteristics Across Winter, Summer, and Rainy Seasons for Selected Agricultural Crops



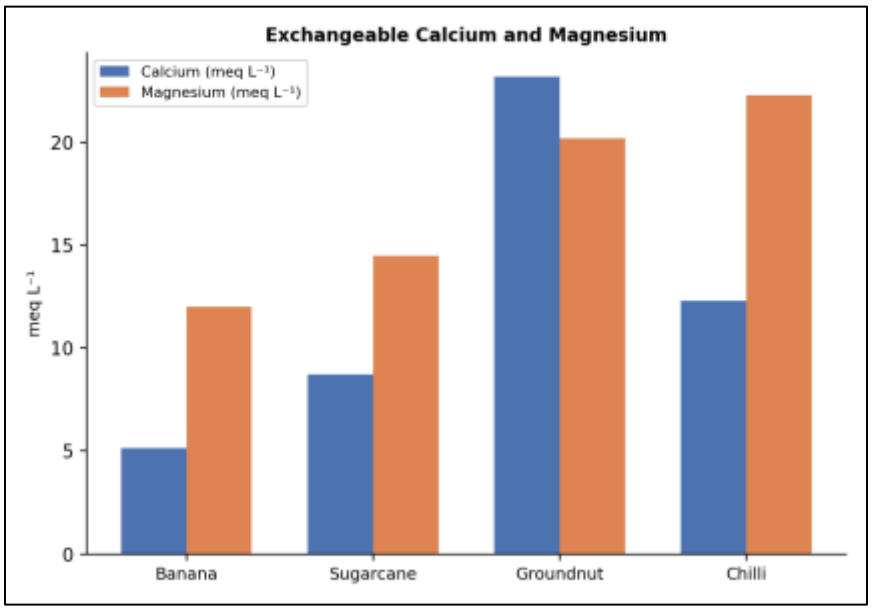


Figure 1. Rhizosphere soil physicochemical characteristics across the four studied crops (values identical to Table 1, re-plotted on scale-matched axes for clarity).

The soil pH ranged from 6.3 to 7.2, indicating slightly acidic to neutral soil conditions among the studied crops. The highest average pH was recorded in sugarcane (7.2), followed by chilli (7.0) and banana (6.7), whereas the lowest pH was observed in groundnut (6.3).

The average soil moisture content varied from 18.0% to 24.2%. Banana recorded the highest moisture content (24.2%), followed by sugarcane (20.2%) and chilli (19.4%), while groundnut exhibited the lowest moisture content (18.0%).

The average soil temperature ranged between 22.4°C and 28.2°C. The highest temperature was observed in the rhizosphere of sugarcane (28.2°C), followed by groundnut (27.9°C) and banana (26.4°C), whereas the lowest temperature was recorded in chilli (22.4°C).

The organic carbon content varied considerably among the crop rhizospheres. The highest organic carbon content was recorded in chilli (0.73%), followed by groundnut (0.71%) and sugarcane (0.57%), while the lowest value was observed in banana (0.21%).

The available nitrogen content ranged from 287.7 to 320.0 kg ha^{-1}. The highest average nitrogen content was recorded in chilli (320.0 kg ha^{-1}), followed by banana (317.5 kg ha^{-1}) and groundnut (297.1 kg ha^{-1}), whereas the lowest value was observed in sugarcane (287.7 kg ha^{-1}).

The soil alkalinity values varied between 0.20 and 0.46 meq/100 g. The highest alkalinity was observed in chilli (0.46 meq/100 g), followed by sugarcane (0.43 meq/100 g) and groundnut (0.23 meq/100 g), while banana exhibited the lowest alkalinity (0.20 meq/100 g).

The available phosphorus content ranged from 21.5 to 31.2 kg ha^{-1}. Sugarcane recorded the highest phosphorus content (31.2 kg ha^{-1}), followed by groundnut (28.0 kg ha^{-1}) and chilli (22.4 kg ha^{-1}), whereas the lowest value was observed in banana (21.5 kg ha^{-1}).

The available potassium content varied between 154.8 and 214.3 kg ha^{-1}. The highest potassium content was recorded in groundnut (214.3 kg ha^{-1}), followed by banana (187.4 kg ha^{-1}) and sugarcane (156.2 kg ha^{-1}), while the lowest value was observed in chilli (154.8 kg ha^{-1}).

The exchangeable calcium content showed considerable variation among the crops, ranging from 5.13 to 23.2 meq L^{-1}. The highest calcium content was recorded in groundnut (23.2 meq L^{-1}), followed by chilli (12.3 meq L^{-1}) and sugarcane (8.71 meq L^{-1}), whereas the lowest value was observed in banana (5.13 meq L^{-1}).

Similarly, the exchangeable magnesium content ranged from 12.0 to 22.3 meq L^{-1}. The highest magnesium content was observed in chilli (22.3 meq L^{-1}), followed by groundnut (20.2 meq L^{-1}) and sugarcane (14.5 meq L^{-1}), while the lowest value was recorded in banana (12.0 meq L^{-1}).

Overall, the average physicochemical characteristics varied among the rhizosphere soils of the four agricultural crops. Banana exhibited higher soil moisture; sugarcane showed the highest pH, temperature, and phosphorus content, groundnut recorded the highest potassium and calcium levels, whereas chilli was characterized by higher organic carbon, available nitrogen, alkalinity, and magnesium content. These observations indicate distinct variations in the physicochemical properties of the rhizosphere soils associated with different crop species.

3.2 Seasonal Fungal Community Composition

S.N.	Fungal Species	Winter (%)	Summer (%)	Rainy (%)
1	Alternaria alternata	18.7	13.3	30.7
2	Aspergillus flavus	11.1	16.6	31.5

3	Aspergillus fumigatus	15.3	15.0	–
4	Aspergillus niger	25.0	22.2	23.0
5	Aspergillus tamarii	–	15.3	5.0
6	Aspergillus terreus	11.1	50.0	15.7
7	Aspergillus ustus	18.7	–	5.0
8	Botrytis cinerea	13.3	–	20.0
9	Chaetomium globosum	–	33.3	23.0
10	Cladosporium oxysporum	11.1	8.3	10.5
11	Curvularia clavata	20.0	9.0	–
12	Curvularia lunata	12.5	7.6	15.0
13	Fusarium solani	18.7	15.3	16.6
14	Mucor racemosus	22.2	16.6	5.2
15	Penicillium aurantiogriseum	–	27.2	6.6
16	Penicillium citrinum	16.6	16.6	31.5
17	Penicillium funiculosum	–	9.0	13.3
18	Penicillium glabrum	8.3	6.6	9.0
19	Pythium debaryanum	18.1	–	20.0
20	Rhizoctonia solani	41.6	11.1	20.0
21	Rhizopus stolonifer	20.0	13.3	–
22	Trichoderma viride	38.4	6.6	50.0

Table 2. Seasonal Percentage Contribution of Rhizosphere Fungal Species During Winter, Summer, and Rainy Seasons

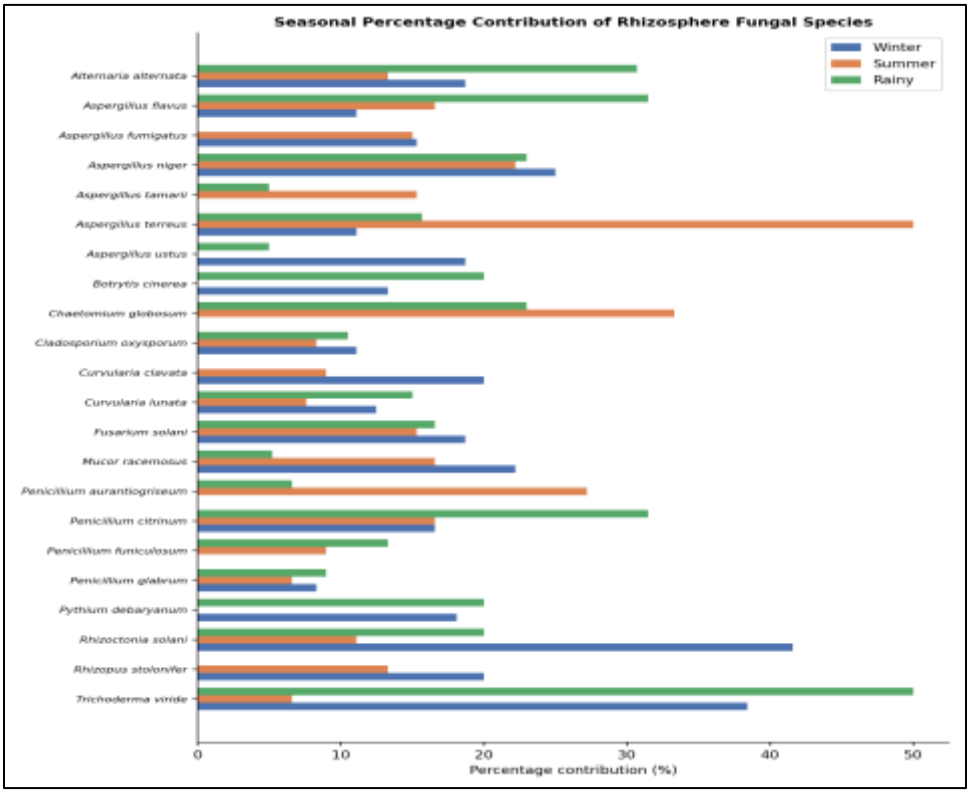


Figure 2. Seasonal percentage contribution of rhizosphere fungal species (values identical to Table 2).

Among the fungal species, Alternaria alternata showed contributions of 18.7% in winter, 13.3% in summer, and 30.7% in the rainy season. Aspergillus flavus contributed 11.1% during winter, 16.6% during summer, and increased to 31.5% in the rainy season. Aspergillus fumigatus recorded 15.3% in winter and 15.0% in summer but was not observed during the rainy season.

Aspergillus niger was recorded consistently in all three seasons with contributions of 25.0% in winter, 22.2% in summer, and 23.0% in the rainy season. Aspergillus tamarii was absent during winter, while it contributed 15.3% in summer and 5.0% during the rainy season. Aspergillus terreus showed 11.1% contribution in winter, reached its maximum contribution of 50.0% during summer, and decreased to 15.7% in the rainy season. Aspergillus ustus contributed 18.7% during winter, was not recorded during summer, and showed 5.0% contribution during the rainy season.

Botrytis cinerea contributed 13.3% in winter, was absent during summer, and recorded 20.0% in the rainy season. Chaetomium globosum was not observed in winter, while it showed 33.3% contribution during summer and 23.0% during the rainy season. Cladosporium oxysporum was present throughout the study with contributions of 11.1%, 8.3%, and 10.5% during winter, summer, and rainy seasons, respectively.

Curvularia clavata recorded 20.0% contribution in winter and 9.0% in summer but was not observed during the rainy season. Curvularia lunata contributed 12.5% in winter, 7.6% in summer, and 15.0% during the rainy season. Fusarium solani was consistently present in all three seasons, recording 18.7% in winter, 15.3% in summer, and 16.6% during the rainy season.

Mucor racemosus contributed 22.2% in winter, 16.6% in summer, and 5.2% during the rainy season. Penicillium aurantiogriseum was absent in winter, whereas it recorded 27.2% in summer and 6.6% in the rainy season. Penicillium citrinum contributed equally (16.6%) during both winter and summer and increased to 31.5% in the rainy season. Penicillium funiculosum was not observed during winter, but showed 9.0% contribution in summer and 13.3% in the rainy season. Penicillium glabrum was present in all seasons with contributions of 8.3%, 6.6%, and 9.0% during winter, summer, and rainy seasons, respectively.

Pythium debaryanum contributed 18.1% during winter, was absent in summer, and recorded 20.0% during the rainy season. Rhizoctonia solani showed the highest contribution during winter (41.6%), followed by 11.1% in summer and 20.0% during the rainy season. Rhizopus stolonifer contributed 20.0% during winter and 13.3% during summer but was not recorded during the rainy season. Trichoderma viride exhibited 38.4% contribution during winter, 6.6% during summer, and reached the highest contribution of 50.0% during the rainy season.

Overall, among the fungal species presented in Table 2, the highest seasonal contribution during winter was recorded by Rhizoctonia solani (41.6%), whereas Aspergillus terreus (50.0%) showed the highest contribution during summer, and Trichoderma viride (50.0%) recorded the highest contribution during the rainy season. Several fungal species were present throughout all three seasons, while others were absent in one or more seasons, indicating seasonal variation in their occurrence.

4. Discussion

The soil pH recorded across all four crops (6.3–7.2) fell within the slightly acidic to neutral range generally considered favourable for the growth of most saprophytic soil fungi, including Aspergillus, Penicillium, and Trichoderma species, which are known to tolerate a wide pH range but proliferate optimally near neutrality (Dandwate & Gasparyan, 2020; Gasparyan, 2023). This is consistent with the dominance of these genera across the fungal community recorded in the present study (Table 2).

The rainy season supported the highest overall fungal contribution among the species that peaked seasonally (e.g., Alternaria alternata, Aspergillus flavus, Penicillium citrinum, and Trichoderma viride), which corresponds with the elevated soil moisture typically available during this period. Adequate moisture promotes spore germination, hyphal extension, and microbial metabolic activity, a pattern also reported for subtropical forest soils where seasonal moisture fluctuation strongly shaped mycoflora composition (Chaudhary et al., 2016). Fungal-mediated soil aggregation, which depends on active hyphal growth, is similarly moisture-dependent (De Goede et al., 2025), supporting the ecological plausibility of the rainy-season peak observed here.

In contrast, Aspergillus terreus reached its highest contribution (50.0%) during summer, when soil moisture was comparatively low and temperatures were highest. This suggests a degree of thermotolerance and desiccation resistance in this species relative to co-occurring fungi, a pattern broadly consistent with the influence of temperature and moisture on fungal ecological succession described for agricultural soils (Das et al., 2021; Dandwate & Gasparyan, 2020).

Chilli and groundnut rhizospheres, which recorded the highest organic carbon content (0.73% and 0.71%, respectively), also supported comparatively higher contributions of Trichoderma viride and Penicillium species, genera widely reported as active decomposers of organic residues and as biocontrol agents against soil-borne pathogens (Chaithra et al., 2020; Hariharan et al., 2022). This aligns with the expectation that organic carbon availability favours saprotrophic and antagonistic fungal taxa capable of exploiting decomposable substrates.

The distinct nutrient profiles observed among the four crops — higher moisture in banana, higher pH/temperature/phosphorus in sugarcane, higher potassium/calcium in groundnut, and higher nitrogen/alkalinity/magnesium in chilli — indicate that each crop cultivates a chemically distinct rhizosphere niche. This is consistent with earlier crop-specific fungal diversity reports from banana (Gnanasekaran et al., 2015; Gaikwad, 2019), chilli (Beatrice Florence Febronia, 2016), and sugarcane (Hartoyo & Trisilawati, 2021), and supports the premise that root exudate chemistry and associated nutrient status, rather than season alone, help structure crop-specific fungal assemblages.

From an applied perspective, the consistent presence of phosphate-solubilizing and plant-growth-promoting genera such as Aspergillus and Penicillium (Elias et al., 2016; Adedayo & Babalola, 2023), together with the biocontrol-associated genera Trichoderma and Chaetomium (Hariharan et al., 2022), suggests that the rhizosphere communities documented here already contain functionally beneficial components that could be targeted for future biofertilizer or biocontrol development in this tribal agricultural landscape.

Taken together, these associations support the study's central premise — that rhizosphere fungal communities respond jointly to seasonal environmental conditions and crop-specific soil chemistry — and extend earlier work on soil–

microbe interactions (Choudhary et al., 2022; Chauhan et al., 2023) into a comparative, multi-crop, multi-season framework for an agro-climatic zone that has previously received limited attention (Fulpagare et al., 2023; Angmo et al., 2024). It should be noted that these interpretations are based on descriptive/observational patterns in the data rather than statistically tested associations (see Section 6, Limitations).

5. Conclusion

The present study provides valuable insights into the rhizosphere fungal diversity and soil physicochemical characteristics associated with four important agricultural crops—banana (Musa paradisiaca L.), sugarcane (Saccharum officinarum L.), groundnut (Arachis hypogaea L.), and chilli (Capsicum annuum L.)—cultivated in Nandurbar District, Maharashtra. The findings revealed clear differences in the physicochemical properties of the rhizosphere soils among the studied crops. Banana was characterized by higher soil moisture, sugarcane exhibited relatively higher pH, soil temperature, and available phosphorus, groundnut contained higher available potassium and exchangeable calcium, whereas chilli recorded comparatively higher organic carbon, available nitrogen, alkalinity, and exchangeable magnesium. These variations indicate that each crop is associated with a distinct rhizosphere environment.

The study also demonstrated noticeable seasonal variation in the occurrence and contribution of fungal species. Several fungi, including Aspergillus niger, Cladosporium oxysporum, Curvularia lunata, Fusarium solani, Penicillium citrinum, and Penicillium glabrum, were consistently recorded throughout the three seasons, whereas other species showed seasonal occurrence or were absent during particular seasons. Among all the recorded fungi, Rhizoctonia solani showed the highest percentage contribution during winter, Aspergillus terreus was dominant during summer, and Trichoderma viride exhibited the highest contribution during the rainy season, highlighting distinct seasonal shifts in fungal distribution.

Overall, the results demonstrate that the rhizosphere fungal community varies across crop species and seasons under the agro-climatic conditions of Nandurbar District. The documented variations in soil physicochemical properties and seasonal fungal occurrence provide baseline information for understanding rhizosphere fungal ecology in the region. These findings contribute to the existing knowledge of soil–plant–microbe interactions and may serve as a useful reference for future studies on rhizosphere microbial diversity and sustainable soil management in agricultural ecosystems.

This study establishes a foundation for further investigations on the ecological role of beneficial rhizosphere fungi and their potential application in sustainable agriculture, particularly under the diverse cropping systems of north-western Maharashtra.

6. Limitations of the Study

Descriptive statistics only: Only mean values are reported; replicate-level raw data were not available for this revision, so inferential tests (ANOVA/Tukey's HSD across crops and seasons, Pearson/Spearman correlation between soil parameters and fungal abundance) could not be performed. The word "significant" has accordingly been replaced with descriptive terms (e.g., "marked", "considerable") throughout, except where a formal test is added.

Morphology-based identification: Fungal isolates were identified using colony and microscopic morphology only; molecular confirmation (e.g., ITS region sequencing) was not performed and would strengthen species-level confidence, particularly for morphologically similar taxa.

Single annual cycle: Sampling covered one winter, one summer, and one rainy season within a single year; inter-annual variability was not captured and multi-year monitoring would improve the robustness of the seasonal trends reported.

Basis of "percentage contribution": The percentage values in Table 2 do not sum to 100% within a season, indicating they represent a frequency/contribution metric rather than strict relative abundance out of a common total. The exact computation basis should be defined explicitly in the manuscript so that reviewers and readers can interpret Table 2 and Figure 2 correctly; a true relative-abundance-based diversity index (e.g., Shannon–Wiener, Simpson's) can then be calculated correctly and added.

Fungal focus only: Bacterial and other microbial groups that also contribute to rhizosphere ecology and soil quality were outside the scope of this study.

7. Future Scope

Future work should include (i) molecular confirmation of key fungal isolates using ITS sequencing; (ii) collection of replicate-level data to enable ANOVA, correlation, and multivariate analyses (e.g., PCA or CCA) directly linking soil physicochemical parameters to fungal community structure; (iii) multi-year sampling to capture inter-annual variability; and (iv) in vitro evaluation of the beneficial isolates identified here (e.g., Trichoderma viride, Aspergillus spp., Penicillium spp.) for their biofertilizer and biocontrol potential under field conditions.

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