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EDAPHIC AND CLIMATIC FACTORS DRIVE MYCORRHIZAL FUNGAL DIVERSITY IN THE MOIST TEMPERATE FOREST, PAKISTAN

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Abstract

Mycorrhizal fungi are vital to forest health because they form symbiotic associations with the roots of over 90% of higher plants. This study aimed to explore the influence of environmental factors on mycorrhizal fungi. This study was conducted in the Murree Forest Division, part of the lower western Himalaya, Pakistan, from April 2023 to November 2024. Fungal specimens were collected using the quantitative quadrat method (10 × 10 m). Climatic and soil data were collected using various instruments, and precipitation data were obtained from NASA's POWER Data Access Viewer. Multiple linear regression models were used for data analysis. The results identified 28 mycorrhizal fungi belonging to 12 families, with a notable diversity. The families Russulaceae (eight species) and Helvellaceae (four species) were the most species-rich, followed by Gomphaceae (three species); the other families had one to two species each. Regression analysis revealed that atmospheric humidity and phosphorus were the strongest positive predictors of mycorrhizal abundance. The soil model explained 96.78% of the variation ($R^2 = 0.9678$), whereas the environmental model explained 92.32% (adjusted $R^2 = 0.9232$). Although parameters such as EC, TDS, OM, N, brightness, and temperature showed visual trends, they were not statistically significant. This study concluded that atmospheric humidity and soil phosphorus significantly influence mycorrhizal fungal abundance. Future research should focus on long-term studies and predictive modeling to understand how climatic conditions affect mycorrhizal communities.

Key words: Mycorrhizal fungi; Edaphic factors; Climatic factors; Abundance; Murree forest division

Introduction

Mycorrhizal fungi are essential components of forest ecosystems (Pérez-Moreno *et al*., 2021). They form symbiotic associations (Ali *et al*., 2021) with the roots of more than 90% of higher plant species (Brundrett & Tedersoo, 2018). This mutual relationship improves plant nutrient uptake(Badshah *et al.,* 2023), particularly nitrogen and phosphorus, and enhances host tolerance to abiotic stresses, such as soil salinity and drought (Begum *et al*., 2019; Ahmad *et al.,* 2026). However, the factors that affect the distribution and interaction of these significant associations under changing environmental conditions remain poorly understood (Hawkes *et al*., 2021). Climatic and edaphic factors are known to regulate the distribution of mycorrhizal fungi; however, the ways in which variations in these factors affect fungal communities and their interactions are still not well understood (Yang *et al*., 2022).

Edaphic factors influence the richness and density of mycorrhizal fungal communities in different ways (Janowaski & Leski, 2022). Soil texture influences water retention and aeration. Clay loam soils support greater fungal diversity by retaining water and nutrients for long periods (Xia *et al*., 2020; Kivlin *et al*., 2014). Soil pH is also an important filter (Glassman *et al*., 2017), with arbuscular mycorrhizal (AM) fungi being most dominant in alkaline to neutral soils, whereas ectomycorrhizal (EcM) fungi are more tolerant of acidic conditions (Van Geel *et al*., 2018; Farghaly *et al*., 2022). Fungal communities are also shaped by nutrient availability, such as nitrogen and phosphorus (Xu *et al*., 2018). Over-fertilization can diminish a host plant's reliance on mycorrhizae and potentially lead to shifts in plant community structure (Camenzind *et al*., 2021). Soil organic matter influences fungal networks by changing microbial activity and soil structure (Soudzilovskaia *et al*., 2020). High organic matter content in the soil can support rich fungal communities (Hobbie *et al*., 2020).

Climatic and edaphic factors shape mycorrhizal patterns at both spatial and temporal scales. Temperature influences fungal decomposition, hyphal growth and fungal development. In warmer climates, elevated temperatures initially promote fungal activity to some extent, but continued increases may eventually exert a suppressive effect (Bennett *et al*., 2020). Precipitation patterns are equally important because prolonged drought and waterlogging disrupt hyphal systems and decrease colonization rates (Kivlin *et al*., 2022). Several fungal taxa show complex seasonal variability and pronounced phenological responses to wet-dry or freeze-thaw cycles (Lankau *et al*., 2022). Additionally, these factors are changing at an unparalleled rate due to climate change, which may disrupt the historically established relationships between fungi and plants while restructuring communities

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below ground (Steidinger *et al*., 2020). Mycorrhizal distribution is influenced by the interactions between climate and soil, a relationship that remains largely unexplored (Bennett & Classen, 2020; Chaudhary *et al*., 2022). It has been suggested that wetter environments may be more strongly affected by climate filtering, whereas fungal communities in nutrient-rich soils may be buffered against extremely high temperatures (Pellitier *et al*., 2021; Linden, 2023). It is crucial to elucidate such interactions to predict how ongoing environmental changes, such as warming (Aber *et al*., 2001), shifts in precipitation regimes, and soil loss, affect the stability of mycorrhizal networks and their associated ecosystem services (Bennett & Classen, 2022). Understanding these mechanisms is crucial for assessing the ecological consequences of rapid environmental changes. This study evaluated the effects of climatic and edaphic factors on the diversity and distribution of mycorrhizal fungi. Specifically, it aims to determine how environmental factors influence the distribution and diversity of mycorrhizal fungi in the rhizosphere. The findings of this study will improve our understanding and better position us to elucidate the interactions between fungi and environmental factors in forest ecosystems.

Materials and Methods

Study area: The present study was conducted in the Murree district of Pakistan. The study area is ecologically significant and consists of dense, moist temperate forests. Murree and its surrounding areas are critical for maintaining biodiversity, climatic control and ecosystem processes. It is dominated by broad-leaved and coniferous tree species, including *Pinus wallichiana*, *Cedrus deodara*, and *Quercus incana* (Zeb *et al*., 2025). It comprises diverse flora, fauna and fungal communities. The topography is heterogeneous, ranging from steep slopes to valleys. The humid weather conditions make the Murree Forest Division an important region for ecological studies, especially in forest ecology, hydrology and climate change research. Murree Tehsil is geographically bounded by several distinct regions. It shares its border with the province of Khyber Pakhtunkhwa in the north. It is adjacent to the Islamabad Capital Territory on the eastern side. The southern boundary extends to the Ari-Kahuta and Kahuta-Matore roads and the Dhan Gali River in the Jhelum region. To the west, the tehsil's limits again touch the boundary of Khyber Pakhtunkhwa, forming a natural and administrative boundary between the two provinces.

Data collection, preservation, and identification of mycorrhizal species: A field survey was conducted from April 2023 to November 2024 in the moist temperate Forest of Murree Division. A sharpened knife was used to carefully remove the fruiting body samples from the hosts. Photographs were taken using a Canon 3000D DSLR Camera equipped with an 18–55 mm DC III Lens. Samples were collected and placed in polythene bags, which were properly labeled with the location, date of collection, and host species. To prevent deterioration, samples were brought back to the lab on the same day and carefully dried for two or three days at 40–45°C before being stored in polythene bags for further research (Ador *et al.,* 2023).

The fungal specimens were closely inspected in the laboratory for macroscopic and microscopic characteristics, including cap size and shape, cap color, gills, spores, cystidia, and the structure of hyphae and mycelia. A light microscope was used to examine the fruiting body sections. These specimens were then cross-checked with published articles, review papers, and relevant taxonomic literature to ensure the accurate identification of the mushrooms (Crous *et al.,* 2004; Hyde *et al.,* 2019). Additional verification was carried out using the Index Fungorum database (http://www.indexfungorum.org/ names/names.asp) and MycoBank (http://www.mycobank.org) (Fungorum, 2018) to confirm the current nomenclature and taxonomy.

Soil analysis: Soil samples were collected from a depth of 0.3 m from every site, stored in labeled polythene bags, and dried at room temperature. To determine soil electrical conductivity (EC) and total dissolved solids (TDS), 20 g of soil was dissolved in 100 ml of distilled water at a 1:5 ratio and stirred for 1 hour, as described by McLean (1983). The resulting suspension was filtered through Whatman No. 42 filter paper, and the EC and TDS of the filtrate were measured with their respective meters. The organic matter content was estimated using the Walkley method (Nelson & Sommers, 1996). One gram of soil was placed in a 500 ml conical flask with 5 ml of potassium dichromate ($K_2Cr_2O_7$) and 10 ml of sulfuric acid (H_2SO_4), shaken, and allowed to cool at room temperature. After cooling, 100–150 ml of distilled water, 0.5 g of sodium fluoride (NaF) or 3 ml of phosphoric acid (H_3PO_4), and 5–10 drops of a suitable indicator were introduced. The solution was titrated with ferrous sulfate ($FeSO_4$) dropwise until the color changed from green to blue. The phosphorus content was measured using an atomic absorption spectrophotometer. One gram of soil was weighed into a 250 ml conical flask for further phosphorus determination, and nitric acid (HNO_3) and perchloric acid ($HClO_4$) were added in a 3:1 ratio. The mixture was left overnight and processed on a hot plate. After cooling, the digest was filtered, and distilled and refined water were added to bring the final volume up to 50 ml. The phosphorus content was determined using an atomic absorption spectrophotometer (VARIAN, AA240FS) (Ahmad *et al.,* 2023).

Climate data collection: Temperature and atmospheric humidity were collected in the field using a Kestrel 5400 WBGT Heat Stress Tracker (HST) and a weather meter. Light intensity data were recorded using a Field Scout ^{TM} 3414 ultraviolet meter with an accuracy of ±5%. The cosine correction is accurate to ±3% at 45° and ±7% at 80°. The ultraviolet meter was calibrated to display the intensity of ultraviolet light in the 250–400 nm wavelength range in units of µmol $m^{-2}s^{-1}$. The meter displayed values ranging from 0 to 199.9 µmol $m^{-2}s^{-1}$.

Precipitation data were obtained from the NASA Power/DAV website (https://power.larc.nasa.gov/data-access-viewer/). First, the NASA POWER Data Access Viewer was accessed, and the "Agroclimatology" data category was selected. The geographic coordinates of the study area (latitude and longitude of the lower western Himalaya) were specified to extract climate data. The dataset's temporal range was chosen to match the study period, enabling the download of the precipitation data.

Data analysis: The study hypothesis was tested using descriptive and inferential statistical analyses. Data from Excel were imported into R for analysis. Pearson correlation analysis was used to identify the relationships between fungi and environmental variables. Multiple regression analysis was used to determine the impact of environmental variables on the abundance of mycorrhizal fungi. The multiple regression model used in this study is presented below:

$$\mathbf{Y = \beta 0 + \beta 1XpH + \beta 2XEC + \beta 3TDS + \beta 4Brightness + \beta 5humidity + \beta 6Xtemp + \varepsilon_i \ldots} \quad \text{(i)}$$

In this model, Y represents the Importance Value Index of abundant fungal species, and X represents the independent variables. We estimated the regression coefficient ($\boldsymbol{\beta}$) and significance (p-value) of environmental variables for each predictor, as well as the goodness-of-fit of the model (R2). The model performance was evaluated using the coefficient of determination (R^2) and the significance of individual predictors.

Result

The present study documented a diverse assemblage of mycorrhizal fungi in the Murree Forest Division, including 28 species from 12 families. The families with the highest species richness were Russulaceae (eight species) and Helvellaceae (four species), followed by Gomphaceae (three species), while the other families were represented by 1–2 species. Morphological variation was observed among the recorded taxa, with stipe lengths ranging from 1 cm (*Helvella latispora*) to 15 cm (*Russula padulosa*) and pileus diameters ranging from 0.5 cm (*Ramaria zippelii*) to 20 cm (*R. padulosa*). Color variation included vibrant pigmentation in *Russula atropurpurea* (red-purple) and *Cantharellus cibarius* (yellow), as well as subdued colors in *Tricholoma terreum* (gray, brown) and *Thelephora terrestris* (brown). White species were dominant in *Hygrophorus eburneus*, *Russula laurocerasi*, and some *Lactarius* species. Morphological observations indicated considerable interspecific differences among co-occurring mycorrhizal fungi, indicating niche differentiation in this forest community (Table 1).

Relationship of mycorrhizal fungi with edaphic: A linear regression model was used to examine the relationship between mycorrhizal abundance and soil physicochemical factors, including Electrical Conductivity (EC), Total Dissolved Solids (TDS), Organic Matter (OM), nitrogen (N), and phosphorus (P), as shown in Fig. 1. The scatter plots with regression lines illustrate these correlations, and the results in Table 2 provide their statistical evaluation.

The model was highly significant, with an R-squared value of 0.9678, indicating that 96.78% of the variation in mycorrhizal abundance was explained by the selected environmental factors. The adjusted R-squared of 0.9608 confirms the model's strength after accounting for the number of predictors. The F-statistics (138.3, $p<0.001$) further confirmed that the overall model was highly significant, indicating that the predictors, as a group, had a strong association with mycorrhizal abundance.

Phosphorus had a highly significant positive influence on mycorrhizal abundance (Estimate = 0.293522, p = 0.000656). This result shows that higher soil phosphorus concentrations were strongly correlated with mycorrhizal abundance. On the other hand, EC, TDS, OM, and N did not individually show statistically significant effects on mycorrhizal abundance, as their p-values were greater than 0.05. Organic matter and nitrogen showed strong linear trends in the scatter plots, especially nitrogen, which closely aligned with mycorrhizal abundance; however, these associations were not statistically supported, perhaps due to multicollinearity or a limited sample size inflating the standard errors (Fig. 2).

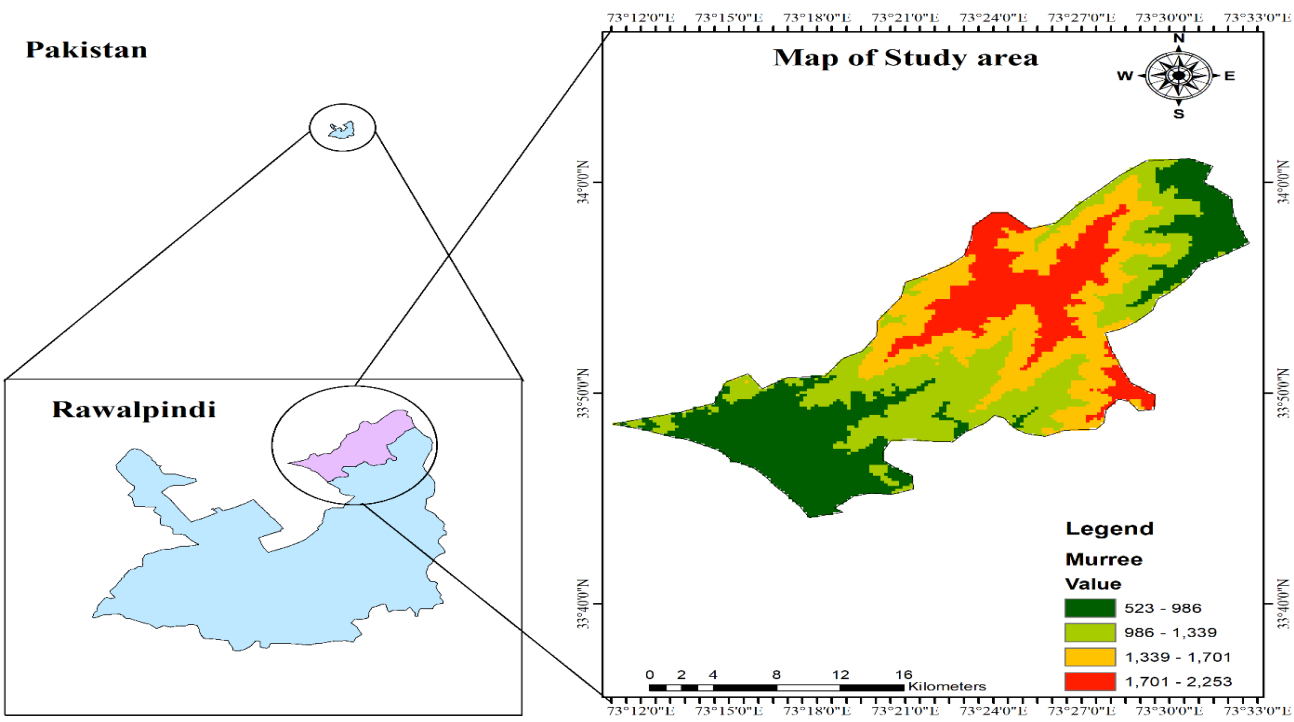


Fig. 1. Map of the study area generated using ArcGIS 10.5 software.

Table 1. List of mycorrhizal fungal species collected from various locations, taxonomic ranking, nutritional habits, and important morphological characters such as stipe length, pileus diameter, and color.

S. No.	Species name	Family	Collection area	Mode of nutrition	Morphology		
					Stipe length (cm)	Pelius diameter (cm)	Colour
1.	*Cantharellus cibarius* Fr.	Cantharellaceae	Muree Forest Division	Mycorrhizal	2–7cm	3–8cm	Yellow
2.	*Cortinarius sanguineus* (Wulfen) Gray	Cortinariaceae	Muree Forest Division	Mycorrhizal	3–6 cm long;	1.5–4.5 cm	Dark red
3.	*Helvella crispa* (Scop.) Fr.	Helvellaceae.	Muree Forest Division	Mycorrhizal	4–8cm	3–8cm	Pinkish or pale
4.	*Helvella dryophila* Vellinga & N.H. Nguyen	Helvellaceae.	Muree Forest Division	Mycorrhizal	3–5.5 cm long	1.5–4.5	Grayish to dark gray
5.	*Hygrophorus eburneus* (Bull.) Fr.	Hygrophoraceae	Muree Forest Division	Mycorrhizal	4–14 cm	2–8 cm	white
6.	*Hygrophorus hypothejus* (Fr.) Fr.	Hygrophoraceae	Muree Forest Division	Mycorrhizal	4–7cm long	3–6cm	Yellow
7.	*Hysterangium affine* Massee & Rodway.	Hysterangiaceae	Muree Forest Division	Mycorrhizal	3–10 cm long	2–12 cm	Brownish yellow
8.	*Lactarius rufulus* Peck.	Russulaceae	Muree Forest Division	Mycorrhizal	4–12cm	3–10cm	Brown
9.	*Ramaria stricta* (Pers.) Quél.	Gomphaceae	Muree Forest Division	Mycorrhizal	4–14 cm high	4–10 cm wide	Purplish brown
10.	*Ramaria zippelii* (Lév.) Corner,	Gomphaceae	Muree Forest Division	Mycorrhizal	3.0 cm	0.5–1.0 cm	Light brownish
11.	*Russula aerugenia* Lindblad ex Fr.	Russulaceae	Muree Forest Division	Mycorrhizal	4–6 cm	5–9 cm	White
12.	*Russula atropurpurea* (Krombh.) Britzelm.	Russulaceae	Muree Forest Division	Mycorrhizal	3–6cm	4–10cm	Red-purple
13.	*Russula emetica* (Schaeff.) Pers.	Russulaceae	Muree Forest Division	Mycorrhizal	4–9cm long	3–10cm	Pink
14.	*Russula laurocerasi* Britzelm.	Russulaceae	Muree Forest Division	Mycorrhizal	2.5–11 cm	3.5–13 cm	White
15.	*Russula paludosa* Britzelm.	Russulaceae	Muree Forest Division	Mycorrhizal	5–15 cm	6–20 cm	Yellow orange
16.	*Thelephora terrestris* Ehrh.	Thelephoraceae	Muree Forest Division	Mycorrhizal	2.3–8cm	2–4 cm	Brownish
17.	*Tricholoma terreum* (Schaeff.) P. Kumm.	Tricholomataceae	Muree Forest Division	Mycorrhizal	3–5 cm long	4–7.5 cm	Gray to brownish gray.
18.	*Xerocomus subtomentosus* (L.) Quél.	Boletaceae.	Muree Forest Division	Mycorrhizal	4–7.5 cm long	3–9.5 cm	Brownish yellow
19.	*Amanita vaginata* (Bull.) Lam.	Amanitaceae	Muree Forest Division	Mycorrhizal	7–15 cm	3–10 cm	Whitish.
20.	*Helvella albella Quél.*	Helvellaceae	Muree Forest Division	Mycorrhizal	3 – 7 cm	1.5–4 cm	Dark brown
21.	*Laccaria bicolor* (Maire) P.D.Orton,	Hydnangiaceae	Muree Forest Division	Mycorrhizal	3–10 cm long	1–8 cm	Whitish.
22.	*Lactarius fuliginosus* (Krapf) Fr.	Russulaceae	Muree Forest Division	Mycorrhizal	3–5cm	4–9cm	White
23.	*Russula betularum* Hora	Russulaceae	Muree Forest Division	Mycorrhizal	4–10.7cm	2–5cm	White
24.	*Suillus granulatus* L.	Suillaceae	Muree Forest Division	Mycorrhizal	5 cm long	7 cm across	Whitish to yellowish
25.	*Helvella latispora* Boud.,	Helvellaceae	Muree Forest Division	Mycorrhizal	1–8.3 cm	1–4.8 cm	Pale brownish
26.	*Ramaria aurea* (Schaeff.) Quél.	Gomphaceae	Muree Forest Division	Mycorrhizal	4–12 cm	3–17 cm	Whitish to Brownish
27.	*Hydnum repandum* L.	Hydnaceae	Muree Forest Division	Mycorrhizal	3–6 cm	6–15 cm	Whitish
28.	*Tricholoma argyraceum* (Bull.)	Tricholomataceae	Muree Forest Division	Mycorrhizal	2–4 cm long	2.4–6.7 cm	Grayish brown

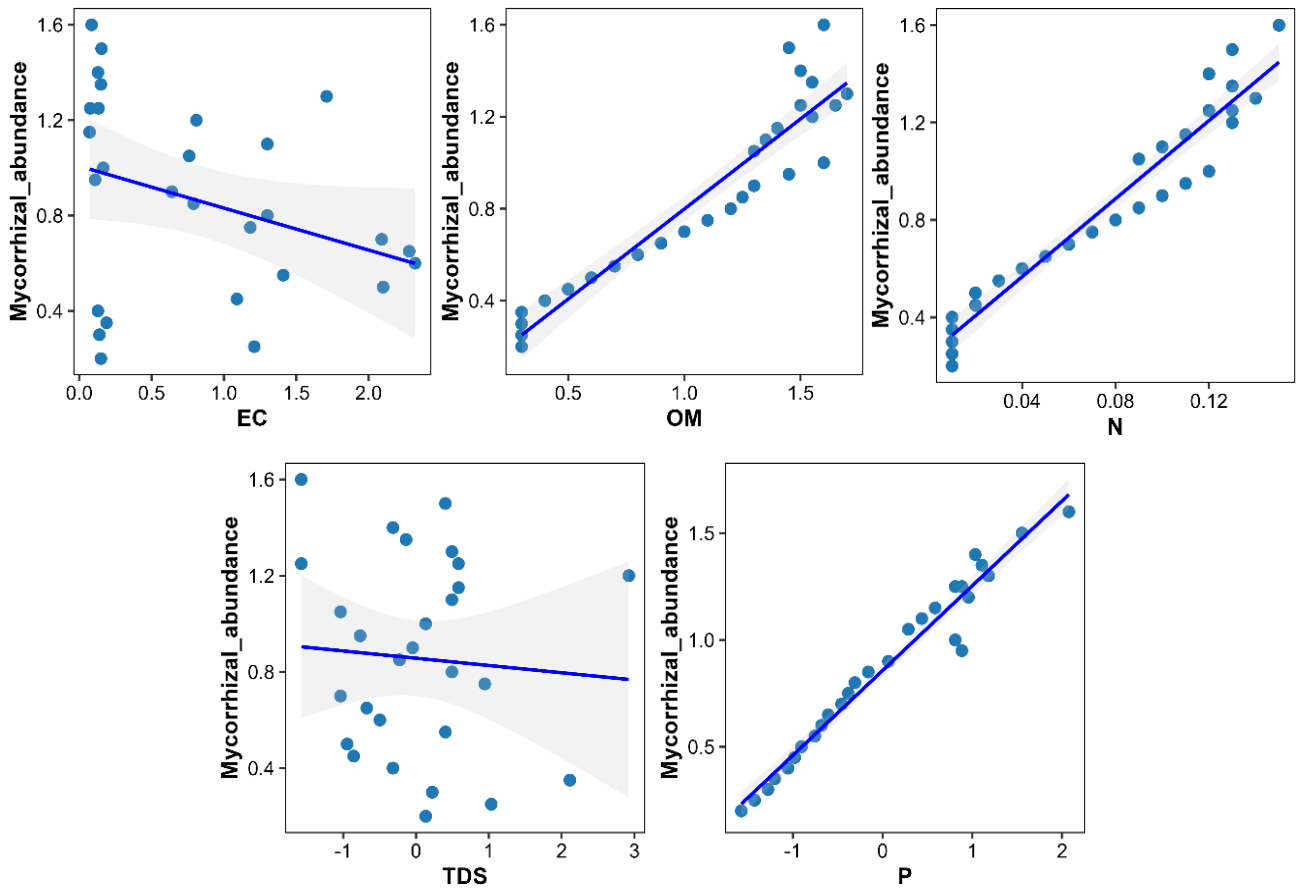


Fig. 2. The relationship between mycorrhizal abundance and different environmental variables, such as electrical conductivity (EC), organic matter (OM), nitrogen (N), total dissolved solids (TDS), and phosphorus (P), was determined.

Table 2. Presents the summary of the multiple linear regression of electrical conductivity (EC), total dissolved solids (TDS), organic matter (OM), nitrogen (N) and phosphorus (P).

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	0.692692	0.103951	6.664	8.48e-07 ***
EC	0.023461	0.025546	0.918	0.367943
TDS	-0.008667	0.017142	-0.506	0.617970
OM	-0.096658	0.244076	-0.396	0.695744
N	3.254065	3.406263	0.955	0.349351
P	0.293522	0.074532	3.938	0.000656 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 0.08004 on 23 degrees of freedom
Multiple R-squared: 0.9678, Adjusted R-squared: 0.9608
F-statistic: 138.3 on 5 and 23 DF, p-value: 2.254e-16

Table 3. presents a summary of the multiple linear regression model for brightness, humidity, precipitation, and temperature.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-1.338e+02	2.780e+01	-4.813	7.41e-05 ***
Brightness	-1.499e+00	9.726e-01	-1.541	0.1370
Humidity	2.664e+00	3.905e-01	6.823	5.87e-07 ***
Precipitation	5.961e-03	3.131e-03	1.904	0.0695
Temperature	-1.787e-01	1.962e-01	-0.911	0.3717

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 2.185 on 23 degrees of freedom
Multiple R-squared: 0.9346, Adjusted R-squared: 0.9232
F-statistic: 82.15 on 4 and 23 DF, p-value: 2.818e-13

Relationship between mycorrhizal fungi and climatic factors: Linear regression analysis was performed to evaluate the relationship between mycorrhizal abundance and four climatic variables: brightness, humidity, rainfall, and temperature (Fig. 3). The model was statistically significant, as indicated by an F-statistic of 82.15 and a p-value of 2.818e-13, indicating that the predictors, as a group, accounted for most of the variation in mycorrhizal abundance, as presented in Table 3. The goodness-of-fit of the model is also evident from the high adjusted R-squared value of 0.9232, which means that the environmental variables included explain approximately 92.32% of the variation in mycorrhizal abundance. Among the predictors, humidity was the most important, with a positive coefficient of 2.664 (p = 5.87e-07), indicating that higher humidity levels are strongly associated with greater mycorrhizal abundance. Precipitation showed a weakly significant positive relationship (coefficient = 5.961e-03, p = 0.0695), with increased precipitation tending to enhance mycorrhizal abundance, although this effect was relatively weak. Conversely, brightness and temperature were not statistically significant predictors of mycorrhizal abundance (p = 0.1370 and p = 03717, respectively). The negative values for brightness (-1.499) and temperature (-1.787e-01) suggest inverse relationships, but these results were not statistically significant. The residuals ranged from -4.1232 to 2.8049, with a median of 0.6829, suggesting a symmetric distribution centered at approximately 0. The residual standard error of 2.185 on 23 degrees of freedom represents the average deviation of the observed values from the fitted regression line.

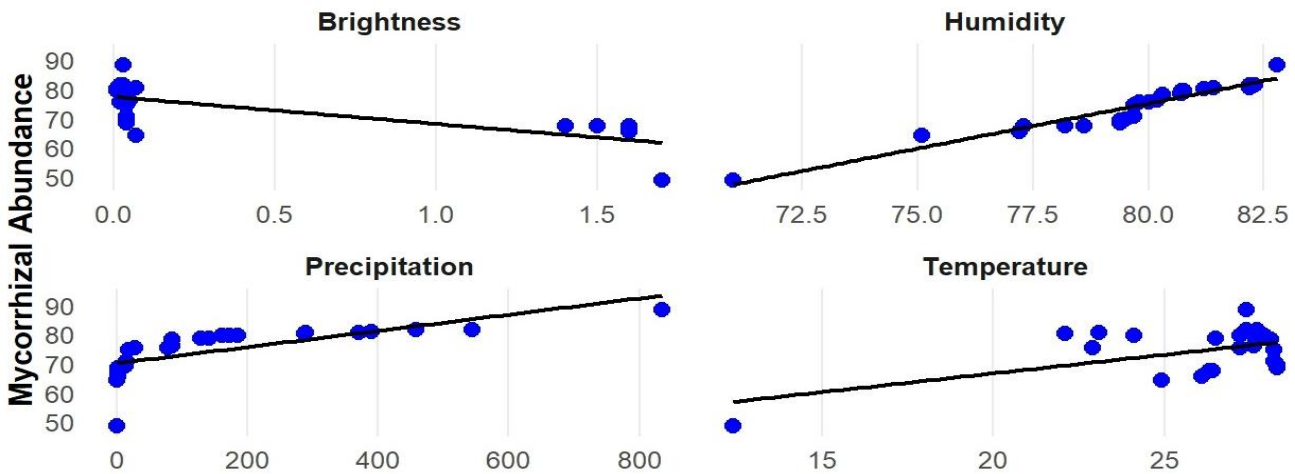


Fig. 3. The relationship between mycorrhizal abundance and different climatic variables, such as brightness or shade scale, humidity, precipitation, and Temperature.

Discussion

The current project on mycorrhizal fungal diversity in the Muree Forest Division provides important insights into the ecological roles of these fungi and their associations with plants. One of the key results was the documentation of 28 species across 12 families, indicating considerable diversity within the mycorrhizal community. The dominance of Russulaceae (eight species) and Helvellaceae (four species) suggests a specific ecological composition, which is well supported by results from studies across biogeographic regions. The documented morphological diversity and interspecific variations among fungi further demonstrate ecological niche differentiation within the Murree Forest Division. Such diversity is ecologically important because different mycorrhizal taxa contribute to forest productivity through complex associations that facilitate plant nutrient acquisition. For example, Liang *et al*., (2022) demonstrated the same dynamics in *Bulbophyllum tianguii*, where mycorrhizal fungal architecture is highly diverse among roots, rhizomes, and soil, with the rhizosphere soil being the most diverse. These findings highlight the ecological dependence of plants on mycorrhizal fungi and support the importance of soil conditions in shaping fungal diversity, as explored in the current study.

Our findings are consistent with those of previous studies showing a close correlation between soil nutrient availability and mycorrhizal fungal diversity. For instance, Averill *et al*., (2022) reported the existence of positive feedback mechanisms in forest mycobiomes, concluding that nutrient cycling and forest ecosystem stability are strongly influenced by diverse mycorrhizal communities (Averill *et al*., 2022). In the present study, the high R-squared values (0.9678) for the soil model and the significant positive relationship between phosphorus and mycorrhizal abundance further support the view that specific soil properties play an important role in shaping fungal communities. Similarly, Ma *et al*., (2021) reported that nutrient enrichment can strongly influence arbuscular mycorrhizal fungal diversity. Moreover, the identification of phosphorus and humidity as key environmental predictors in the present study agrees with the findings of Jacquemyn *et al*., (2012). Their research showed that mycorrhizal associations play an important role in seedling recruitment and population dynamics, thereby contributing to the maintenance of plant community health (Jacquemyn *et al*., 2012).

This study emphasizes the importance of maintaining populations of mycorrhizal fungi to support biodiversity and ecosystem processes. Although Muree Forest research identifies phosphorus as a key variable, it must acknowledge that other variables, such as nitrogen and electrical conductivity, are not significant. This is consistent with the results reported in research such as Kivlin's, where bidirectional interactions between fungi and environmental variables need to be considered carefully (Kivlin, 2020). In addition, the absence of statistically significant correlations for certain soil parameters may indicate interactions not captured in the analysis or other factors, such as soil type or microbial interactions not recorded here. The ecological implications of such research highlight that the mycorrhizal method may vary across ecosystems and plant species, with conservation and restoration implications for diverse mycorrhizal groups. Management interventions, such as those reported by Pánková *et al*., (2014), emphasize how habitat types and in situ ecological conditions can affect mycorrhizal colonization and the resulting plant fitness (Pánková *et al*., 2014), again emphasizing the value of site-specific research in multicomponent systems. The Muree Forest research affirms the literature and underscores the vital role of mycorrhizal fungi in forests and their direct impact on forest productivity and resistance. As research has also been favorable, studies such as those by Kartzinel *et al*., (2013) and Zhou *et al*., (2022) have shown that the associations between mycorrhizal fungal abundance and soil conditions warrant further inquiry to elucidate the complex forces that structure these integral ecological interactions.

Conclusion

This study highlights the ecological significance of mycorrhizal fungi in the Muree Forest Division, where 28 species belonging to 12 families were recorded. The dominance of Russulaceae and Helvellaceae, together with substantial morphological diversity, reflects ecological niche differentiation and a well-developed symbiotic network that contributes to forest productivity and stability. Multiple

regression analysis identified phosphorus and humidity as major predictors of mycorrhizal abundance, with phosphorus exhibiting the strongest positive association. Although other parameters, such as nitrogen, organic matter, electrical conductivity, and temperature, showed visual trends, these were not statistically significant and could have been influenced by predictor interdependence or limited sample size. These findings confirm the role of specific soil nutrients and environmental factors in shaping mycorrhizal communities and underscore the importance of conserving forest ecosystems that support these symbiotic relationships. Future studies should include multicollinearity diagnostics, such as the variance inflation factor (VIF), to better assess the independence of predictors. In addition, future VIF research should incorporate higher spatial and temporal resolutions, soil microbial interactions, and comparisons across multiple forest types to understand the drivers of mycorrhizal function and diversity under changing environmental conditions.

Conflict of Interest: All the authors declare no competing interests.

Author's Contribution: SAZ: Field Work, First Draft writing; **AA**: Help in Field Work Writing and Data Analysis. **ZA**: Help in Field Work Writing and Data Analysis; **MS:** Fungi Identification; **MF:** Fungi Identification and Lab Facilities provision; **SMK:** Supervision, Manuscript and Idea Finalization

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