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Vegetation structure, microclimate, and edaphic variables as determinants of macrofungi occurrence in the Maros-Pangkep Karst Area, Indonesia

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Abstract. *Salman AH, Restu M, Larekeng SH, Pryudyaningsih R. 2026. Vegetation structure, microclimate, and edaphic variables as determinants of macrofungi occurrence in the Maros-Pangkep Karst Area, Indonesia. Biodiversitas 27 (3): d270303. https://doi.org/10.13057/biodiv/d270303.* The Maros-Pangkep karst region in South Sulawesi, Indonesia, is known as the second largest karst in the world with a unique tower karst landscape and high biodiversity, including macrofungi. This study aimed to analyze the relationship between the presence of macrofungi and edaphic, microclimate, and vegetation factors to deepen the understanding of fungal ecology. Field surveys were conducted across 15 sampling plots representing different vegetation conditions. Macrofungi composition was recorded alongside measurements of microclimate variables (air temperature, humidity, light intensity) and edaphic properties (soil moisture, pH, organic carbon, total nitrogen, and available phosphorus). A total of 52 macrofungi species, belonging to 35 genera and 24 families, were documented, with Polyporaceae as the most dominant family. Species richness and diversity indices varied among plots, reflecting differences in vegetation complexity and environmental conditions. Principal Component Analysis (PCA) indicated that air humidity and soil moisture were the strongest variables associated with macrofungi occurrence, while higher temperature and light intensity showed negative associations. Edaphic factors, particularly soil moisture and organic carbon, contributed more strongly to macrofungi abundance than soil nutrient concentrations. Vegetation structure, especially sapling density and herbaceous cover, was associated with macrofungi abundance, whereas tree density was more closely related to species richness. These results demonstrate that macrofungi occurrence in karst ecosystems is shaped by the interaction of microclimatic conditions, soil properties, and vegetation structure rather than by single environmental drivers. The study highlights the importance of maintaining humid microhabitats and heterogeneous vegetation to support macrofungi diversity in karst landscapes. These findings provide a deeper understanding of macrofungi ecology and serve as an important basis for identifying macrofungi species with potential for utilization in various fields.

Keywords: Edaphic, karst, macrofungi, microclimate, vegetation

INTRODUCTION

Indonesia possesses the second-largest biodiversity globally, following Brazil (Von Rintelen et al. 2017). The Maros-Pangkep karst area in South Sulawesi is among the largest and most ecologically diverse karst regions in Indonesia. Maros Pangkep karst area possesses a distinctiveness absent in other karst regions of Indonesia, characterized by a landscape referred to as karst tower (tower karst) (Ahmad and Hamzah 2016). Karst ecosystems generally feature limestone formations, high porosity, and complex underground drainage systems, creating unique environmental conditions and playing an important ecological role in shaping biological communities (Aprilia et al. 2021). These ecosystems are often fragile and highly sensitive to environmental changes, making them important areas for biodiversity conservation (Clements et al. 2006). This area's great biodiversity provides a habitat for several species of flora and wildlife, including macrofungi.

Macrofungi constitute a vital element of biodiversity and serve as natural decomposers within ecosystems (Chen et al. 2018), facilitating the cycling of materials and energy by breaking down dead wood into lignin, cellulose, and hemicellulose, which are ultimately transformed into glucose, fructose, and other compounds (Petre et al. 2017). Moreover, the comprehensive influence of macrofungi within an ecosystem can enhance the interaction between plants and soil, augment soil organisms, refine soil structure, optimize plant organ functionality, and combat root infections in plants (Zhu et al. 2003). However, research on macrofungi diversity in the Maros Pangkep karst region is still relatively limited, especially in relation to environmental parameters associated with their occurrence.

Diverse species within forest ecosystems possess varying habitat suitability requirements, and these environmental traits will delineate the community of a specific species (Lai et al. 2009). A defining characteristic is microclimate, an environmental condition that significantly influences the distribution and abundance of macrofungi. Variations in temperature, air humidity, and light intensity within each microhabitat can influence the life cycle of fungi, particularly the development of fruiting bodies characteristic of macrofungi (Hu 2022). Besides microclimate, edaphic variables also influence macrofungi diversity (Tuo et al. 2022). Alem et al. (2021) similarly articulated that edaphic and spatial characteristics influence the macrofungi community. Soils in karst regions exhibit unique properties, including elevated lime concentration, significant porosity, and fluctuating fertility levels. These traits may serve as either constraints or facilitators for fungal growth, underscoring the necessity to ascertain the impact of edaphic variables on fungal diversity in these regions. Kujawska et al. (2021) emphasize that soil pH affects the abundance and distribution of macrofungi because many species have specific pH tolerances. Other edaphic factors, such as soil temperature and altitude (Luo et al. 2016), also determine the suitability of microhabitats for fungal growth. In addition, organic matter content—including leaf litter, decaying wood, and other organic debris—is an important nutrient source for saprophytic fungi and has been shown to influence species diversity (Zhang et al. 2023).

Vegetation in karst regions significantly contributes to the sustenance of fungal diversity. Vegetation supplies organic materials through leaf litter and degraded wood, serving as the primary substrate for fungi. Tuo et al. (2022) identified several vegetation types that exhibit a favorable link with the abundance of Ectomycorrhizal fungi. Studies indicate that vegetation pattern and tree species diversity significantly affect the occurrence of functional categories of macrofungi (Gómez-Hernández et al. 2012). Furthermore, plant size, tree density, herbaceous richness, and evenness may also affect macrofungal composition (Wang et al. 2020).

This study examines how vegetation structure, microclimate, and edaphic factors jointly influence macrofungi occurrence in a tropical karst ecosystem. Specifically, it asks which environmental variables are most strongly associated with macrofungi species richness and abundance across different vegetation conditions in the Maros-Pangkep Karst. We hypothesize that macrofungi occurrence is positively associated with higher air humidity, soil moisture, and structurally complex vegetation, and negatively associated with increased light intensity and air temperature.

MATERIALS AND METHODS

Site location

This research was conducted during July 2024 - July 2025. This research began with macrofungi sampling in the karst area of Balocci District, Pangkajene, South Sulawesi, Indonesia (Figure 1). This karst area is formed from the Tonasa formation with the uniqueness of having a unique and distinctive landscape commonly called tower karst. In the area, towering limestone hills with challenging cliffs. The towers are 50-200 m high, have steep slopes, and are flat at the top. Between the hills are narrow, flat-bottomed, and elongated valleys (Utama et al. 2016). Analysis of fungal samples was carried out at the Laboratory of Biotechnology and Tree Breeding and Integrated Laboratory, Faculty of Forestry, Universitas Hasanuddin, Karst Microbial Microbiology Laboratory, and edaphic analysis was carried out in the Silviculture and Tree Physiology laboratory, Faculty of Forestry, Universitas Hasanuddin. Macrofungi sampling was conducted during two seasonal periods, namely the dry season (2024) and the rainy season (2025), to assess temporal variation in macrofungi occurrence.

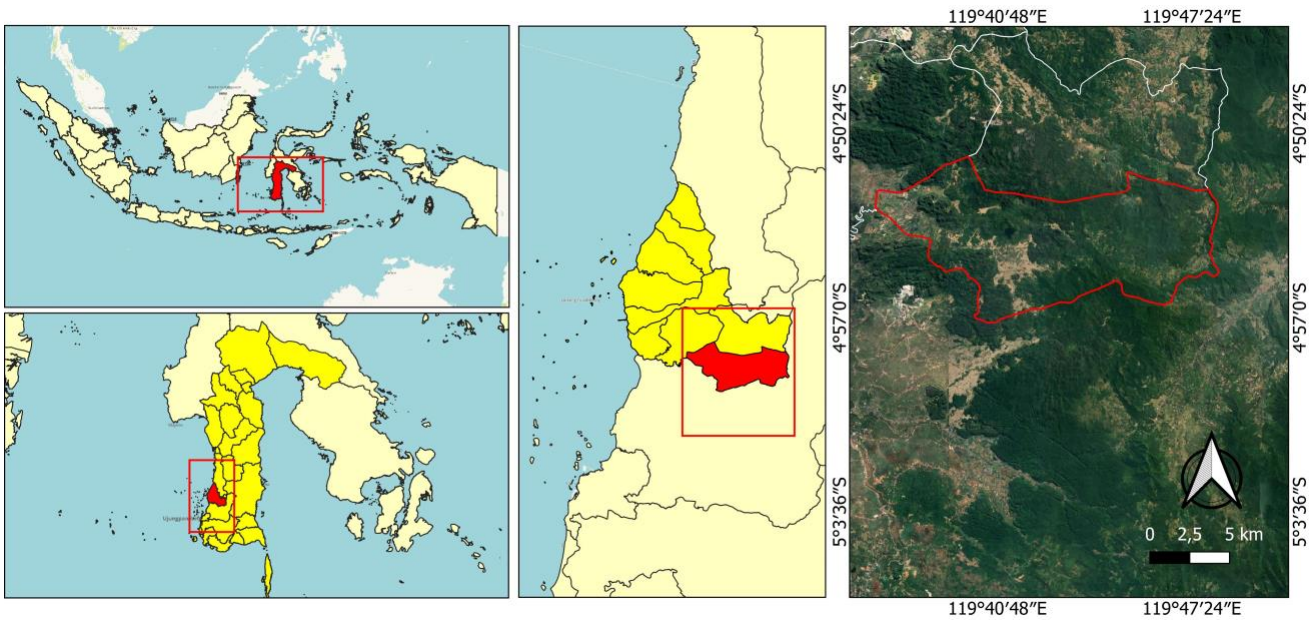

Figure 1. Macrofungi sampling locations at Maros Pangkep karst area, Balocci District, Pangkajene, South Sulawesi, Indonesia

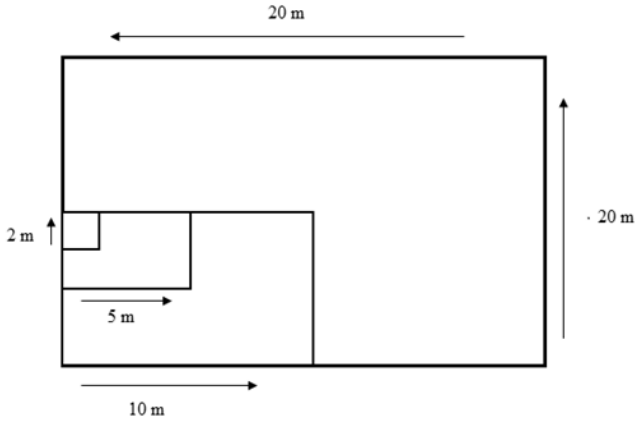

Figure 2. Plot design for macrofungi

Macrofungi sampling

The method used was purposive sampling by exploring the karst area based on a transect line that runs along the sampling location. Then observation plots measuring 20 × 20 m were placed with a distance between plots along the transect line of 100 m, as can be seen in Figure 2 (Djuku et al. 2022). A total of 15 plots (each measuring 20 × 20 m) were systematically established. All measurements of macrofungi, vegetation, edaphic factors, and microclimate were recorded consistently using the same sampling protocol in each plot to ensure replication and comparison between locations.

Identification macrofungi

The macroscopic description of the fungi was used as a reference for identification. Taxonomic identity was observed at the genus and species level. Identification of macroscopic mushroom species found using several guidebooks and monographs from several references and other methods, including Guide to Mushrooms by Pacioni et al. (1995), How to Identify Mushrooms to Genus I, II and III: Macroscopic Features by Largent (1973), the book Edible and Poisonous Mushrooms of the World by Hall et al. (2003), other literature such as apps, websites, and official journals: fungi bolets, mycoweb and related theses or journals. Selected macrofungi specimens, especially those with ambiguous or incomplete macroscopic characteristics, are analyzed molecularly to ensure accurate species identification and complement morphological examination. After identification, the samples were dried and stored as dry specimens. All specimens were stored at the Biotechnology and Tree Breeding Laboratory, Faculty of Forestry, Universitas Hasanuddin, Indonesia.

Vegetation sampling

To identify the relationship between vegetation type and the quantity of individuals and species of macrofungi, a vegetation inventory was conducted on the plots that had been designated for mushroom fruiting body sampling. Large trees outside the plots whose crowns overhung the plots were included in the observations because they were thought also to influence the presence of fungi (Collins et al. 2018). Identification of plant species found was carried out with the help of tree identifiers and compared with some literature. The creation of vegetation observation plots was carried out every time macrofungi were found. In this method, a path is made with observation plots consisting of 1 × 1 m plots used to analyze herbaceous level vegetation. For 5 × 5 m plots used to analyze sapling-level vegetation, 10 × 10 m plots for pole-level vegetation analysis, and 20 × 20 m plots used for tree-level vegetation analysis are depicted in Figure 2.

Edaphic sampling

Environmental data measurements were also conducted at the same location as the macrofungi and vegetation sampling (Figure 2), to observe the association between macrofungi composition and edaphic variables. Measurements of edaphic factors and soil sampling were carried out on each plot. The edaphic factors measured were soil moisture, soil temperature, and soil pH using measuring devices for each measurement variable (Nasution et al. 2018). Meanwhile, the collection of soil samples was carried out destructively and non-destructively. Destructive soil sampling was done by taking it at 4 points at each corner of the plot and 1 point in the middle of the plot. Non-destructive soil sampling was done using a sampling ring. Soil sampling was then observed by analyzing pH (H2O), N-organic content, C/N, availability of P (P_2O_5), magnesium (Mg), Potassium (K), and Cation Exchange Capacity (CEC), Ca, and CaCO3.

Microclimate data

Microclimate variables were measured to observe the association between microclimate and the quantity of individuals and species of macrofungi, with microclimate factors measured in each observation plot (Figure 2), including air humidity and air temperature using a thermohygrometer, and sunlight intensity using a lux meter.

Data analysis

The macrofungi data obtained from this study were then analyzed using the Shannon and Wiener (1994) diversity index (H'), Margalef (1958); Gamito (2010) richness index (Dmg), Pielou (1966) evenness index; Odum (1993) (E), and the dominance index by Ludwig and Reynold (1998); Ludwig and Reynold (1988); Supriadi et al. (2015) (D).

Vegetation, microclimate, and edaphic data obtained from all observation plots were first averaged based on the number of observation plots. Principal Component Analysis (PCA) was then performed using the correlation matrix in Minitab 22 to identify the main patterns as an analysis of the association between vegetation structure, microclimate conditions, and edaphic characteristics with the presence of macrofungi individuals and macrofungi species.

Ethical considerations and research permits

All field surveys were conducted with permission from local authorities and land managers in the Maros-Pangkep Karst area. Sampling of macrofungi and associated environmental variables was carried out in accordance with local regulations, and no protected species were collected.

The study did not involve human subjects or vertebrate animals and therefore did not require formal ethical clearance.

RESULTS AND DISCUSSION

Composition of macrofungi

Research conducted in the Maros-Pangkep Karst region found 52 species of macroscopic fungi. The Polyporaceae family dominated with more than 120 individuals of macrofungi and a highly variable number of macrofungi species compared to other families, as shown in Figure 3; multiple recorded species belong to the family Polyporaceae. The Auriculariaceae and Schizophyllaceae families followed each with fewer than 60 individuals, suggesting that both families are relatively common in the study area, although less abundant than Polyporaceae (Figure 4).

The macrofungi diversity index for 15 plots in the Maros-Pangkep Karst area showed the highest value in plot 1 (1.81) with a moderate category and the lowest value in plot 13 (0.34) with a low category. The macrofungi richness index showed plot 1 with the highest value (8.73) in the high category and plot 7 with the lowest value (2.28) in the moderate category. The highest macrofungi evenness index value (0.75) was found in plot 7 in the high category, the lowest value in plot 13 (0.11) in the low category, and the highest dominance value (0.84) was found in plot 13 in the high category, while the lowest dominance value was in plot 1 (0.23) in the low category (Table 1).

List of macrofungi species and substrates

Table 2 shows a list of macrofungi species found in the Maros Pangkep karst area, consisting of 52 macrofungi species comprising 49 species from the Basidiomycota phylum and 3 species from the Ascomycota phylum, along with 24 families and 35 genera, and the substrates on which they grow. Most macrofungi were found growing on dead wood substrates. Several species were also found growing on soil, such as *Mycena* sp. and *Podoscypha petalodes*, but their numbers were smaller than those found on dead wood. From the results obtained, 90% of macrofungi were found growing on dead wood substrates, while only 10% were found on soil (Figure 5).

Table 1. Macrofungi diversity index, richness index, evenness index, and dominance index

Plot	H'	Dmg	E	D
1	1.81	8.73	0.49	0.23
2	1.06	4.70	0.32	0.45
3	1.57	6.71	0.45	0.26
4	1.43	4.63	0.53	0.26
5	1.18	3.70	0.36	0.36
6	1.13	3.68	0.36	0.37
7	1.04	2.28	0.75	0.38
8	1.50	4.70	0.45	0.25
9	0.68	2.54	0.31	0.63
10	1.42	4.67	0.47	0.28
11	1.26	4.65	0.45	0.36
12	0.80	3.67	0.26	0.60
13	0.34	2.69	0.11	0.84
14	0.94	2.65	0.32	0.43
15	1.48	5.67	0.50	0.27

Note: H': diversity index, Dmg: richness index, E: evenness index, and D: dominance index

Figure 3. Macrofungi belonging to the Polyporaceae family are frequently found in the Maros-Pangkep karst region: A. *Hexagonia tenuis*, B. *Polyporus grammocephalus*, C. *Favolus* sp., D. *Panus* sp., E. *Microporus xanthopus*, F. *Earliella scabrosa*

Relationships between macrofungi and microclimate factors

The average air temperature in the Maros-Pangkep karst area is 28.43°C, with an air humidity of 83.88% and an average light intensity of 626.87 lux (Table 3). Air humidity shows positive association with the quantity of macrofungi individuals and species (Figure 6; Table 4), while light intensity and air temperature show a negative association with both variables (Figure 7; Table 5).

Table 2. Macrofungi discovered in Maros Pangkep karst area

Phyllum	Family	Species	Substrates
Basidiomycota	Auriculariaceae	*Auricularia auricula-judae* (Bull.) Quél.	Dead wood
Basidiomycota	Auriculariaceae	*Auricularia cornea* Ehrenb.	Dead wood
Basidiomycota	Auriculariaceae	*Auricularia delicata* (Mont. ex Fr.) Henn.	Dead wood
Basidiomycota	Auriculariaceae	*Auricularia mesenterica* (Dicks.) Pers.	Dead wood
Basidiomycota	Auriculariaceae	*Auricularia polytricha* (Mont.) Sacc.	Dead wood
Basidiomycota	Dacrymycetaceae	*Calocera cornea* (Batsch) Fr.	Dead wood
Basidiomycota	Xylariaceae	*Xylaria furcata* Fr.	Soil
Ascomycota	Sarcoscyphaceae	*Cookeina tricholoma* (Mont.) Kuntze	Dead wood
Basidiomycota	Psathyrellaceae	*Coprinopsis atramentaria* (Bull.) Redhead, Vilgalys & Moncalvo	Dead wood
Basidiomycota	Crepidotaceae	*Crepidotus epibryus* (Fr.) Quél.	Dead wood
Basidiomycota	Crepidotaceae	*Crepidotus mollis* (Schaeff.) Staude	Dead wood
Basidiomycota	Marasmiaceae	*Crinipellis scabella* (Alb. & Schwein.) Murrill	Dead wood
Ascomycota	Xylariaceae	*Daldinia concentrica* (Bolton) Ces. & De Not.	Dead wood
Basidiomycota	Polyporaceae	*Earliella scabrosa* (Pers.) Gilb. & Ryvarden	Dead wood
Basidiomycota	Pleurotaceae	*Pleurotus djamor* (Rumph. ex Fr.) Boedijn	Dead wood
Basidiomycota	Polyporaceae	*Favolus emerici* (Berk. ex Cooke) Imazeki	Dead wood
Basidiomycota	Polyporaceae	*Favolus pseudoemerici* Jun L.Zhou & B.K.Cui	Dead wood
Basidiomycota	Irpicaceae	*Flavodon flavus* (Klotzsch) Ryvarden	Dead wood
Basidiomycota	Ganodermataceae	*Ganoderma applanatum* (Pers.) Pat.	Dead wood
Basidiomycota	Pluteaceae	*Pluteus septocystidiatus* Ševčíková, Antonín & Borov.	Dead wood
Basidiomycota	Polyporaceae	*Hexagonia tenuis* (Fr.) Fr.	Dead wood
Ascomycota	Hypoxylaceae	*Hypoxylon haematostroma* Mont.	Dead wood
Basidiomycota	Inocybaceae	*Inocybe lacera* (Fr.) P.Kumm.	Soil
Basidiomycota	Polyporaceae	*Lentinus squarrosulus* Mont.	Dead wood
Basidiomycota	Gymnopilaceae	*Gymnopilus purpuratus* (Cooke & Massee) Singer	Dead wood
Basidiomycota	Marasmiaceae	*Marasmiellus candidus* (Fr.) Singer	Dead wood
Basidiomycota	Polyporaceae	*Microporus xanthopus* (Fr.) Kuntze	Dead wood
Basidiomycota	Mycenaceae	*Mycena crocea* Maas Geest.	Soil
Basidiomycota	Polyporaceae	*Neofavolus alveolaris* (DC.) Sotome & T.Hatt.	Dead wood
Basidiomycota	Polyporaceae	*Panus* sp.	Dead wood
Basidiomycota	Marasmiaceae	*Parasola* sp.	Dead wood
Basidiomycota	Hymenochaetaceae	*Phellinus tremulae* (Bondartsev) Bondartsev & P.N.Borisov	Dead wood
Basidiomycota	Phanerochaetaceae	*Phlebiopsis crassa* (Lév.) Floudas & Hibbett	Dead wood
Basidiomycota	Pleurotaceae	*Pleurotus ostreatus* (Jacq.) P.Kumm.	Dead wood
Basidiomycota	Podoscyphaceae	*Podoscypha petalodes* (Berk.) Boidin	Dead wood
Basidiomycota	Podoscyphaceae	*Podoscypha venustula* (Speg.) D.A.Reid	Dead wood
Basidiomycota	Polyporaceae	*Polyporus arcularius* (Batsch) Fr.	Dead wood
Basidiomycota	Polyporaceae	*Polyporus grammocephalus* Berk.	Dead wood
Basidiomycota	Meripilaceae	*Rigidoporus lineatus* (Pers.) Ryvarden	Dead wood
Basidiomycota	Schizophyllaceae	*Schizophyllum commune* Fr.	Dead wood
Basidiomycota	Lachnocladiaceae	*Scytinostromella heterogenea* (Bourdot & Galzin) Parmasto	Dead wood
Basidiomycota	Stereopsidaceae	*Stereopsis hiscens* (Berk. & Ravenel) D.A.Reid	Soil
Basidiomycota	Marasmiaceae	*Tetrapyrgos subdendrophora* (Redhead) E.Horak	Dead wood
Basidiomycota	Thelephoraceae	*Thelephora ganbajun* M.Zang	Soil
Basidiomycota	Thelephoraceae	*Thelephora terrestris* Ehrh. ex Fr.	Dead wood
Basidiomycota	Polyporaceae	*Trametes elegans* (Spreng.) Fr.	Dead wood
Basidiomycota	Polyporaceae	*Trametes gibbosa* (Pers.) Fr.	Dead wood
Basidiomycota	Polyporaceae	*Trametes ochracea* (Pers.) Gilb. & Ryvarden	Dead wood
Basidiomycota	Polyporaceae	*Trametes vespacea* (Pers.) Zmitr., Wasser & Ezhov	Dead wood
Basidiomycota	Xylariaceae	*Xylaria hypoxylon* (L.) Grev.	Dead wood
Basidiomycota	Xylariaceae	*Xylaria longiana* Rehm	Dead wood
Basidiomycota	Xylariaceae	*Xylaria polymorpha* (Pers.) Grev.	Dead wood

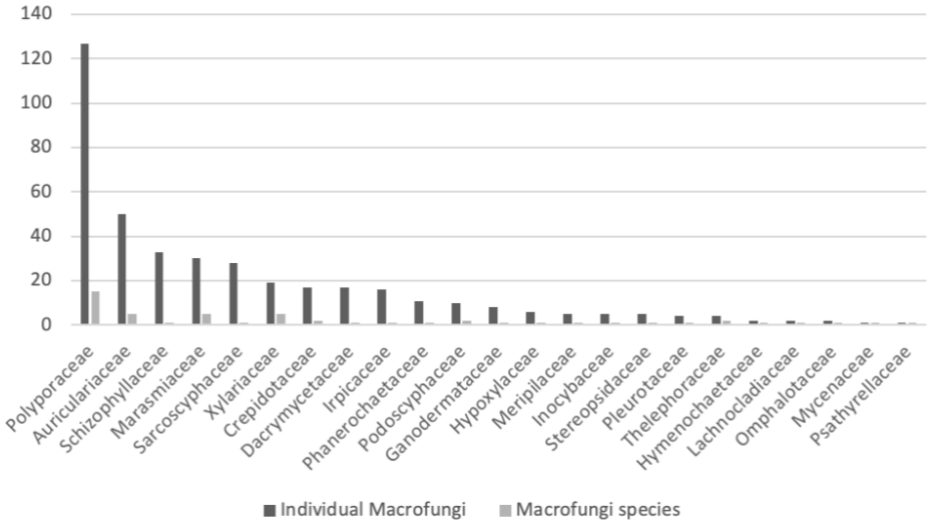

Figure 4. Composition of macrofungi families in the Maros Pangkep karst area

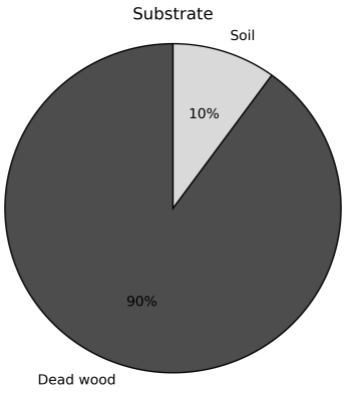

Figure 5. Substrates of macrofungi discovered in the Maros Pangkep karst area

Table 3. Average climate in the Maros Pangkep karst area

Parameter	Average
Air temperature (°C)	28.43
Air humidity (%)	83.88
Light (lux)	626.87

Table 4. Eigenvector PCA values of microclimate factors on the quantity of individual macrofungi

Variable	PC1	PC2
Quantity of individual macrofungi	0.24	-0.71
Air temperature	-0.65	-0.07
Air humidity (%)	0.24	0.70
Light (lux)	-0.68	0.06

Relationships between macrofungi and edaphic factors

The average values of these edaphic parameters provide an overview of soil conditions in Maros Pangkep karst area (Table 6). The PCA results linking edaphic parameters with the quantity of individual macrofungi show that soil moisture has the strongest positive association, as indicated by the highest eigenvector value, while pH is negatively associated with the highest eigenvector value (Figure 8; Table 7). The same pattern was also found in the quantity of macrofungi species, which was associated with soil moisture as the strongest positive association, while the CEC and pH variables were negatively associated with the highest eigenvector value (Figure 9; Table 8).

Relationships between macrofungi and vegetation factors

Vegetation growth rates in karst areas show variation between vegetation types. In this area, the number of stems per hectare for the Herbs vegetation type reaches a very high number, which is around 24,500 stems/Ha. This is much higher than other vegetation types, such as Trees, which only recorded 226 stems/Ha, Poles, 340 stems/Ha, and Saplings, 560 per hectare (Figure 10). The PCA analysis results show that woody vegetation at the sapling level has the strongest positive association with the quantity of individual macrofungi, as indicated by the highest eigenvector value, while herbaceous vegetation shows the strongest negative association (Figure 11; Table 9). Conversely, herbaceous vegetation contributed most strongly to the quantity of Macrofungi Species, while sapling vegetation contributed most negatively (Figure 12; Table 10).

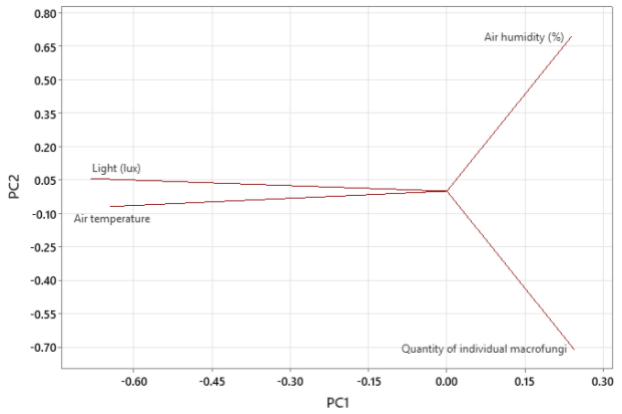

Figure 6. PCA of microclimate variables on the quantity of individual macrofungi

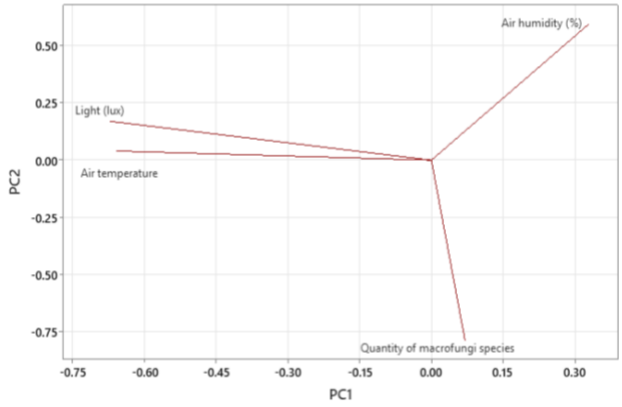

Figure 7. PCA of microclimate variables on the quantity of macrofungi species

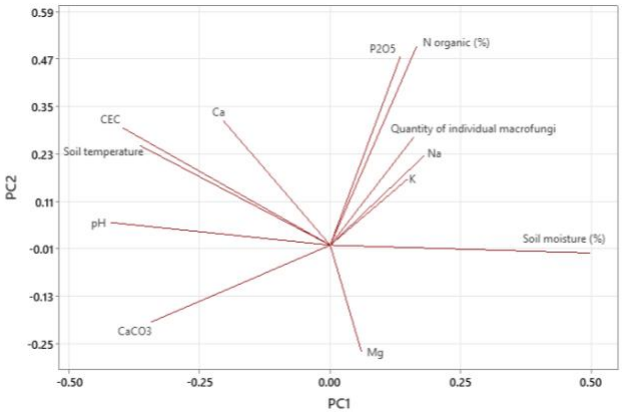

Figure 8. PCA of edaphic factors on the quantity of individual macrofungi

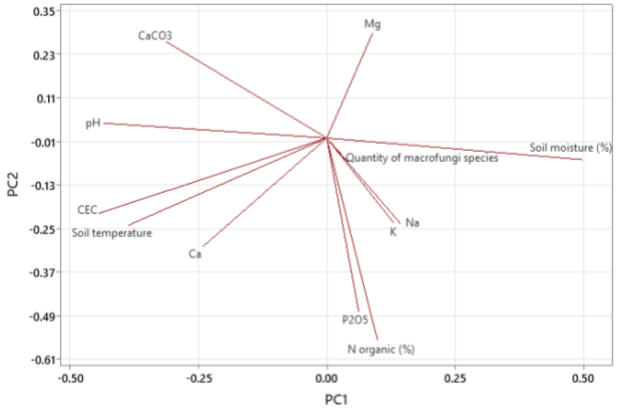

Figure 9. PCA of edaphic factors on the quantity of macrofungi species

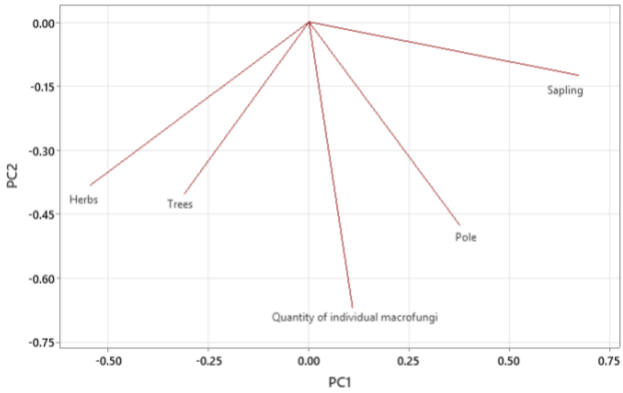

Figure 11. PCA of vegetation factors on the quantity of individual macrofungi

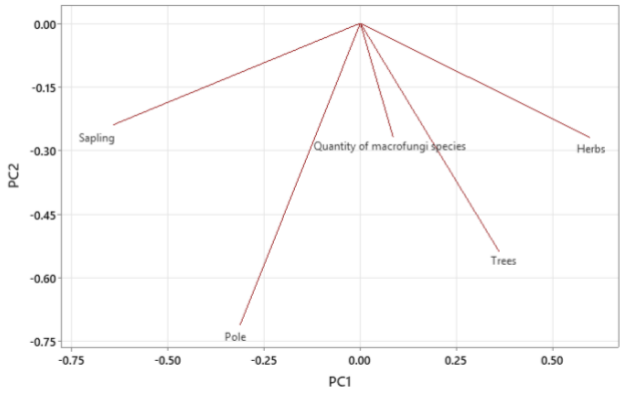

Figure 12. PCA of vegetation factors on the quantity of macrofungi species. *The contrasting loading patterns between Figures 11 and 12 suggest scale-dependent vegetation effects on macrofungi communities

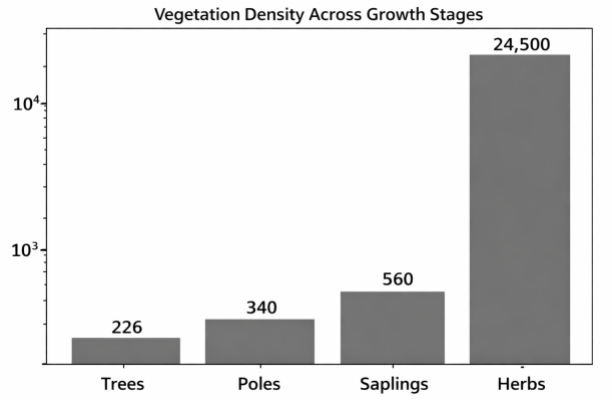

Figure 10. Graph of the quantity of vegetation types

Table 5. Eigenvector PCA values of microclimate factors on the quantity of macrofungi species

Variable	PC1	PC2
Quantity of macrofungi species	0.07	-0.79
Air temperature	-0.66	0.04
Air humidity (%)	0.33	0.59
Light (lux)	-0.67	0.17

Table 6. Average measurements of edaphic variables in Maros-Pangkep karst area

Parameter	Average
pH	7.10
N organic (%)	0.19
P_2O_5	14.02
Ca	9.96
Mg	1.14
K	0.33
Na	0.46
CEC	22.82
$CaCO_3$	6.86
Soil temperature	27.53
Soil moisture (%)	22.20

Table 7. Eigenvector PCA values of edaphic variables on the quantity of individual macrofungi

Variable	PC1	PC2
Quantity of individual macrofungi	0.16	0.27
pH	-0.42	0.06
N organic (%)	0.17	0.50
P_2O_5	0.14	0.48
Ca	-0.20	0.31
Mg	0.06	-0.27
K	0.15	0.17
Na	0.18	0.23
CEC	-0.40	0.30
$CaCO_3$	-0.34	-0.20
Soil temperature	-0.36	0.25
Soil moisture (%)	0.50	-0.02

Table 8. Eigenvector PCA values of edaphic variables on the quantity of macrofungi species

Variable	PC1	PC2
Quantity of macrofungi species	0.04	-0.06
pH	-0.44	0.04
N organic (%)	0.10	-0.56
P_2O_5	0.06	-0.48
Ca	-0.24	-0.30
Mg	0.09	0.29
K	0.13	-0.23
Na	0.14	-0.24
CEC	-0.44	-0.21
$CaCO_3$	-0.31	0.27
Soil temperature	-0.39	-0.24
Soil moisture (%)	0.50	-0.06

Discussion

The influence of microclimate factors on macrofungi occurrence

High humidity allows fungal spores to germinate and develop into fruiting bodies (Tjiu et al. 2022). This is consistent with sunlight that is not too intense. This moderate light intensity can be a favorable factor for the growth of macrofungi, considering that many fungi grow well in places that are not exposed to direct sunlight, such as under the shade of trees or in dark karst caves. High light intensity inhibits fungal growth, while low light intensity promotes fungal growth (Noverita et al. 2019; Yeni et al. 2025).

The PCA graph illustrates the relationship between microclimate variables (air humidity, air temperature, and light intensity) and the quantity of macrofungi individuals (Figure 6). Air humidity (%) is a climate variable that is positively associated with the quantity of macrofungi individuals, indicating that an increase in air humidity is associated with an increase in the quantity of macrofungi individuals, while high air temperature and light intensity (lux) are negatively associated. The placement of the light intensity vector parallel to air temperature indicates that this variable is negatively associated with the quantity of macrofungi individuals. Low light intensity (<1000 lux) facilitates the formation of macrofungi fruiting bodies, while high light levels can reduce the emergence of some macrofungi, as shown by Straatsma et al. (2001).

The quantity of macrofungi species in the Maros Pangkep karst area, as well as the quantity of associated macrofungi individuals, correlates positively with air humidity (Figure 7), as indicated by the large air humidity vector length and positive relationship with the quantity of macrofungi species on PC1. Air temperature and light (lux) show a negative association with macrofungi species, indicating that all three have comparable strengths. Kutszegi (2020) explains that air humidity is associated with macrofungi species diversity, thereby increasing the presence and abundance of saprophytic fungi in forest ecosystems. Baldrian (2017) confirms that increased humidity and decreased light levels generally increase macrofungi diversity, especially among saprophytic taxa such as Polyporaceae.

Table 9. Eigenvector PCA values of vegetation factors on the quantity of individual macrofungi

Variable	PC1	PC2
Quantity of individual macrofungi	0.11	-0.67
Trees	-0.31	-0.40
Pole	0.38	-0.48
Sapling	0.67	-0.13
Herbs	-0.55	-0.38

Table 10. Eigenvector PCA values of vegetation factors on the quantity of macrofungi species

Variable	PC1	PC2
Quantity of macrofungi species	0.09	-0.27
Trees	0.36	-0.54
Pole	-0.31	-0.71
Sapling	-0.64	-0.24
Herbs	0.60	-0.27

The influence of edaphic factors on macrofungi occurrence

The measured soil pH ranged from 6.47 to 7.40, indicating neutral conditions (Chang and Goldsby 2016). Neutral pH creates optimal conditions for macrofungal growth. Fungi generally show higher tolerance to neutral to slightly acidic pH, which facilitates enzymatic processes important for mycelium development (Chang and Miles 2004). In addition, high calcium levels can neutralize soil pH, creating an environment conducive to fungal proliferation and promoting strong mycelium development (Smith and Read 2008), while low sodium concentrations indicate that the soil does not contain salt. The CEC value obtained is quite high, indicating the soil's ability to store and supply nutrients effectively, thus creating stable conditions for microorganisms, including macroscopic fungi (Brady and Weil 2002). Organic nitrogen, with a low average concentration, is very important for macrofungi, especially saprotrophs, which depend on carbon-rich organic matter for their metabolism (Treseder 2008). Low nitrogen levels can be offset by high phosphorus and cation exchange capacity.

Based on PCA (Figure 8), it was found that several edaphic factors were related to the presence of macrofungi, represented by the quantity of individual macrofungi. Soil moisture had the highest eigenvector value, followed by organic N (%) and Na, indicating a stronger positive association with the presence of macrofungi in the Maros-Pangkep karst area. Soil moisture plays an important role in supporting the growth of macrofungi because it provides an ideal microenvironment for enzymatic activity and fungal metabolism. According to Liu et al. (2019), soil moisture is a key factor in supporting fungal mycelium development. The organic nitrogen content provides the necessary nutrients for macrofungi growth. Organic nitrogen, as part of the nitrogen cycle, is associated with the availability of organic substrates that can be used by fungi (Gulis et al. 2009). P_2O_5, and K also showed a positive association with the quantity of individual macrofungi, although with a lower contribution. Soils that are rich in organic matter, have sufficient moisture, and adequate phosphate content tend to increase the presence of macrofungi (Prasetyaningsih and Rahardjo 2015). Meanwhile, factors such as pH, $CaCO_3$, and Mg tend to have a negative contribution to the presence of macrofungi at this research site. High $CaCO_3$ content can increase soil pH, making it less ideal for some types of fungi. This is in accordance with research by Paul et al. (2007), who found that high alkalinity levels can inhibit the metabolic activities of fungi. Soil temperature and CEC also showed a negative association with the quantity of macrofungi individuals. It is important to note that the relationship between soil pH and macrofungi abundance is likely non-linear, rather than strictly positive or negative. Many macrofungi exhibit optimal growth ranges around slightly acidic to neutral pH, with reduced performance at both lower and higher pH extremes. Therefore, although neutral conditions are generally suitable, a shift towards higher alkalinity beyond the optimal threshold may explain the negative pH load observed in the PCA analysis. In summary, although neutral pH conditions are generally favorable, findings indicate that mild alkalinity outside the optimum range for fungi can act as a limiting factor, rather than soil acidity. The interaction between moisture availability and a narrow optimal pH window is likely associated with the distribution pattern of macrofungi in the Maros-Pangkep karst ecosystem.

PCA analysis was also conducted to examine the effect of edaphic factors on the quantity of macrofungal species in the Maros Pangkep karst area (Figure 9). The positive association between soil moisture and the quantity of macrofungi species indicates that water availability in the soil is the main limiting factor for fungal growth. In addition to moisture, organic Na and K also contributed positively to macrofungi species quantity, with K and Na values on PC1. These results are in line with previous studies showing that nutrients are an important factor in supporting macrofungi growth (Xiong et al. 2021). Conversely, soil pH has a negative effect on the quantity of macrofungi species. Other edaphic variables, such as Mg, organic nitrogen, and $P2O_5$, can also make a positive contribution, but their influence is smaller than that of soil moisture. Phosphorus content in the soil is important for the enzymatic activity of macrofungi and sporocarp development. Phosphorus supports energy metabolism through the production of ATP, which is important in the reproductive activities of macrofungi (Kamal 2012).

The influence of vegetation factors on macrofungi occurrence

Herbaceous plants produce organic matter that decomposes quickly, providing a substrate that favors the presence of saprophytic macrofungi. In contrast, trees, although slightly lower on average than herbs, contribute dead wood and litter as substrates for macrofungi (Khayati 2018). Saprotroph macrofungi, such as species that degrade organic litter, tend to dominate in habitats with high herbaceous vegetation, as Brundrett (2009) explains that

saprotroph fungi play an important role in recycling nutrients from rapidly decomposing organic matter, such as herbaceous litter. The Maros-Pangkep karst region is characterized by rocky soil with high $CaCO_3$ content, which tends to form soil with neutral to alkaline pH. These conditions influence the dynamics of vegetation growth phases, which in turn are associated with macrofungi diversity.

The results of PCA analysis show that vegetation structure plays an important role in observing the distribution patterns of macrofungi in the Maros-Pangkep karst region, an ecosystem characterized by shallow edaphic conditions, limited nutrient availability, and relatively extreme microclimate fluctuations. In the karst context, the relationship between vegetation and macrofungi is not only structural, but also reflects complex ecological mechanisms related to substrate provision, moisture retention, and the dynamics of organic matter decomposition. The positive association between sapling density and the quantity of individual macrofungi indicates that this phase of vegetation growth provides microhabitat conditions that support macrofungi growth with an eigenvector value of 0.67, while herbaceous vegetation is negatively associated with the quantity of individual macrofungi with an eigenvector value of -0.55 (Figure 11). Saplings contribute to the accumulation of leaf litter and small-diameter wood that decomposes relatively quickly, producing a stable supply of carbon for saprotrophic fungi. This pattern is consistent with the findings of Gulis et al. (2009), which confirm that the availability of small-diameter wood substrate increases fungal decomposition activity. Therefore, it can be assumed that sapling density increases the quantity of macrofungi individuals through a stable supply of easily decomposed substrate, but does not directly promote increased species quantity. In addition, the sparse canopy of saplings allows moderate light penetration, which helps maintain soil moisture without increasing extreme temperatures. In karst ecosystems with high rock porosity and low water storage capacity, the microclimate created by young trees is a key factor facilitating an increase in the quantity of individual macrofungi, although it does not always increase the quantity of species.

Herbaceous vegetation is positively associated with species richness, with an eigenvector value of 0.60, whereas saplings are negatively associated with species richness, with an eigenvector value of -0.64 (Figure 12). Zubek et al. (2024) revealed that herbaceous vegetation creates microhabitat heterogeneity and influences the composition and diversity of saprotrophic fungal communities. This pattern shows differences in ecological mechanisms between controlling individual numbers and regulating species richness. Herbaceous vegetation generally produces less biomass and is spatially unstable, thus not supporting intensive colonization by one or a few dominant fungal species. However, the diversity of herbaceous litter types, short life cycles, and chemical heterogeneity of organic matter (e.g., cellulose and easily degradable compounds) create various ecological niches that allow for the coexistence of more macrofungal species. Furthermore, Pecoraro et al. (2021) emphasize that herbaceous vegetation contributes to microclimate dynamics, such as fluctuations in soil temperature and moisture, which indirectly influence the emergence and composition of macrofungal sporocarps. These conditions support the coexistence of various functional groups of macrofungi and explain the positive association between herbaceous cover and macrofungi species quantity observed in their multivariate analysis.

The negative relationship between saplings and the quantity of macrofungi species reinforces the hypothesis that environments with a relatively homogeneous substrate supply tend to support the dominance of a few competitive species, thereby suppressing overall species richness. Under these conditions, fungi that are efficient in utilizing young wood substrate can develop massively, increasing the quantity of individuals but reducing the opportunities for other species to colonize. This phenomenon is in line with the concept of trade-off between dominance and diversity in fungal communities, especially in ecosystems with limited resources such as karst areas. The role of tree and pole vegetation on macrofungi appears to be more moderate and contextual. Although trees provide large amounts of biomass, the slow decomposition rate of hardwood and limited soil moisture in karst areas can limit fungal colonization, especially in the short term. Therefore, tree vegetation functions more as a provider of specific habitats for certain groups of fungi (e.g., lignolytic or mycorrhizal fungi) than as a major driver of the overall abundance or richness of macrofungi.

In conclusion, macrofungi occurrence in the Maros-Pangkep Karst is strongly structured by interactions among vegetation, microclimate, and edaphic conditions. Across 15 sampling plots, a total of 52 macrofungi species representing 35 genera and 24 families were recorded, with Polyporaceae emerging as the most dominant family. Diversity indices varied among plots, reflecting heterogeneity in vegetation structure and local environmental conditions. Multivariate analysis showed that air humidity and soil moisture were the strongest factors associated with macrofungi occurrence, while higher air temperature and light intensity were negatively associated. Edaphic variables, particularly soil moisture and organic carbon, exerted stronger associations with macrofungi abundance than soil nutrient concentrations. Vegetation structure also played a key role: sapling density and herbaceous cover were more closely linked to macrofungi abundance, whereas tree density was more strongly related to species richness. These findings indicate that macrofungi diversity in karst ecosystems is not governed by single environmental drivers but by the combined effects of humid microclimates, favorable soil conditions, and structurally diverse vegetation. Maintaining microhabitat heterogeneity, therefore, appears essential for sustaining macrofungi diversity in tropical karst landscapes. A limitation of this study was the restricted spatial scope due to the steep and rugged karst terrain, which made accessing certain areas challenging. Specialized tools and preparation were needed to reach various regions, potentially leading to incomplete coverage and the exclusion of areas with distinct macrofungi species. Expanding research across multiple karst systems would

enhance understanding of macrofungi ecology and support conservation of karst biodiversity.

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