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Research Article

Ecology and diversity of family Scytonemataceae in selected regions of the Western Ghat mountain range of Kerala, a biodiversity hotspot in India

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Abstract

The Scytonemataceae family is known for its taxonomic diversity and broad distribution. It is the only traditional cyanobacterial family exhibiting the false branching phenotype and includes ecologically significant species, making it particularly interesting for biotechnological applications. The present study was carried out on the diversity of the family Scytonemataceae in 52 sampling sites falling in Palakkad, Malappuram, Kozhikode, and Wayanad districts of the Western Ghat mountain chain region of Kerala, South India. Collection of cyanobacterial specimens and assessment of their microclimatic conditions were carried out on a seasonal basis. Apart from the diversity assessments, the study focused on the spatio-temporal patterns, and factors influencing the growth and distribution of the Scytonemataceae family in the Western Ghat mountain chain region. For assessing the diversity of Scytonemataceae, indices such as the Simpson Index, Shannon-Weiner index, evenness index, and Menhinick's index were worked out. Moreover, the Pearson correlation coefficient matrix and principal component analysis were performed for the analysis and subsequent interpretation of data. A total of 35 species belonging to the Scytonemataceae family were identified, of which 23 are new to Kerala and 16 are new to India. The present study shows that seasonal variation had the most significant effect on the cyanobacteria belonging to the family Scytonemataceae. From a spatial perspective, environmental factors such as moisture, atmospheric temperature, surface temperature, and diurnal temperature are strong determinants of the growth of the Scytonemataceae family during all seasons.

1. Introduction

Cyanobacteria are a large group of ecologically significant, photosynthetic, prokaryotic micro-organisms with a long evolutionary history [1, 2]. They can be found in nearly every habitat on Earth [3]. Cyanobacteria have several advantages as hosts for biotechnological applications, such as minimal growth requirements, easy genetic manipulation, and appealing platforms that enable carbon-neutral production processes [4, 5]. Their occurrence and distribution differ widely due to changing environmental conditions, showing a difference in their growth pattern [6]. The Scytonemataceae populations are the most prominent among them, found abundantly on rock surfaces [7]. This family has great potential application in the field of agriculture as they have the capacity for nitrogen fixation, thereby making promising contributions in the field of agriculture [8]. Understanding spatio-temporal changes in microbial populations related to environmental factors is crucial in understanding their distribution, ecology, and resultant responses to environmental changes [9-11]. The systematic classification and distribution of cyanobacteria, especially the Scytonemataceae family, are still less understood [12]. A recent study [7] focused on the diversity of the family Scytonemataceae and reported 19 species from the Wayanad district in the Western Ghats region of Kerala. In the current study, the spatial as well as temporal variations of the Scytonemataceae family along selected locations of the Western Ghats were analyzed and compared to identify the predominant geo-environmental conditions influencing their growth and distribution.

Kerala, a landmass sandwiched between the Western Ghats and the Arabian Sea, is one of the least explored regions in the field of Scytonematacean taxonomy. Existing literature on cyanobacterial taxa concerning Kerala reveals that research on the diversity in the Scytonemataceae family is limited. Furthermore, the Western Ghats region of Kerala, which is considered one of the global biodiversity hotspots [13] offers a spectrum of microhabitats and has not been thoroughly researched for cyanobacterial diversity, particularly within the Scytonemataceae family. The present study deals with the spatio-temporal diversity of the Scytonemataceae family from selected regions of the Western Ghats, falling in Palakkad, Malappuram, Kozhikode, and Wayanad districts of Kerala. As stated, research on the occurrence, species diversity, and habitat diversity of cyanobacteria in general, and Scytonemataceae, in particular, is limited in this region (Palakkad, Malappuram, Kozhikode, and Wayanad) and hence warrants a detailed study as it forms one among the four biodiversity hotspots in India.

2. Materials and methods

2.1. Study area

Kerala state is located in the south-western region of India, between northern latitudes 8°18' and 12°48' and eastern longitudes 74°52' and 77°22'. The present study was carried out in 52 sampling sites of the Western Ghats, adjoining Palakkad, Malappuram, Kozhikode, and Wayanad districts. The Palakkad district (10.7867°N,76.6548°E) has a gap in the Western Ghats region, which is a major determinant of the climate of Kerala. The highest elevation is at Anginda Peak, standing at 2,383 m above MSL, located on the border of Palakkad, Nilgiris, and Malappuram districts within the Silent Valley National Park. The district covers an area of 4,480 km^2 (1,730 sq mi), making it one of the largest districts in Kerala, and accounting for 11.5% of the state's total land area. Forests cover 1,360 km^2 (530 sq mi) of the total land area. The district receives sufficient rainfall, more than the extreme southern districts of Kerala.

The Malappuram district is located within the geographic coordinates of 75°E - 77°E longitude and 10°N - 12°N latitude. It has a coastal area along the Arabian Sea, a midland in the center, and a hilly terrain adjoining the Western Ghat regions. The district has a steady tropical climate with significant rainfall throughout most months and a short dry season. The average annual temperature is 27.3 °C, and the yearly rainfall averages 2,952 millimeters (116.2 in). The summer spans from March to May, and the monsoon season is from June to September, and the district experiences both southwest and northeast monsoons. Winter occurs from December to February.

Kozhikode district is located on India's southwest coast and is bordered by the Malappuram district to the south, Kannur district to the north, Wayanad district to the east, and the Arabian Sea to the west (11.2588°N, 75.7804°E). Kozhikode is divided into three distinct regions: the lateritic midland, the sandy region, and the rocky highlands, which is a mountainous section of the Western Ghats. The stony highlands cover approximately 637.65 square kilometers of the total 2344 square kilometers. The sandy coastal belt and lateritic midlands cover 362.85 sq. km. and 1343.5 sq. km., respectively. The district has a humid climate with a hot season from March to May. The South-West monsoon, starting in the first week of June and lasting through September, brings the year's rainfall. From the second half of October and extending to November, there is North East monsoon. The average annual rainfall is 3,266 mm.

The Wayanad district is situated in the north-eastern

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part of the state (11.6994°N,76.0773°E). It covers a major area of the Western Ghats and is positioned on the southernmost part of the Deccan plateau. The district covers an area of 885.92 km² and is predominantly covered with forests. Wayanad is surrounded by a network of protected areas that house various biological reserves. The district enjoys a pleasant climate throughout the year, with an average rainfall of 2322 mm. Lakkidi, Vythiri, and Meppadi receive the highest amount of rainfall, ranging between 3,000 to 4,000 mm each year. The year is categorized into four seasons: cold weather (December-February), hot weather (March-May), southwest monsoon (June-September), and northeast monsoon (October-November). The Lakkidi valley, nestled among the hills of Vythiri taluk, receives the highest average rainfall in Kerala.

A significant characteristic of the Western Ghats is the exceptionally high level of biological diversity and endemism. Also, the area is ecologically sensitive and constitutes a higher diversity of species belonging to various families within the cyanobacteria group. The sampling locations are represented using the Arc GIS software. The sampling sites at different elevations is shown in Fig. 1.

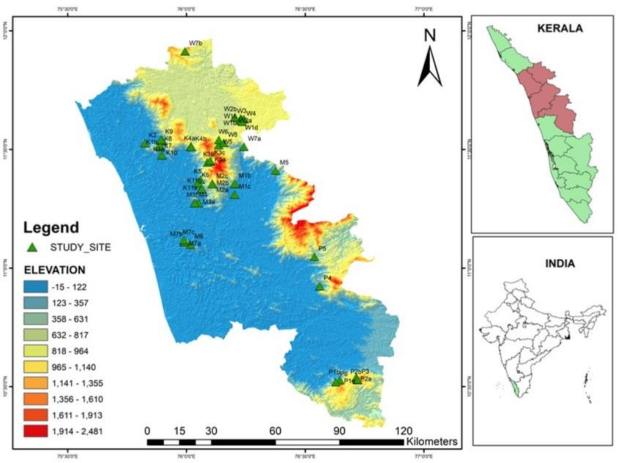

Figure 1. Map of the study area showing sampling sites at different elevations (meters).

2.2. Collection, culturing and identification

Specimens were collected on a seasonal basis (pre-monsoon, monsoon, and post-monsoon) from 52 sites of the Western Ghats, falling in Palakkad, Malappuram, Kozhikode, and Wayanad districts (Fig. 2). The sampling coordinates were marked with an Etrex 20X Garmin GPS.

Also, the cyanobacterial patches were collected from the various rock surfaces of the sampling sites using scalpels and spatulas and were kept in collection bottles. Microclimatic parameters associated with the habitat, such as atmospheric temperature (Divinext digital thermometer), surface temperature (Metravi AVM-08 IR thermometer), humidity (Divinext digital hygrometer), and wind velocity (Prova AVM -01 anemometer) were recorded. Diurnal temperature, relative humidity, and moisture (precipitation) data were acquired from Google Earth Pro [14]. Other habit and habitat characteristics of patches were identified and recorded. Each specimen was given a voucher number for identification.

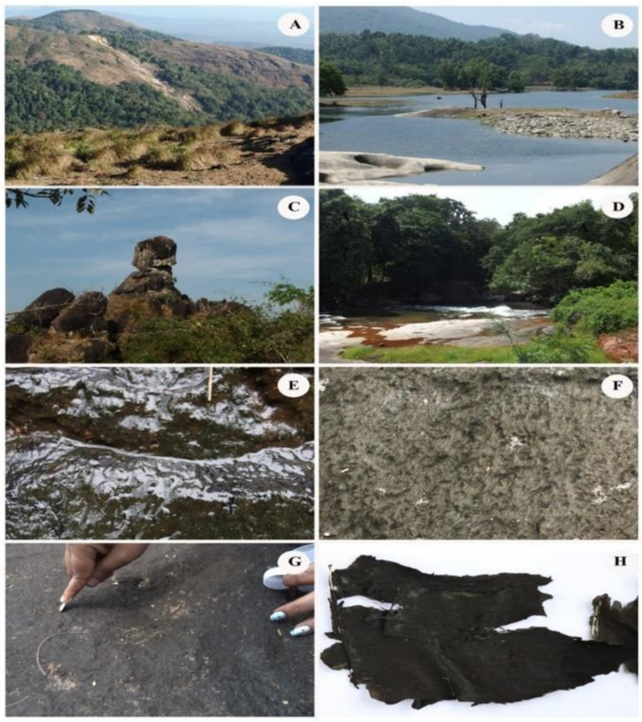

Figure 2. A-D. Selected sampling locations. A. Mattumala, Palakkad B. Thonikadavu, Kozhikode C. Phantom rock, Wayanad D. Adyanpara, Malappuram. E-F. Nature of habitat of epilithic cyanobacterial encrustations (Scytonemataceae). G. Specimen collection. H. Cyanobacterial mat (Scytonemataceae).

Collected cyanobacterial specimens were brought to the laboratory for further studies. To get rid of any debris and impurities, the samples were first cleansed with distilled water. They were then cultured in BG-

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11 medium [15], which is a nitrogen-free medium prepared by omitting the sodium nitrate. The pH of the medium was adjusted to 7.4 using a digital pH meter and autoclaved at 121°C for 20 minutes. The cleaned samples were transferred to conical flasks containing the culture medium under a laminar airflow chamber. The specimens were then kept at a temperature of 25 ± 2°C and 3000 lx illumination by altering light/dark periods of 16:8 h.

The specimens collected were examined under 20X, 40X, and 100X objectives with a Leica DM6B compound microscope, and the photomicrographs of each were taken. Morphometric analyses were done based on the type and size of the filaments, the size and colour of the trichomes, the colour and size of the sheath and the nature of the heterocysts and heterocyst colour. Standard taxonomic manuals by Desikachary [16] and Komarek [17] were used for the identification of specimens.

2.3. Statistical analysis

For analyzing the diversity of the members falling in the Scytonemataceae family, diversity indices such as the Simpson index, Shannon-Weiner index, Evenness index, and Menhinick's index were performed using PAST 4.03 statistical software. The environmental parameters associated with cyanobacterial diversity were assessed using the 'R' statistical software. Also, the Pearson correlation coefficient matrix and principal component analysis (PCA) were employed to identify relationships among variables, simplifying complex datasets and aiding in interpreting results.

3. Results and discussion

The present study was conducted at 52 sampling sites in the Western Ghats, encompassing the Palakkad, Malappuram, Kozhikode, and Wayanad districts. Specimens were collected on a seasonal basis (pre-monsoon, monsoon, and post-monsoon periods). A total of 35 species belonging to the Scytonemataceae family were identified. This study documents new additions to the cyanobacterial flora of both Kerala and India. Specifically, 23 new species were recorded in the cyanobacterial flora of the Western Ghats in Kerala. Of these, 16 species represent new records for the cyanobacterial flora of India. Our previous work [9] reported 19 species, including new records, from the Wayanad district. In the current study, (Figs. 3 & 4) we identified 16 species from the Palakkad, Malappuram, and Kozhikode districts. These species include *Petalonema crassum* (Nageli in Kutzing) Migula 1907, *Scytonema coactile* Montagne ex Bornet et Flahault 1886, *Scytonema longiarticulatum* Gardner 1927, *Scytonema papilli-capitatum* C.L. Sant'Anna & J. Komarek 2013, *Scytonema torulosum* C.-C.Jao 1940, from Palakkad district; *Scytonema chiastum* Geitler

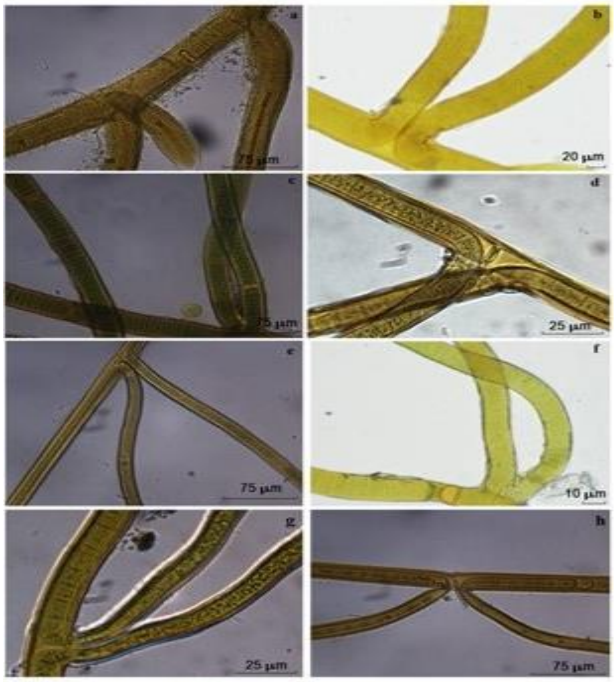

Figure 3. a. *Petalonema crassum, b. Scytonema chiastum,* c. *Scytonema cincinnatum,* d. *Scytonema coactile*, e. *Scytonema fritschii* f. *Scytonema hyalinum* g. *Scytonema javanicum* h. *Scytonema longiarticulatum.*

1925, *Scytonema fritschii* Ghose 1924, *Scytonema javanicum* Bornet ex Bornet & Flahault 1886, *Scytonema pascheri* Bharadwaja 1934, *Scytonema twymanianum* Welsh 1966 from Kozhikode district; *Scytonema cincinnatum* Thuret ex Bornet & Flahault 1886, *Scytonema hyalinum* Gardner 1927, *Scytonema millei* Bornet ex Bornet & Flahault 1886, *Scytonema praegnans* Skuja 1937, and *Scytonema sanpaulense* Sant'Anna 1988, and *Scytonema schmidtii* Gomont 1901, from Malappuram district. Species such as *Petalonema crassum* (Nageli ex Bornet & Flahault) Migula 1905, *Scytonema chiastum* Geitler 1925, *Scytonema fritschii*

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Ghose 1924, and *Scytonema twymanianum* Welsh 1966 are recognized as new additions to the cyanobacterial flora of the Western Ghats region of Kerala. Among the 16 species, five are regarded as new records for the cyanobacterial flora of India. These include *Scytonema hyalinum* Gardner 1927, *Scytonema longiarticulatum* Gardner 1927, *Scytonema papilli-capitatum* C.L. Sant'Anna & J. Komarek 2013, *Scytonema praegnans* Skuja 1937, and *Scytonema sanpaulense* Sant'Anna 1988.

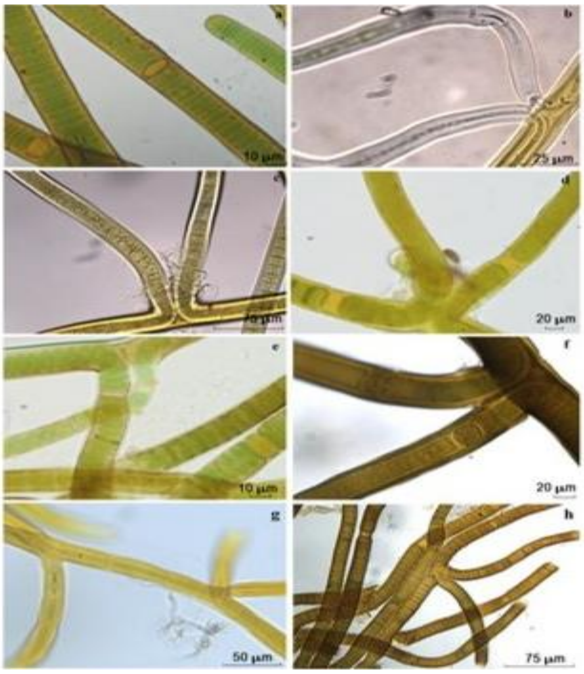

Figure 4. a. *Scytonema millei,* b. *Scytonema papilli-capitatum*, c. *Scytonema pascheri* d. *Scytonema praegnans* e. *Scytonema sanpaulense* f. *Scytonema schmidtii* g. *Scytonema torulosum* h. *Scytonema twymanianum.*

3.1. Spatio-temporal diversity of Scytonemataceae

Specimens were collected seasonally (pre-monsoon, monsoon, and post-monsoon) from all 52 sites. Each cyanobacterial patch was taken as the unit for diversity analysis. From the current study (Table 1), it is observed that the highest number of species were observed during the monsoon season (35), followed by the post-monsoon season (30), and the lowest in the pre-monsoon season (22). The current study also revealed that the highest no. of patches was found during monsoon (216), followed by post-monsoon (53), and pre-monsoon (30). The Shannon Diversity index value typically ranges from 0 to 4.5, considering both the species richness and the evenness of their distribution. According to another research, a Shannon-Weiner index value of 3.00-4.50 indicates high diversity, 2.00-3.00 indicates moderate diversity, 1.00-2.00 indicates less diversity and 0.00-1.00 indicates very low diversity [18]. The Shannon diversity index was performed and the results ranged between 3.045 and 3.435, which indicates that the habitat structure is stable. The highest value (3.435) was recorded during the monsoon season, followed by the post-monsoon (3.232) and the pre-monsoon seasons (3.045). A higher Shannon diversity index value indicates greater sample diversity, which means that the monsoon season had the highest cyanobacterial diversity, while the pre-monsoon season had comparatively the lowest. A Simpson index was performed and the values were between 0.949-0.963, revealing higher diversity among the three seasons. Another study [19] suggested interpreting the Simpson index in further detail, with a score of 0.00 indicating a complete absence of diversity or homogeneity, 0.01-0.40 indicating a low degree of diversity, 0.41-0.60 indicating a moderate degree of diversity, 0.61-0.80 indicating a moderately high degree of diversity, 0.81-0.99 indicating a high degree of diversity, and 1.00 indicating absolute or perfect diversity or heterogeneity. In the present study, all three seasons possess a high degree of cyanobacterial diversity, whereas the comparatively highest value was reported during the monsoon (0.963), followed by post-monsoon (0.9536) and the lowest was during the pre-monsoon season (0.9497). A higher index value indicates greater diversity. The Menhinick diversity index was calculated to assess the richness of species and the values were between

Table 1. Diversity analysis: Diversity indices of family Scytonemataceae during different seasons.

Items	Pre-monsoon	Monsoon	Post monsoon
Number of species	22	35	30
Number of patches	30	216	53
Simpson (1-D)	0.94	0.96	0.95
Shannon (H)	3.04	3.43	3.23
Evenness	0.95	0.88	0.84
Richness	4.31	4.85	4.24

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4.243 and 4.854, indicating higher species richness. This suggests that several different species were present within the sample, reflecting a diverse ecological community. Higher values indicate greater species richness, relative to the number of individuals, suggesting a more diverse community. Conversely, lower values suggest lower species richness relative to the number of individuals, indicating less diversity. Another research showed [20], a Menhinick diversity index value of >1.96 indicates high diversity and <0.80 indicates low diversity. In the current study, the highest value of 4.854 was observed during the monsoon season, followed by the pre-monsoon season with a value of 4.315. The comparatively lowest value of 4.243 was recorded during the post-monsoon period. Since higher values indicate greater species richness relative to the number of individuals, suggesting a more diverse community, the study demonstrated that all three seasons exhibit higher species richness. However, the slight drop in post-monsoon suggests a potential impact of seasonal changes on species composition and abundance. In this study, evenness values ranging from 0.8447 to 0.9548 were recorded, suggesting that the species in the community are evenly distributed. Another research subdivided the evenness value into three categories: balanced (>0.8-0.9), semi-balanced (>0.5-0.8), and unbalanced (≤0.5) [21]. While the value of 0.954 (pre-monsoon) indicates the highest level of evenness among the three, all values were sufficiently higher to suggest a well-balanced community, with low dominance by any single species and high species evenness. Overall, the highest diversity was found during monsoon, followed by post-monsoon, and the least during pre-monsoon season.

Analysis showing seasonal variation in patch numbers across different sites was done (Fig. 5, Table 2). The highest mean patch numbers were observed during the monsoon season. The mean patch number is less during the post-monsoon, followed by the pre-monsoon. During the pre-monsoon season, the highest diversity is found in the Wayanad district, followed by the monsoon season, with the highest diversity in the Palakkad district, while Wayanad shows the highest diversity during the post-monsoon season. Diversity indices were carried out to know the

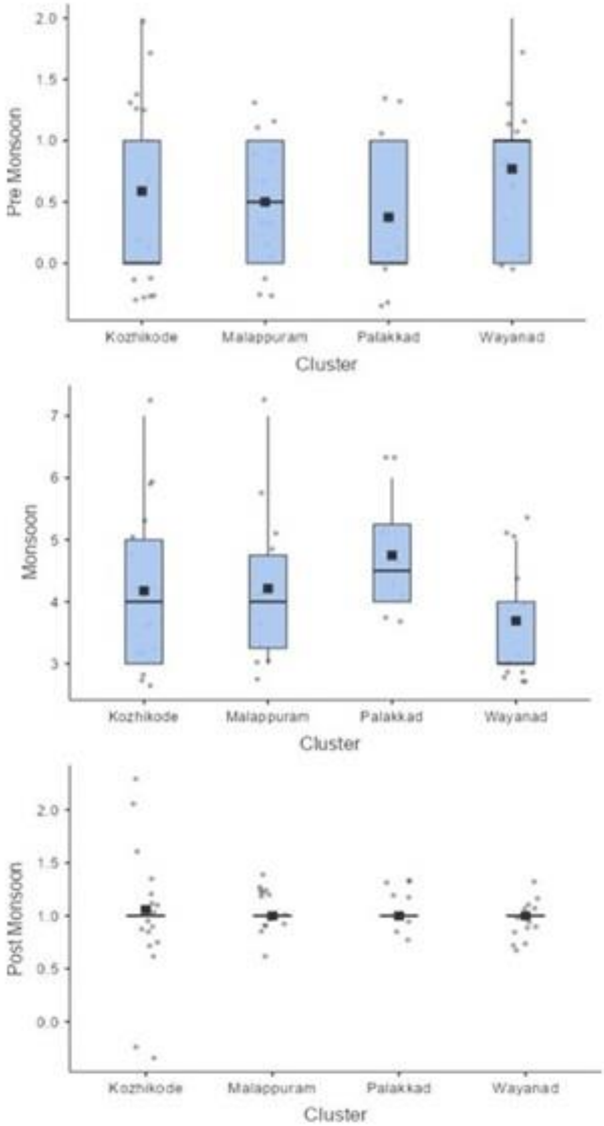

Figure 5. Box plots showing seasonal variations in patch numbers across different sites.

Table 2. Analysis showing seasonal variation in Patch numbers across different sites and mean values.

Season	Districts	Mean
Pre-monsoon	Kozhikode	0.58±0.71
	Malappuram	0.50±0.51
	Palakkad	0.37±0.51
	Wayanad	0.76±0.59
Monsoon	Kozhikode	4.18± 1.29
	Malappuram	4.21±1.19
	Palakkad	4.75±0.88
	Wayanad	3.69±0.85
Post-monsoon	Kozhikode	1.06±0.55
	Malappuram	1.00±0.00
	Palakkad	1.00±0.00
	Wayanad	1.00±0.00

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Table 3. Diversity across districts during different seasons.

Season	Items	Palakkad	Malappuram	Kozhikode	Wayanad
Pre-Monsoon	Number of Species	3	7	7	9
	Simpson 1-D	0.66	0.85	0.85	0.88
	Shannon H	1.09	1.94	1.94	2.19
	Evenness e^H/S	1	1	1	1
	Menhinick	1.73	2.64	2.64	3
Monsoon	Number of Species	8	14	17	13
	Simpson 1-D	0.87	0.92	0.94	0.92
	Shannon H	2.07	2.63	2.83	2.56
	Evenness e^H/S	1	1	1	1
	Menhinick	2.82	3.74	4.12	3.60
Post-Monsoon	Number of Species	8	14	15	13
	Simpson 1-D	0.87	0.92	0.93	0.92
	Shannon H	2.07	2.63	2.70	2.56
	Evenness e^H/S	1	1	1	1
	Menhinick	2.82	3.74	3.87	3.60

members of the family Scytonemataceae across four districts during the three seasons (Table 3). During the pre-monsoon season, Wayanad exhibits the highest species diversity, with a Simpson's Index value of 0.8889, indicating the most diverse ecosystem. In contrast, Palakkad exhibits the lowest species diversity with a Simpson's Index of 0.6667, indicating a moderately diverse community. The different study regions display varying levels of species diversity. Palakkad has the lowest diversity, with a Shannon Index value of 1.099, while Wayanad has the highest species diversity, with a Shannon Index of 2.197. The distribution of individuals among species in all four districts (Palakkad, Malappuram, Kozhikode, and Wayanad) is perfectly even, with an evenness value of 1. This suggests that there is no single dominating species, suggesting a well-balanced community structure across all regions. Wayanad has the highest species richness with a Menhinick's Index of 3.000, indicating the richest species in the community. Palakkad has the lowest species richness with a Menhinick's Index value of 1.732, indicating fewer species relative to the number of individuals sampled. During the monsoon season, Simpson's Diversity Index in Kozhikode indicates (0.9412) the highest species diversity and evenness, suggesting a very healthy and balanced ecosystem. Despite having the lowest index among the four, Palakkad shows a relatively diverse ecosystem. The index value in Palakkad (0.875) suggests relatively lower cyanobacterial diversity compared to the other regions. Though still diverse, it indicates that fewer species or a less even distribution of cyanobacteria are present compared to the other regions. The high Shannon Diversity Index in Kozhikode district (2.833) indicates the highest species diversity and evenness, showing a very healthy and balanced ecosystem, while Palakkad has the lowest diversity, with a Shannon Index value of 2.079. In all four districts, there is perfect evenness, with a value of 1 indicating that the distribution of individuals among species is completely even within each region, without any single species dominating the other, suggesting a well-balanced community structure across all regions. The Menhinick index indicated the species richness of cyanobacteria during the monsoon season in each district, with higher values representing greater richness. Present data shows that Kozhikode has the highest species richness of cyanobacteria (4.123) and the lowest in Palakkad district (2.828) and other regions in between.

The Simpsons index value in the post-monsoon season in Kozhikode district (0.9333) shows the highest diversity, with no single species dominating the community, suggesting a rich and balanced ecosystem, while Palakkad has the lowest index among the four, with a value of 0.875, still showing a significant level of biodiversity. This value indicates

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that although certain species may have some dominance, the overall biodiversity remains notable. The Shannon Diversity Index indicates that Kozhikode has the highest species diversity (2.708) among the four districts. The Palakkad exhibits the lowest species diversity among the listed regions. During the post-monsoon season, all four districts (Palakkad, Malappuram, Kozhikode, and Wayanad) exhibit perfect evenness. This denotes that individuals are evenly distributed among different species in each region, contributing to a balanced ecosystem from the perspective of species representation. According to the Menhinick Index, Kozhikode has the highest species richness with a value of 3.873, while Palakkad exhibits the lowest species richness among the listed regions. Seasonal variations in patch size were analyzed (Fig. 6 & Table 4).

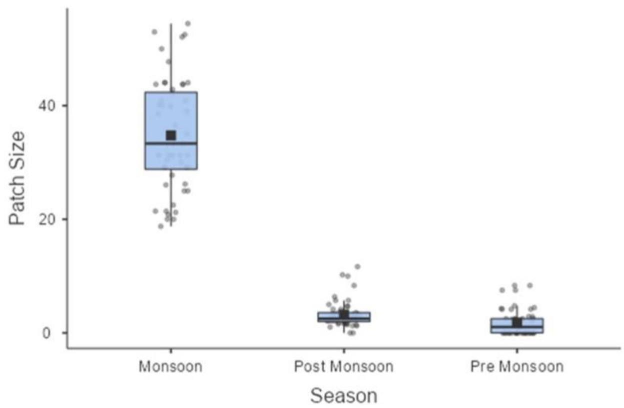

Figure 6. Analysis showing seasonal variations in patch size.

Table 4. Analysis showing the seasonal variations in patch size.

Season	Patch size
Monsoon	34.8±9.65
Post monsoon	3.24±2.40
Pre-monsoon	1.79±2.33

The highest patch size was observed during the monsoon season. The mean patch size during monsoon season was 34.8 ± 9.65, followed by post-monsoon. The lowest patch size was found during the pre-monsoon (1.79±2.33). Since there was less moisture and rainfall available during the pre-monsoon, it is obvious from our study that there were fewer and smaller patches during that time of the year. This finding supports the fact that cyanobacteria can thrive more vigorously during wet seasons.

3.2. Habitat characteristics

To analyze the habitat preferences of the members of the family Scytonemataceae, various environmental parameters were assessed (Tables 5-8). Pearson correlation was done to check how patch size was related to different environmental parameters. During the pre-monsoon season, it was revealed that the environmental parameters such as moisture, atmospheric temperature, surface temperature, and diurnal temperature showed a significant correlation with patch size. In both pre-monsoon and monsoon seasons, the same environmental parameters showed a significant correlation with patch size. That is during monsoon season, it is noticed that the moisture, atmospheric temperature, surface temperature, and diurnal temperature showed significant correlations with patch size. During the post-monsoon season, moisture, atmospheric temperature, surface temperature, diurnal temperature, relative humidity, and wind speed showed significant correlation with patch size.

This study shows that environmental factors are strong determinants in the growth of family Scytonemataceae during all seasons. The Pearson correlation table shows that the moisture ($r = 0.921$, *** $p < .001$), atmospheric temperature ($r=0.407$, ** $p < .01$), surface temperature ($r=0.702$, *** $p < .001$) and diurnal temperature ($r=0.491$, *** $p < .001$) are positively correlated during Pre-monsoon season in a significant level; moisture ($r=0.849$, *** $p < .001$), atmospheric temperature ($r=0.774$, *** $p < .001$), surface temperature ($r=0.715$, *** $p < .001$), diurnal temperature ($r=0.693$, *** $p < .001$) and altitude ($r=0.287$, * $p < .05$) are positively correlated during monsoon season in a significant way; and moisture ($r=0.749$, *** $p < .001$), atmospheric temperature ($r=0.673$, *** $p < .001$), surface temperature ($r=0.747$, *** $p < .001$) and diurnal temperature ($r=0.579$, *** $p < .001$), relative humidity ($r=0.486$, *** $p < .001$) are significantly correlated during post-monsoon season.

In all seasons, moisture, atmospheric temperature, surface temperature, and diurnal temperature are positively related to the patch size of species of the another study [22] was on Pearson correlation analyses between various independent meteorological variables, such as relative humidity,

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Table 5. Different environmental parameters across different sites of 3 seasons.

Site id	Cluster	Pre-monsoon					Monsoon					Post-monsoon				
		Atm temp	Surface temp	Hmdty	Relative hum	Diurnal temp	Atm temp	Surface temp	Hmdty	Relative hum	Diurnal temp	Atm temp	Surface temp	Hmdty	Relative hum	Diurnal temp
P1a	Palakkad	36	67.2	31	64.25	10.82	22.2	37.8	71	89.07	7.925	34.6	30.3	22	87.14	9.3
P1b	Palakkad	32.2	83.8	22	64.25	10.82	22.3	32.7	72	89.07	7.925	38.3	30.7	21	87.14	9.3
P2a	Palakkad	25.7	86.1	26	64.25	10.82	26.5	97.6	64	89.07	7.925	31.3	30.4	24	87.14	9.3
P2b	Palakkad	25.8	114.2	25	64.25	10.82	26.3	95.8	63	89.07	7.925	29.1	26.8	24	87.14	9.3
P3	Palakkad	24.7	87.3	26	64.25	10.82	25.5	42.7	65	89.07	7.925	32.8	39.5	29	87.14	9.3
P4	Palakkad	44.1	88.6	30	66.65	10.82	25.1	63.8	64	90.03	7.925	41.6	57.7	36	82.59	9.3
P5	Palakkad	33	89.3	55	66.65	12.3	21.7	47.9	74	90.03	8.05	35.3	32.6	34	82.59	10.67
P6	Palakkad	37.9	92.8	31	64.25	10.82	21.7	37.8	73	89.07	7.925	32.1	31.3	31	87.14	9.3

Atm temp-Atmospheric temperature (°C), Surface temp-Surface temperature (°C), Hmdty- Humidity (%), Relative hum-Relative humidity (%), Diurnal temp-Diurnal temperature(°C)

Table 6. Different environmental parameters across different sites of 3 seasons.

Site id	Cluster	Pre-monsoon					Monsoon					Post-monsoon				
		Atm temp	Surface temp	Hmdty	Relative hum	Diurnal temp	Atm temp	Surface temp	Hmdty	Relative hum	Diurnal temp	Atm temp	Surface temp	Hmdty	Relative hum	Diurnal temp
M1a	Malappuram	38.5	87.3	40	65.11	10.12	31.5	53.1	52	90.04	6.77	36.7	59.3	41	83.82	9.22
M1b	Malappuram	37.8	93.2	41	65.11	10.12	33.7	51.6	47	90.04	6.77	34	38.7	43	83.82	9.22
M1c	Malappuram	37.4	10.2	40	65.11	10.12	35.8	50.2	47	90.04	6.77	39.7	56.6	37	83.827	9.22
M2a	Malappuram	33.6	37.2	49	65.11	10.12	31.8	84.6	56	90.04	6.77	40.8	45.2	30	83.82	9.22
M2b	Malappuram	38.8	37.5	44	65.11	10.12	33.3	82.8	63	90.04	6.77	40.1	44.5	31	83.82	9.22
M2c	Malappuram	34.7	39.2	46	65.11	10.12	32.8	89.6	63	90.04	6.77	40.3	48.5	30	83.82	9.22
M3a	Malappuram	29.7	40.6	68	65.11	10.12	30.1	92.8	70	90.04	6.77	31.2	49.7	58	83.82	9.22
M3b	Malappuram	31.7	41.2	69	65.11	10.12	30.7	93.3	68	90.04	6.77	33.4	64.6	57	83.82	9.22
M4	Malappuram	30.3	105.2	60	65.11	10.12	28.7	72.9	73	90.04	6.77	31.5	51.8	52	83.82	9.22
M5	Malappuram	33.4	87.3	44	65.11	10.12	30.3	68.7	60	90.04	6.77	37.3	58.3	32	83.82	9.22
M6	Malappuram	36.3	45.7	35	66.65	10.12	32.1	93.8	60	90.03	6.77	34.8	34.8	49	82.59	9.22
M7a	Malappuram	35.4	48.5	33	66.65	8.1	38.8	86.4	61	90.03	5.55	32.6	40.2	56	82.59	8.4
M7b	Malappuram	35.3	58.7	34	66.65	8.1	32.3	90.2	63	90.03	5.55	32.4	40.1	55	82.59	8.4
M7c	Malappuram	35.7	87.3	33	66.65	8.1	32.7	78.4	57	90.03	5.55	32.1	42.3	56	82.59	8.4

Atm temp-Atmospheric temperature (°C), Surface temp-Surface temperature (°C), Hmdty- Humidity (%), Relative hum -Relative humidity (%), Diurnal temp -Diurnal temperature (°C)

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Table 7. Different environmental parameters across different sites of 3 seasons.

Site id	Cluster	Pre-monsoon					Monsoon					Post-monsoon				
		Atm temp	Surface temp	Hmdty	Relative hum	Diurnal temp	Atm temp	Surface temp	Hmdty	Relative hum	Diurnal temp	Atm temp	Surface temp	Hmdty	Relative hum	Diurnal temp
K1a	Kozhikode	35.3	20.56	45	70.29	9.25	28.3	93.3	71	88.32	5.77	34.1	40.4	46	78.04	8.9
K1b	Kozhikode	34.8	21.3	44	70.29	9.25	28.3	102.8	70	88.32	5.77	34	41.8	46	78.04	8.9
K1c	Kozhikode	34.8	117.2	42.20	70.29	9.25	29.2	107.5	70.00	88.32	5.77	33.6	47.6	44.00	78.04	8.9
K2	Kozhikode	35.8	93.2	42	70.29	9.25	27.3	72.6	68	88.32	5.77	36.1	49.3	37	78.04	8.9
K3a	Kozhikode	32	25.2	42	65.11	10.12	23.8	66.1	70	90.04	6.77	35	32.2	37	83.82	9.225
K3b	Kozhikode	29.1	25.94	40	65.11	10.12	23.7	72.1	71	90.04	6.77	35.1	32.1	38	83.82	9.225
K3c	Kozhikode	31.2	26.3	40	65.11	10.12	23.6	67.2	70	90.04	6.77	35.4	32.4	39	83.82	9.225
K4a	Kozhikode	33.1	27.8	48	65.11	11.47	25.3	72.7	52	90.04	7.02	30.3	41	35	83.8	9.9
K4b	Kozhikode	33.8	93.2	44	65.11	11.47	25.7	23.2	62	90.04	7.02	30.7	39	62	83.82	9.9
K5	Kozhikode	34.8	29.8	52	65.11	10.12	33.1	89.2	67	90.04	6.77	32.5	34.8	54	83.82	9.22
K6	Kozhikode	33.9	30.8	50	65.11	10.12	32.3	93.7	61	90.04	6.77	32.5	39.1.7	51	83.82	9.22
K7	Kozhikode	33.1	30.8	51	70.29	9.25	27.7	80.1	74	88.32	5.77	31.5	31.6	53	78.04	8.9
K8	Kozhikode	34.3	117.2	50	70.29	9.25	28.7	71.8	75	88.32	5.77	32.4	31.8	52	78.04	8.9
K9	Kozhikode	33.4	32.2	39	70.29	9.25	30.3	68.7	63	88.32	5.77	30.8	32.7	54	78.04	8.9
K10	Kozhikode	31.4	17.8	53	70.29	8.1	29.1	56.4	59	88.32	5.55	30.4	33.4	53	78.04	8.4
K11a	Kozhikode	32.8	18.3	47	65.11	10.12	33.1	126.8	54	90.04	6.77	36.3	48.8	53	83.82	9.22
K11b	Kozhikode	33.6	19.4	45	65.11	10.12	33.2	97.4	55	90.04	6.77	33.8	25.9	49	83.82	9.22

Atm.Temp.-Atmospheric temperature (°C), Surface temp-Surface temperature (°C), Hmdty- Humidity (%), Relative hum -Relative humidity (%), Diurnal temp -Diurnal temperature (°C)

Table 8. Different environmental parameters across different sites of 3 seasons.

Site id	Cluster	Pre-monsoon					Monsoon					Post-monsoon				
		Atm temp	Surface temp	Hmdty	Relative hum	Diurnal temp	Atm temp	Surface temp	Hmdty	Relative hum	Diurnal temp	Atm temp	Surface temp	Hmdty	Relative hum	Diurnal temp
W1a	Wayanad	29.2	93.2	37	65.11	11.47	29.4	96.4	59	90.04	7.02	34	40.4	59	83.82	9.9
W1b	Wayanad	35.2	98.1	39	77.62	11.47	28.7	88.9	59	91.12	7.02	35.3	37.9	48	78.88	9.9
W1c	Wayanad	33.7	101.3	39	65.11	11.47	29.7	88.5	54	90.04	7.02	35.7	37.8	48	83.82	9.9
W1d	Wayanad	34.1	102.5	37	65.11	11.47	29.9	70.9	58	90.04	7.02	29.9	37.8	52	83.82	9.9
W2a	Wayanad	32.6	103.8	41	65.11	11.47	30.2	84.3	58	90.04	7.02	30.9	34.6	26	83.82	9.9
W2b	Wayanad	35	108.2	37	65.11	11.47	30.1	90.5	59	90.04	7.02	31.8	31.2	36	83.82	9.9
W3	Wayanad	30.7	111.4	38	65.11	11.47	28.3	84.3	63	90.04	7.02	33.3	34.9	45	83.82	9.9
W4	Wayanad	33.8	112.8	35	65.11	11.47	27.6	92.3	66	90.04	7.02	32.6	31.1	34	83.82	9.9
W5	Wayanad	30.4	117.2	51	65.11	11.47	31.8	96.3	55	90.04	7.02	34.3	24.4	34	83.82	9.9
W6	Wayanad	30.4	118	52	65.11	11.47	33.2	108.6	59	90.04	7.02	33.3	28.8	31	83.82	9.9
W7a	Wayanad	32.3	119	42	65.11	11.47	29.8	89.3	54	90.04	7.02	31.8	33.7	44	83.82	9.9
W7b	Wayanad	33.7	121.6	41	59.87	9.25	29.2	88.7	55	88.28	5.77	31.2	49.9	46	83.34	8.9
W8	Wayanad	33	123.8	43	65.11	11.47	32.5	90	48	90.04	7.02	31.3	27.1	36	83.82	9.9

Atm temp-Atmospheric temperature (°C), Surface temp-Surface temperature (°C), Hmdty- Humidity (%), Relative hum -Relative humidity (%), Diurnal temp -Diurnal temperature (°C)

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Table 9. Correlation Matrix of different environmental parameters of 3 seasons showing how different parameters related to patch size.

Environmental factors	Pre-monsoon Patch Size	Monsoon Patch Size	Post-monsoon Patch Size
Moisture	0.92***	0.84***	0.74***
Wind speed	-0.00	0.24	-0.10
Atm_temp	0.40**	0.77***	0.67***
Surface_temp	0.70***	0.71***	0.74***
Diurnal	0.49***	0.69***	0.57***
RH	0.26	0.27	0.48***
Altitude	-0.14	0.28*	-0.25

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

temperature, and daily cumulative rainfall, to identify the factors influencing the occurrence of cyanobacteria. The results suggest a strong correlation between cyanobacteria concentration and relative humidity, aligning with our findings. However, the correlation with temperature was found to be negative in contrast to our results. In the present study, we observed a positive correlation between temperature and moisture across all three seasons: pre-monsoon, monsoon, and post-monsoon. Additionally, according to their findings, they suggest a positive but less significant correlation with rainfall. The current study agrees with the findings of the previous report [23], which stated that temperature is the key environmental factor for the growth of bacterial communities.

Principal component analysis (PCA) was employed to find out the relation of different environmental parameters with patch size. In the current study, principal component analysis was performed among the three seasons to know what all the environmental parameters are the influencing factors of patch size. The results of PCA were carried out in two main components, PC1 and PC2. It is comprised of environmental parameters such as moisture, atmospheric temperature, relative humidity, altitude, surface temperature, diurnal temperature, and wind speed.

Principal component analysis was performed for the pre-monsoon season, indicating Eigenvalues of 4.16104 and 3.04696 for PC1 and PC2 respectively (Table 10). The two principal components explained 90.1 % of the variability in the data. The effective loading score of patch size was observed in PC 2 and the value for the same was observed as 0.5624 in the pre-monsoon. The table shows that during the pre-monsoon season, it is observed that moisture, atmospheric temperature, and diurnal temperature are the influencing factors of patch size.

Table 10. Principal Component Analysis- Loading scores of Pre-monsoons.

Sl. No.	Parameters	PC 1	PC 2
1	Eigenvalue	4.16	3.04
2	% variance	52.01	38.08
3	Patch size	0.005	0.56
4	Moisture	-0.32	0.41
5	Atmospheric temperature	0.37	0.37
6	Surface temperature	0.41	0.02
7	RH	0.30	-0.29
8	Diurnal	0.13	0.52
9	Altitude	0.48	0.06
10	Wind speed	0.48	-0.06

Table 11. Principal component analysis -loading scores of monsoons.

Sl. No	Parameters	PC 1	PC 2
1	Eigenvalue	5.17	1.64
2	% variance	64.74	20.55
3	Patch size	0.405	0.29
4	Moisture	0.40	0.30
5	Wind speed	-0.25	0.61
6	Atmospheric temperature	0.41	0.24
7	Surface temperature	0.32	-0.39
8	Diurnal	0.10	-0.47
9	RH	0.37	0.02
10	Altitude	0.41	-0.03

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The eigenvalue is 5.17959 for PC1 and 1.64404 for PC2 during monsoon season (Table 11) and the data shows 85.29 variabilities. The effective loading score of patch size was observed in PC 1 and the value for the same was observed as 0.40574 in the monsoon season. The above-mentioned data shows that during the monsoon season, moisture, atmospheric temperature, relative humidity, and altitude are the influencing factors of patch size.

Eigenvalues show 5.97381 and 1.43657 for PC1 and PC2 respectively. The effective loading score of patch size was observed in PC 2 and the value for the same was observed as 0.62011 during the post-monsoon season. The table also shows that moisture and relative humidity are the influencing factors of patch size (Table 12). The result is graphically represented in (Figs. 7-9).

Table 12. Principal component analysis -loading scores of post-monsoons.

Sl. No.	Parameters	PC 1	PC 2
1	Eigenvalue	5.97	1.43
2	% variance	74.67	17.95
3	Patch size	0.27	0.62
4	Moisture	0.37	0.30
5	Wind speed	-0.37	-0.07
6	Atmospheric temperature	0.37	-0.31
7	Surface temperature	0.39	0.03
8	Diurnal	0.33	-0.13
9	RH	-0.26	0.63
10	Altitude	-0.40	-0.02

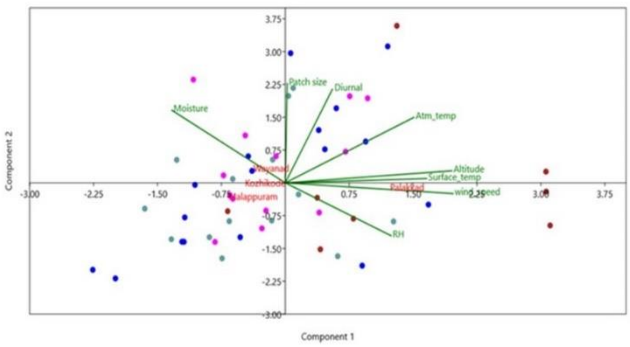

Figure 7. The results of principal component analysis during pre-monsoon.

Logistic regression is a statistical tool used for modeling the relationship between a dependent

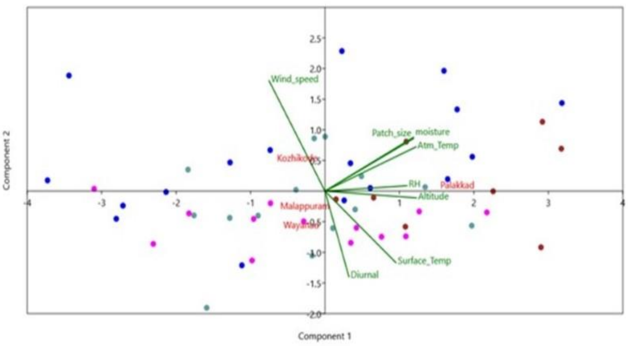

Figure 8. The results of principal component analysis during monsoon.

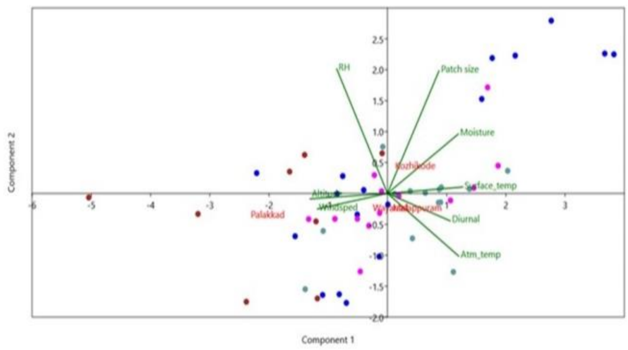

Figure 9. The results of principal component analysis during post-monsoon.

binary variable and one or more independent Variables.

Moreover, logistic regression helps identify key environmental factors or conditions affecting the presence or absence of specific microbial species. The research conducted performed logistic regression models to predict the best climatic niche for the family Scytonemataceae based on various environmental parameters during all three seasons (Table 13). Based on the data, the best-fit model during the pre-monsoon season consists of moisture and altitude, which account for 63% of the weightage. This model shows the lowest AICc, indicating the best fit among the tested models. The cumulative weights suggest that the top two models encompass 85% of the probability, implying that moisture and altitude, with minor contributions from wind speed, are the most influential factors in predicting patch size during pre-monsoon season.

Meanwhile, during the monsoon season, the best model with the lowest AICc incorporates moisture,

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Table 13. Logistic regression model.

Model season	Sl. No		K	AICc	Δ AICc	AICcWt	Cum.Wt	LL
Model-Pre-monsoon	1	ps~mst+alt	4	242.03	0.00	0.63	0.63	-116.59
	2	ps~mst+alt+ws	5	244.11	2.08	0.22	0.85	-116.40
	3	ps~mst+alt+ws+at	6	245.93	3.90	0.09	0.94	-116.03
	4	ps~mst+alt+ws+at+st	7	247.91	5.88	0.03	0.97	-115.68
	5	ps~mst+alt+ws+at+st+rh+dt	9	249.03	7.01	0.02	0.99	-113.37
	6	ps~mst+alt+ws+at+st+rh	8	250.28	8.25	0.01	1.00	-115.47
Model-Monsoon	1	ps~mst+alt+ws+at+st	7	328.56	0.00	0.36	0.36	-156.01
	2	ps~mst+alt+ws+at+st+rh	8	328.92	0.37	0.30	0.66	-154.79
	3	ps~mst+alt+ws	5	330.34	1.78	0.15	0.81	-159.52
	4	ps~mst+alt+ws+at+st+rh+dt	9	331.74	3.18	0.07	0.88	-154.73
	5	ps~mst+alt+ws+at	6	331.74	3.18	0.07	0.96	-158.94
	6	ps~mst+alt	4	332.77	4.22	0.04	1.00	-161.96
Model-Post monsoon	1	ps~mst+alt	4	202.57	0.00	0.61	0.61	-96.86
	2	ps~mst+alt+ws+at	6	204.78	2.22	0.20	0.82	-95.46
	3	ps~mst+alt+ws	5	204.98	2.42	0.18	1.00	-96.84

(ps-patch size, mst-moisture, alt-altitude, ws-windspeed, at-atmospheric temperature, st-surface temperature, rh-relative humidity, dt-diurnal temperature)

altitude, wind speed, atmospheric temperature, surface temperature, and relative humidity. The cumulative weights indicate that the top two models account for 66% of the probability. This suggests that moisture, altitude, wind speed, atmospheric temperature, and surface temperature are the most influential factors, with possible minor contributions from relative humidity.

Finally, during the post-monsoon season, the best model comprises moisture and altitude, which represents 61% of the weightage. The cumulative weights indicate that the top two models account for 82% of the probability, suggesting that moisture and altitude, along with minor contributions from wind speed and atmospheric temperature, are the most influential factors in predicting the patch size for the family Scytonemataceae during the post-monsoon season.

Based on this data, it can be concluded that a combination of environmental parameters such as moisture, altitude, wind speed, atmospheric temperature, surface temperature, and relative humidity plays a significant role in determining the best climatic niche for the family Scytonemataceae. For example, during the pre-monsoon season, factors like moisture and altitude promote the growth of the Scytonemataceae family, making it the best model for observing their enrichment during that particular season. This pattern also holds true for all other seasons, where the ideal combination of environmental parameters leads to cyanobacterial enrichment.

A complex interplay of environmental factors influences the growth of cyanobacteria on rocks. Factors such as light availability, temperature, moisture, nutrient levels, relative humidity (air), and substrate characteristics [24] play significant roles in determining the viability and proliferation of these organisms in different habitats. According to another study [25], water availability is the most important factor for the development of all microorganisms. Sufficient water availability combined with moderate temperature allows for the growth of a variety of cyanobacteria, despite their high resistance to desiccation [26]. The colonization of cyanobacteria has been correlated with air humidity and light intensity [27]. Other environmental factors, such as temperature, light intensity, and pH, influence the distribution of microorganisms [28]. Understanding these factors is essential for predicting cyanobacteria's distribution and ecological impact in natural environments.

The current study focused on the spatio-temporal diversity as well as the habitat characteristics of the

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family Scytonemataceae. Seasonal variation had the biggest impact on the cyanobacteria in the Scytonemataceae family on a temporal scale. The current study shows that cyanobacterial diversity appeared to be maximum during the monsoon season, which is in confirmation of the earlier findings of previous research [29]. This trend is contrary to the work by another study [30], in which cyanobacterial diversity was maximum during summer and lowest in the monsoon season. Consistent with the findings of other researchers [31], the current study revealed that cyanobacterial species richness was found to be maximum during the monsoon season, followed by the pre-monsoon, whereas it was minimal during the post-monsoon season.

From various studies, it is well recognized that several environmental factors like the availability of water, the intensity of the light, the temperature, and relative air humidity have an impact on the distribution and abundance of cyanobacteria [24, 25, 27, 32, 33]. The present study results show that environmental parameters such as atmospheric temperature, moisture, surface temperature, and diurnal temperature have a significant correlation with patch size during all three seasons. In addition to those parameters, relative humidity showed a positive correlation to patch size during the post-monsoon season.

The present study demonstrated that moisture is the key factor determining the growth of the cyanobacterial population, as their full flourishment can be seen during the wet season. Cyanobacteria are more frequently seen in wet and less frequently in dry seasons [33]. According to another study [34], the abundance of microalgae is mostly influenced by the availability of water. Since there was less moisture and rainfall available during the pre-monsoon, it is evident from the current study that there were fewer and smaller patches during that time of the year. This finding supports that cyanobacteria can thrive more vigorously during wet seasons.

Another study [35] performed the principal component analysis to investigate the seasonal diversity of cyanobacteria and its ecological attributes. The researchers assessed various ecological parameters, including temperature, relative humidity, and light intensity. They found that cyanobacteria are more susceptible to changes in diversity throughout the seasons, with a higher diversity of phototrophs observed in December. Their findings corroborated the present findings that all cyanobacterial groups exhibited a positive connection with relative humidity and water content.

The logistic regression model, the best model to predict the climatic niche of Scytonemataceae was performed. The data revealed that the combination of moisture and altitude was the best model during the pre-monsoon and post-monsoon seasons, whereas the combination of moisture, altitude, wind speed, atmospheric temperature, and surface temperature was found to be the best model during the monsoon season.

4. Conclusions

This study revealed the spatio-temporal patterns and habitat characteristics of the Scytonemataceae family in selected locations of the Western Ghats region of Kerala state, India. The current study analyzed and compared the spatial and temporal variations of cyanobacteria belonging to the family Scytonemataceae along the Western Ghats to identify the predominant influencing factors. The study conducted a diversity analysis across three seasons, revealing that the monsoon season had the highest cyanobacterial diversity, followed by the post-monsoon season and in contrast, the pre-monsoon season, exhibited relatively lower cyanobacterial diversity. The study concluded that, in terms of temporal scale, seasonal variation had the most significant effect on the cyanobacteria belonging to the family Scytonemataceae. They were mostly abundant during monsoon, followed by post-monsoon seasons. The variations in important environmental factors that impact the survival and growth of microorganisms can be reflected in spatial variability. From the spatial scale, environmental factors such as moisture, atmospheric temperature, surface temperature, and diurnal temperature are strong determinants of the growth of the Scytonemataceae family during all seasons. The

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research indicates that seasonal variations and specific environmental factors strongly influence the diversity of the family Scytonemataceae.

Disclaimer (artificial intelligence)

Author(s) hereby state that no generative AI tools such as Large Language Models (ChatGPT, Copilot, etc.) and text-to-image generators were utilized in the preparation or editing of this manuscript.

Authors' contributions

Field visits, data collection, sample analysis, data generation, interpretation and drafted the manuscript, S.K.; Supervision and edited the manuscript, H.C.C.

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Availability of data and materials

All data will be made available on request according to the journal policy

Conflicts of interest

There is no conflict of Interest.

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