



Research Article

CROP-SPECIFIC VARIATION IN RHIZOSPHERE FUNGAL POPULATION AND SOIL PHYSICO-CHEMICAL PROPERTIES: A TWO-YEAR CASE STUDY FROM AKKALKUWA TEHSIL, NANDURBAR DISTRICT

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ABSTRACT

Fungi that live around crop roots help the plant in many simple but important ways they break down plant waste, release nutrients trapped in the soil, and often protect the plant from harmful soil germs. But the number and type of these fungi keep changing with the crop, the season and the condition of the soil. This study looks at that change for four crops commonly grown in Akkalkuwa Tehsil of Nandurbar District, Maharashtra banana, sugarcane, groundnut and chilli by comparing the rhizosphere fungi recorded over two years, 2021-22 and 2022-23. Soil samples were collected from farmers' fields every season (winter, summer and rainy), and fungi were grown and counted using the standard dilution-plate method, then identified up to genus or species level. Along with this, soil pH, moisture, temperature, organic carbon and available nitrogen were also recorded. In total, 26 fungal species were found in 2021-22 and 21 in 2022-23, with 14 species common to both years. Overall, the average fungal count across all four crops went up from 17,559.7 CFU/g of soil in the first year to 20,343.8 CFU/g in the second year, a rise of about 16%. This rise was not the same for every crop groundnut and sugarcane showed the biggest increase (34.8% and 26.1%), banana increased only slightly, and chilli actually went down by about 8%. In all four crops and in both years, the rainy season had the highest fungal count and summer the lowest, matching the pattern of soil moisture. The types of fungi present also kept changing: genera such as *Aspergillus*, *Penicillium*, *Mucor*, *Rhizopus*, *Chaetomium* and *Trichoderma* were found throughout the study, but which species led each crop's rhizosphere shifted clearly between the two years most noticeably in groundnut, where *Rhizopus stolonifer*, not found at all in the first year, became the leading species in the second. Soil pH, moisture and available nitrogen also increased from the first year to the second in most crops, especially in banana and groundnut, more or less matching the rise seen in fungal numbers. These results suggest that soil moisture and nutrient level are the main factors behind the year-to-year change in rhizosphere fungi of this semi-arid, tribal farming belt, and this two-year record can serve as a useful reference for future soil-health studies and for finding useful biocontrol fungi in the region.

Keywords: Rhizosphere fungi, Fungal population, Species composition, Comparative study, Soil moisture.

INTRODUCTION

Just beneath the surface of every cultivated field lies a narrow, root-influenced zone of soil the rhizosphere that is disproportionately rich in microbial life compared with soil only a few centimetres away. Root exudates such as sugars, amino acids and organic acids feed this activity, drawing in bacteria and fungi that, in turn, shape how well the plant above them grows (Kennedy & de Luna, 2004; Choudhary *et al.*, 2022; Katiyar, 2022). Fungi are among the more consequential residents of this zone: they break down crop residue and organic matter, release phosphorus

and other nutrients that would otherwise stay locked in the soil matrix, form beneficial associations with roots, and in several well-documented cases suppress pathogenic fungi and nematodes that would otherwise attack the crop (Raaijmakers *et al.*, 2009; Jacoby *et al.*, 2017; Murali *et al.*, 2021; Muhilan *et al.*, 2024). Species of *Trichoderma*, *Aspergillus* and *Penicillium* in particular have repeatedly been linked to improved phosphate availability, siderophore production and induced resistance in the host plant (Naziya *et al.*, 2020; Bhullar, 2020; Adedayo & Babalola, 2023; Kumar *et al.*, 2024; Tatung *et al.*, 2025).

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None of this is fixed, though. Season, host crop and the physical and chemical condition of the soil pH, moisture, temperature, organic carbon, available nitrogen all pull the rhizosphere fungal community in different directions from one sampling to the next (Chaudhary *et al.*, 2016; Swer *et al.*, 2008; Shivanna & Vasanthakumari, 2011; Wang *et al.*, 2017). Rainfall and temperature swings change how much substrate is available and how osmotically stressed the root zone becomes, and different fungal taxa respond to that stress, or that opportunity, quite differently (Sarkar *et al.*, 2024; Zhang *et al.*, 2019). Because these dynamics are so tightly tied to local conditions, there is real value in documenting them crop by crop and region by region not only to build an accurate soil-health baseline, but also because a locally adapted biocontrol or plant-growth-promoting fungal strain is far more likely to be found by looking where the crop of interest is actually grown (Todorovic *et al.*, 2023; Panneerselvam *et al.*, 2019; Thepbandit & Athinuwat, 2024).

Banana, sugarcane, groundnut and chilli are four of the principal crops grown across the Khandesh-Satpura tribal belt of north Maharashtra, of which Akkalkuwa Tehsil in Nandurbar District forms a part (Government of Maharashtra, 2025). Rhizosphere mycoflora has been studied for banana in the neighbouring districts of Nandurbar, Jalgaon and Pune (Gaikwad, 2019; Shitole *et al.*, 2019; Shelke & Borse, 2023; Shelke & Kishor, 2024), and for sugarcane, groundnut and chilli rhizospheres elsewhere in the country (Hartoyo & Trisilawati, 2021; Elias *et al.*, 2016; Febronia, 2016; Gayathri & D.A., 2014); these studies consistently report strong crop- and season-linked variation in fungal community structure, yet comparable multi-crop, multi-year data from Akkalkuwa itself have not, to our knowledge, been reported. Regional soil surveys of this same Khandesh belt have already noted considerable year-to-year variability in organic carbon, available nitrogen and aggregate stability (Ingle *et al.*, 2018; Fulpagare *et al.*, 2023), which raises the reasonable expectation that the resident fungal community would shift in step, and continuous-cropping studies elsewhere have shown exactly this kind of compositional turnover in response to changing soil conditions from one cropping cycle to the next (Tan *et al.*, 2017).

With this background in view, the present study set out (i) to isolate and enumerate the rhizospheric fungal population of banana, sugarcane, groundnut and chilli in Akkalkuwa Tehsil across the winter, summer and rainy seasons of two consecutive agricultural years, 2021-22 and 2022-23; (ii) to compare how the fungal species composition of each crop's rhizosphere changed between the two years; (iii) to record and compare the corresponding seasonal soil physico-chemical properties; and (iv) to examine whether the year-on-year changes observed in the fungal population and community line up with the changes recorded in soil physico-chemical status.

MATERIALS AND METHODS

Study area

Fieldwork was carried out in Akkalkuwa Tehsil, Nandurbar District, Maharashtra, a hilly, largely tribal, semi-arid tract of the Satpura range bordering Gujarat and Madhya Pradesh (Government of Maharashtra, 2025; Indian Space Research Organisation, 2025). Rhizosphere soil was collected from farmers' fields growing the four crops that dominate cultivation in the tehsil banana (*Musa* spp.), sugarcane (*Saccharum officinarum*), groundnut (*Arachis hypogaea*) and chilli (*Capsicum annuum*) chosen because together they represent the region's perennial, cash and rain-fed cropping systems.

Soil sampling

Samples were drawn season-wise winter (November-February), summer (March-June) and rainy (July-October) over two consecutive agricultural years, 2021-22 and 2022-23. At each visit, soil closely adhering to the active root zone (0-15 cm depth) was collected from several plants within a field, pooled into a single composite sample, air-dried in the shade and sieved through a 2 mm mesh. Part of each composite sample went directly into fungal isolation within 48 hours of collection; the rest was retained for physico-chemical analysis.

Isolation, enumeration and identification of rhizosphere fungi

Fungi were isolated using the standard serial dilution and pour-plate technique on potato dextrose agar, following the general approach used in comparable regional surveys (Gaikwad, 2019; Kumar *et al.*, 2015; Gaddeyya & Niharika, 2018). One gram of soil from each sample was serially diluted up to 10^{-3} , and 1 mL aliquots from the appropriate dilution were plated in triplicate and incubated at 27 ± 2 °C for five to seven days. Colonies were counted at the end of incubation and expressed as colony-forming units per gram of dry soil (CFU/g soil). Distinct colony types were sub-cultured to purity and identified to genus or species level from their colony characters and lacto-phenol cotton-blue mounts, following standard taxonomic keys and the identification approach used in earlier regional mycoflora surveys (Aleruchi *et al.*, 2015; Madavi & Wadekar, 2018; Majaw & Kayang, 2018; Kaur *et al.*, 2019).

Soil physico-chemical analysis

Soil pH, colour and texture were recorded following standard procedures (Ministry of Agriculture of India, 2011). Moisture content (%) was determined gravimetrically and soil temperature (°C) recorded in the field at the time of sampling. Organic carbon (%) was estimated by the Walkley-Black wet-oxidation method, available nitrogen (kg/ha) by the alkaline permanganate method, available phosphorus (kg/ha) colorimetrically, and available potassium (kg/ha) by ammonium acetate extraction, broadly following methodology already applied

to soils of this same region (Bazargan *et al.*, 2024; Patel *et al.*, 2014; Ingle *et al.*, 2018). Exchangeable calcium and magnesium (meq/L) and titratable alkalinity (meq/100 g) were determined by standard volumetric procedures (Rahman *et al.*, 2008; Dandwate & Gasparyan, 2020; Gasparyan, 2023).

Data analysis

Colony counts, CFU/g soil values and physico-chemical readings are presented throughout as seasonal means for each crop and year. Crops and years were compared on these pooled seasonal means, and the percentage change between 2021-22 and 2022-23 was worked out as $[(\text{Year 2} - \text{Year 1}) / \text{Year 1}] \times 100$. Species lists for each crop were also compared year-on-year to identify which fungal taxa were shared between the two years and which appeared in only one of them. Comparative bar and line charts were prepared to visualise these seasonal and inter-annual patterns in fungal population and soil physico-chemical parameters.

RESULTS AND DISCUSSION

Seasonal and annual mean fungal populations for the four crops in both study years are set out in Table 1 and Figure 1. A clear and consistent pattern emerges regardless of crop or year: the rainy season carried the heaviest fungal load and summer the lightest, which fits with what one would expect given how strongly fungal growth depends on available soil moisture. Looking across the two years, the overall mean fungal population across all four crops climbed from 17,559.7 CFU/g soil in 2021-22 to 20,343.8 CFU/g in 2022-23 – a rise of close to 16%. That increase, however, was far from even. Groundnut posted the largest gain of any crop (18,252.3 to 24,601.3 CFU/g soil; +34.8%), sugarcane followed (17,717.3 to 22,346.7 CFU/g soil; +26.1%), and banana rose only modestly (18,495.0 to 19,865.3 CFU/g soil; +7.4%). Chilli stood apart as the one crop where the fungal population actually fell, from 15,774.0 to 14,562.0 CFU/g soil, a decline of roughly 7.7%.

Table 1. Comparative seasonal and annual mean rhizospheric fungal population (CFU/g soil) of four crops in Akkalkuwa Tehsil, 2021-22 and 2022-23.

Crop	Year	Winter	Summer	Rainy	Annual mean
Banana	2021-22	17,241	11,578	26,666	18,495.0
Banana	2022-23	18,292	16,304	25,000	19,865.3
Sugarcane	2021-22	16,867	8,888	27,397	17,717.3
Sugarcane	2022-23	20,481	15,053	31,506	22,346.7
Groundnut	2021-22	18,750	12,631	23,376	18,252.3
Groundnut	2022-23	23,170	17,777	32,857	24,601.3
Chilli	2021-22	17,647	8,247	21,428	15,774.0
Chilli	2022-23	16,024	7,526	20,136	14,562.0

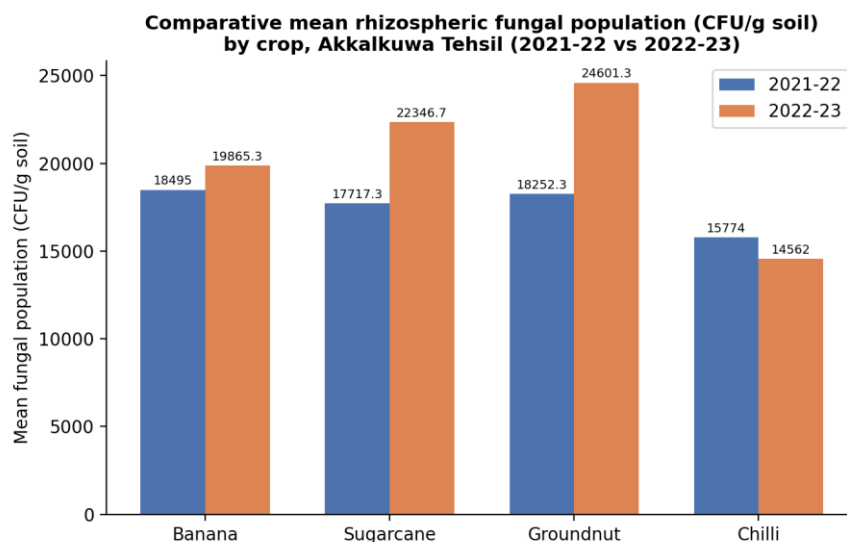


Figure 1. Comparative mean rhizospheric fungal population (CFU/g soil) of four crops, Akkalkuwa Tehsil, 2021-22 vs 2022-23.

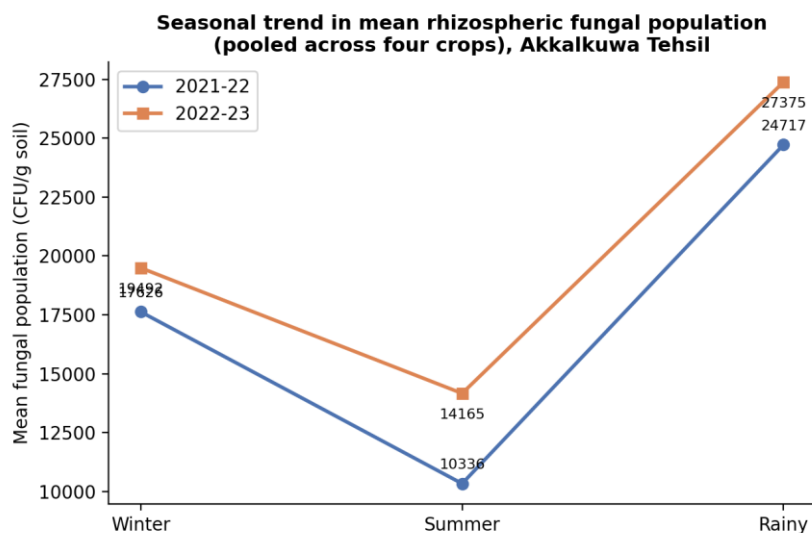


Figure 2. Seasonal trend of mean rhizospheric fungal population, pooled across the four crops, Akkalkuwa Tehsil, 2021-22 vs 2022-23.

Across the four crops combined, 26 fungal taxa were recorded in 2021-22 compared with 21 in 2022-23 genera spanning *Absidia*, *Alternaria*, *Aspergillus*, *Botrytis*, *Chaetomium*, *Cladosporium*, *Curvularia*, *Fusarium*, *Mucor*, *Penicillium*, *Pythium*, *Rhizopus*, *Trichoderma* and *Verticillium*. Fourteen species were common to both years, among them *Absidia glauca*, *Aspergillus flavus*, *A. kanagawaensis*, *A. niger*, *Botrytis* sp., *Chaetomium globosum*, *Curvularia lunata*, *Mucor mucedo*, *M. racemosus*, *Penicillium aurantiogriseum*, *P. chrysogenum*, *Pythium debaryanum*, *Rhizopus microsporus* and *R. oryzae*. A further twelve species *Alternaria alternata*, *Aspergillus fumigatus*, *A. ustus*, *Cladosporium herbarum*, *Fusarium oxysporum*, *Trichoderma harzianum* and *Verticillium* sp. among them turned up only in 2021-22, while seven others, including *Alternaria brassicicola*, *Aspergillus nidulans*, *A. terreus*, *Cladosporium cladosporioides*, *Penicillium citrinum*, *Rhizopus stolonifer* and *Trichoderma viride*, were recorded only in 2022-23. This degree of turnover suggests that the change between the two years was not simply a matter of the same species becoming more or less abundant; the composition of the community itself shifted.

The clearest such shift was seen in groundnut, where *Rhizopus stolonifer* absent from the 2021-22 collections altogether became the single most dominant species across all three seasons of 2022-23, contributing 21.7-31.5% of colonies depending on the season. Sugarcane told a similar story: *Aspergillus flavus* and *Penicillium chrysogenum* led the winter community in 2021-22, but by 2022-23 these had been overtaken by *Penicillium citrinum* (35.2% of winter colonies) and *Mucor mucedo* (35.7% of summer colonies), alongside a newly prominent, season-persistent population of *Alternaria brassicicola*. Banana and chilli, by contrast, showed comparatively gentler shifts banana moved from an *Alternaria alternata*-led community in 2021-22 toward a more *Alternaria brassicicola*- and *Aspergillus*-led one in 2022-23, while chilli retained a

broadly similar cast of dominant genera across both years, with *Trichoderma* present in both (as *T. harzianum* in the first year and *T. viride* in the second). Within banana, *Alternaria alternata* dominated the winter and summer collections of 2021-22 (26.6% and 36.3% of colonies respectively), whereas in 2022-23 dominance passed to *Alternaria brassicicola* in winter (33.3%) and to a more even spread across several *Aspergillus* species during summer and the rainy season. In sugarcane, as already noted, *Aspergillus flavus* and *Penicillium chrysogenum* were the leading winter species in 2021-22; a year later, *Penicillium citrinum* and *Mucor mucedo* had taken over, and *Alternaria brassicicola* appeared consistently in every season rather than being confined to one. Groundnut's rhizosphere was led by *Aspergillus niger* and *A. kanagawaensis* in 2021-22, but by 2022-23 *Rhizopus stolonifer* had become dominant across the board a genuinely different community from the one recorded the previous year. Chilli saw *Aspergillus fumigatus*, *Penicillium aurantiogriseum*, *Rhizopus oryzae* and *Trichoderma harzianum* figure prominently in 2021-22, while in 2022-23 *Aspergillus flavus* (up to 33.3% of rainy-season colonies) and *Chaetomium globosum* moved to the fore, with *Trichoderma viride* maintaining a steady presence across seasons worth flagging given *Trichoderma*'s established track record as a biocontrol agent against soil-borne pathogens (Chaithra *et al.*, 2020; Hariharan *et al.*, 2022). Table 2 and Figures 3-7 set out the seasonal-mean physico-chemical properties of the rhizosphere soils for each crop in both years. Soil pH rose between 2021-22 and 2022-23 in three of the four crops, most noticeably under banana (6.26 to 7.59) and groundnut (6.47 to 7.48), while sugarcane held roughly steady and chilli edged slightly downward. Moisture increased in banana, sugarcane and groundnut, though only marginally in chilli which already carried the highest baseline moisture of the four crops in both years (18.8-19.4%), consistent with its greater irrigation requirement. Available nitrogen rose under sugarcane (235.3 to 291.3 kg/ha) and

groundnut (231.7 to 283.3 kg/ha), tracking the same two crops that recorded the largest gains in fungal population, whereas banana's available nitrogen actually fell (315.3 to 263.4 kg/ha) even as its fungal population rose only slightly. Organic carbon increased most under groundnut (0.57% to 0.87%), again the crop with the single largest jump in fungal CFU/g; chilli, the only crop where the

fungal population declined, was also the only crop where organic carbon fell (0.63% to 0.51%). Soil temperature varied comparatively little between years within each crop, and texture stayed broadly the same (predominantly sandy loam to clay loam), though groundnut's soil darkened somewhat between the two years, consistent with its rising organic-carbon content.

Table 2. Comparative seasonal-mean physico-chemical properties of rhizosphere soils under four crops, Akkalkuwa Tehsil, 2021-22 and 2022-23.

Crop	Year	pH	Moisture (%)	Temperature (°C)	Organic carbon (%)	Available N (kg/ha)
Banana	2021-22	6.26	8.30	28.00	0.64	315.3
Banana	2022-23	7.59	9.07	27.32	0.58	263.4
Sugarcane	2021-22	6.90	16.60	28.27	0.56	235.3
Sugarcane	2022-23	6.92	17.47	27.42	0.49	291.3
Groundnut	2021-22	6.47	12.50	27.07	0.57	231.7
Groundnut	2022-23	7.48	14.00	30.08	0.87	283.3
Chilli	2021-22	6.86	18.77	28.06	0.63	279.7
Chilli	2022-23	6.77	19.43	28.40	0.51	313.7

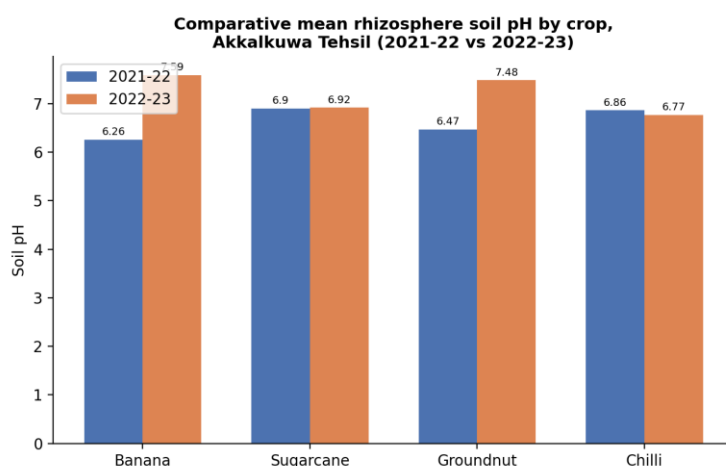


Figure 3. Comparative mean rhizosphere soil pH by crop, Akkalkuwa Tehsil, 2021-22 vs 2022-23.

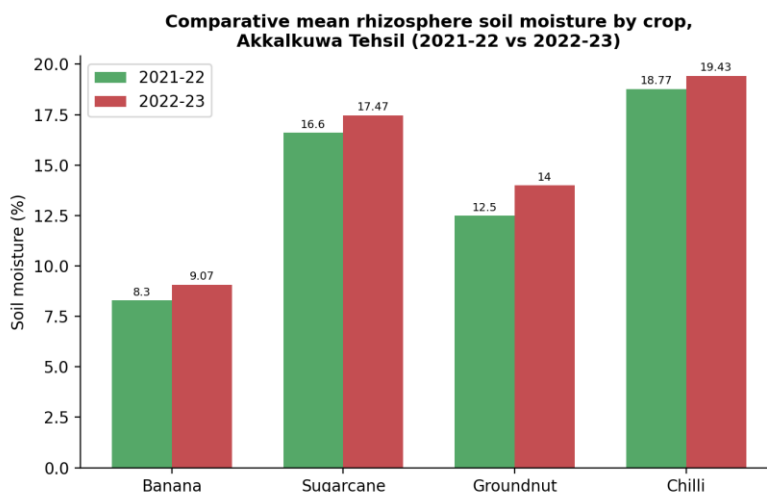


Figure 4. Comparative mean rhizosphere soil moisture (%) by crop, Akkalkuwa Tehsil, 2021-22 vs 2022-23.

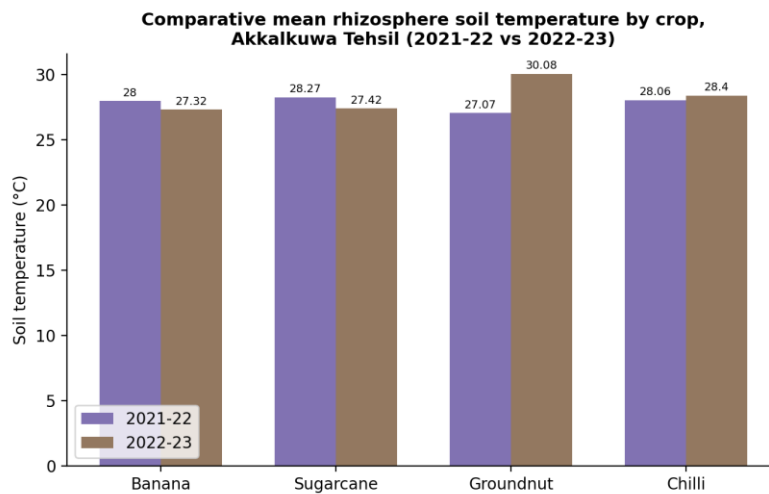


Figure 5. Comparative mean rhizosphere soil temperature (°C) by crop, Akkalkuwa Tehsil, 2021-22 vs 2022-23.

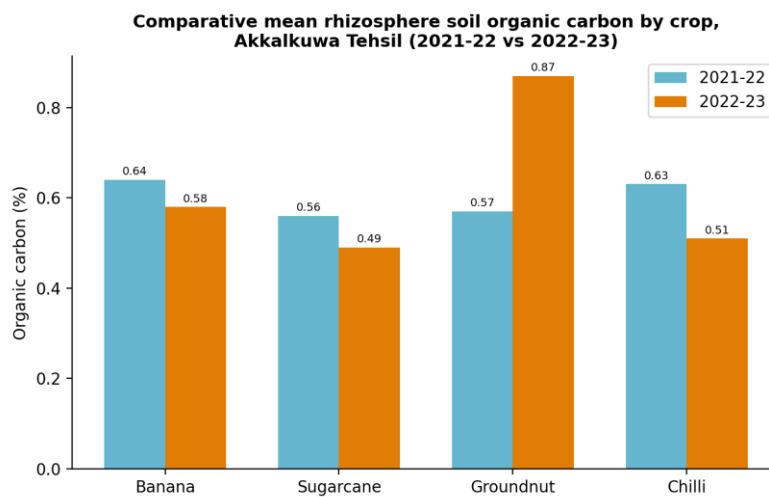


Figure 6. Comparative mean rhizosphere soil organic carbon (%) by crop, Akkalkuwa Tehsil, 2021-22 vs 2022-23.

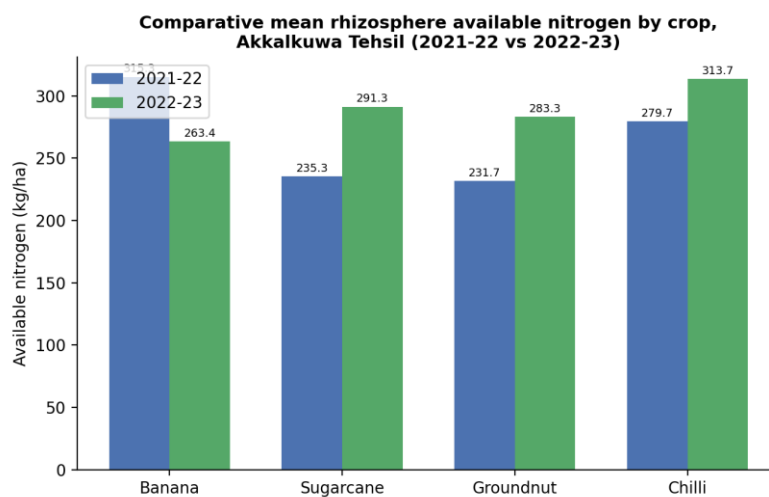


Figure 7. Comparative mean rhizosphere available nitrogen (kg/ha) by crop, Akkalkuwa Tehsil, 2021-22 vs 2022-23.

Taken together, these results suggest that both the size and the make-up of the rhizosphere fungal community in Akkalkuwa Tehsil shift measurably from one cropping year to the next, and that neither the direction nor the extent of that shift is the same across crops. The rainy season came out on top for fungal load in both years and in every crop studied, which lines up comfortably with earlier seasonal surveys of mycoflora elsewhere in India that report the same monsoon-linked peak (Chaudhary *et al.*, 2016; Swer *et al.*, 2008; Shivanna & Vasanthakumari, 2011). Soil moisture is generally regarded as the single most influential physico-chemical driver of culturable fungal abundance, since it governs spore germination and hyphal growth directly (Wang *et al.*, 2017; Zhang *et al.*, 2019; Sarkar *et al.*, 2024); the fact that the crop-seasons with the highest recorded moisture in this study – rainy-season sugarcane and groundnut – were also the ones with the highest CFU/g values fits that expectation well. What stands out more is how differently the four crops behaved from each other. Groundnut and sugarcane, the two crops with the steepest rise in fungal population between years, were also the two where the species composition changed the most – a handful of species (*Rhizopus stolonifer* in groundnut; *Penicillium citrinum* and *Mucor mucedo* in sugarcane) came to dominate the rhizosphere in 2022-23 having been minor or entirely absent the year before. This kind of pattern, where one or two fast-growing, opportunistic genera surge forward as overall fungal load rises, has been reported before in soils receiving higher nutrient or moisture inputs, where copiotrophic, quick-colonising fungi tend to out-compete the rest of the community under enriched conditions (Wang *et al.*, 2017; Kurm *et al.*, 2023; Zinati *et al.*, 2025), and continuous-cropping studies elsewhere have documented broadly similar compositional turnover from one cropping cycle to the next in response to shifting soil conditions (Tan *et al.*, 2017). The rise in organic carbon and available nitrogen recorded here for groundnut in 2022-23 supports this reading, since both are known to favour fast-colonising *Mucor* and *Rhizopus* species over slower-growing taxa (Dighton, 2018; Mishra *et al.*, 2024).

Banana and chilli, which changed the least in terms of fungal population between the two years, also showed the gentlest shift in which species dominated their rhizospheres. This relative stability may simply reflect the more buffered, perennial growing environment that banana offers (Temjen *et al.*, 2022; Shelke & Kishor, 2024), and the more consistently managed moisture regime typical of irrigated chilli cultivation (Febronia, 2016; Gayathri & D.A., 2014), compared with the more rain-fed, seasonally extreme conditions that sugarcane and groundnut fields in this tract are exposed to. The genera that turned up again and again across crops, seasons and years – *Aspergillus*, *Penicillium*, *Mucor*, *Rhizopus* and *Chaetomium* – match closely with what has been reported for banana, groundnut, sugarcane and chilli rhizospheres elsewhere in India and beyond (Gaikwad, 2019; Gnanasekaran *et al.*, 2015; Shitole *et al.*, 2019; Elias *et al.*, 2016; Hartoyo & Trisilawati, 2021), which is not altogether surprising given how ecologically adaptable these genera are known to be in tropical and subtropical agricultural soils generally (Murali

et al., 2021; Adedayo & Babalola, 2023). Rather more interesting, from an applied standpoint, is the steady presence of *Trichoderma* in the chilli rhizosphere across both years – *T. harzianum* in 2021-22, *T. viride* in 2022-23 – given how well documented *Trichoderma*'s antagonism toward soil-borne pathogens such as *Sclerotium*, *Fusarium* and *Rhizoctonia* already is (Chaithra *et al.*, 2020; Hariharan *et al.*, 2022; Sehwat & Sindhu, 2019); it would be worth isolating and testing these particular strains for biocontrol potential in future work. On the other side of the ledger, *Fusarium oxysporum* and *Pythium* species turned up repeatedly in the banana, sugarcane and chilli rhizospheres in 2021-22, both genera with a well-established capacity to cause disease in these same crops (Gayathri & D.A., 2014; Sreenivasa *et al.*, 1992; Sreenivasa & Krishnaraj, 1992) – a reminder that the rhizosphere mycoflora recorded here is a mixed bag of beneficial, saprophytic and potentially pathogenic organisms, all of them apparently sensitive to the same seasonal and soil factors examined in this study.

The upward drift in soil pH under banana and groundnut, together with the rise in available nitrogen under sugarcane and groundnut, is in keeping with what regional soil surveys of the Khandesh belt have already described as considerable year-to-year variability in soil chemistry, generally put down to differences in fertiliser use, monsoon strength and cropping intensity between seasons (Ingle *et al.*, 2018; Fulpagare *et al.*, 2023; Patel *et al.*, 2014). Soil pH and nutrient availability are known to influence which fungal taxa establish and persist in a given soil (Meng *et al.*, 2015; Rani *et al.*, 2017; Yadav *et al.*, 2024), so the fact that the physico-chemical data and the fungal data both moved in step across the same two years is reassuring – it suggests that the changes recorded here reflect a genuine response to changing soil conditions rather than an artefact of sampling. On the whole, the picture that emerges is one of a rhizosphere fungal community that responds quite readily to both season and to shorter-term, year-to-year change in soil moisture and nutrient status, and that a rise in fungal numbers does not necessarily mean a healthier or more balanced community in groundnut and sugarcane, at least, it appeared to go hand in hand with a narrower set of dominant species rather than a broader one (Panneerselvam *et al.*, 2019; Todorovic *et al.*, 2023; Beattie *et al.*, 2025). These two years of data give a working, quantitative point of reference against which future soil-health monitoring, crop-rotation decisions and biocontrol-strain searches in this comparatively under-studied tribal agricultural belt can be measured.

CONCLUSION

This two-year comparison of the rhizosphere mycoflora of banana, sugarcane, groundnut and chilli in Akkalkuwa Tehsil shows that fungal population and species composition both changed measurably between 2021-22 and 2022-23, and that the direction and scale of that change depended on the crop in question and tracked fairly closely with concurrent changes in soil moisture, pH, organic carbon and available nitrogen. The rainy season carried the

heaviest fungal load in both years and across all four crops, confirming moisture as the main proximate driver of rhizosphere fungal dynamics in this semi-arid tract. Groundnut and sugarcane saw the largest rises in fungal numbers, accompanied by a marked shift toward dominance by a small number of fast-growing species, while banana and chilli held comparatively steady across both years. Genera of clear agronomic interest *Trichoderma*, *Aspergillus*, *Penicillium*, *Mucor* and *Rhizopus* were present in the rhizosphere of all four crops throughout the study, which is a reasonable starting point for future work aimed at isolating and testing locally adapted plant-growth-promoting or biocontrol fungal strains from this under-studied tribal agricultural region. The two-year, four-crop, three-season dataset assembled here should serve as a useful reference for ongoing soil-health monitoring and for informing more soil- and fungus-aware crop management in Akkalkuwa Tehsil and comparable agro-ecological zones of Maharashtra.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declare that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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