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DIVERSITY AND DISTRIBUTION OF CYANOBACTERIA IN THE CHALLENGING ENVIRONMENT OF PADDY FIELDS IN COASTAL KARNATAKA, INDIA

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ABSTRACT

Cyanobacteria are key contributors to nutrient cycling and nitrogen fixation in paddy ecosystems. This study examined the diversity and ecological associations of coccoid cyanobacteria in relation to soil properties across the coastal districts of Karnataka, India. Soil samples from Uttara Kannada, Udupi, and Dakshina Kannada were analyzed for pH, electrical conductivity (EC), organic carbon (OC), and macronutrients (N, P, and K), while cyanobacteria were isolated and morphologically identified. A total of 46 species belonging to 20 genera were recorded, dominated by *Aphanothece*, *Chroococcus*, *Merismopedia*, and *Gloeocapsa*. Significant regional variation was observed in pH, EC, OC, N, and K, which strongly influenced diversity indices. Dakshina Kannada exhibited higher nutrient content and diversity (H′ = 3.09) than Udupi (H′ = 2.48). PCA and cluster analyses revealed strong correlations between soil nutrients and biodiversity, with Dakshina Kannada forming a distinct ecological group. Overall, soil fertility gradients regulate cyanobacterial diversity and community structure in coastal rice ecosystems, highlighting the ecological significance of native coccoid taxa in sustaining soil productivity.

INTRODUCTION

Cyanobacteria are ecologically significant photoautotrophic prokaryotes that contribute to nutrient cycling, nitrogen fixation, and soil fertility in agricultural ecosystems. In paddy fields, they form a major component of the microbial community, enhancing productivity through biological nitrogen fixation and organic matter enrichment (Wu et al., 2022). Among them, coccoid cyanobacteria such as *Chroococcus*, *Aphanothece*, and *Gloeocapsa* exhibit high adaptability to fluctuating moisture, salinity, and nutrient conditions typical of flooded rice soils (Whitton, 2002). The structure and diversity of cyanobacterial communities are strongly influenced by edaphic and environmental parameters, including soil pH, organic carbon, electrical conductivity, and macronutrient availability (Song et al., 2022). Coastal paddy ecosystems, characterized by variable salinity and high organic inputs, provide diverse microhabitats that favor distinct cyanobacterial assemblages (Prasanna et al., 2009). Despite their ecological relevance, information on cyanobacterial diversity in the coastal agroecosystems of southwestern India remains limited. The coastal belt of Karnataka, comprising Uttara Kannada, Udupi, and Dakshina Kannada, exhibits pronounced soil and climatic gradients influencing microbial diversity. This study aims to evaluate the diversity and distribution of coccoid cyanobacteria in relation to soil physicochemical properties across these Coastal Karnataka regions. Multivariate analyses were employed to elucidate nutrient-diversity relations and provide baseline insights into the ecological role of native cyanobacteria in coastal rice ecosystems.

MATERIALS AND METHODS

Study area and sampling

Soil and water samples were collected from paddy fields located in the Uttara Kannada, Udupi, and Dakshina Kannada districts of Coastal Karnataka. The samples were randomly collected during the active cropping season from the upper 0 to 15 cm layer of soil. These samples were then placed in sterile containers and processed within a 24-hour period.

Physicochemical analysis of soil

Air-dried and sieved soils (2 mm diameter) were analyzed in accordance with standard methodologies (Piper, 2019). Soil pH and electrical conductivity (EC) were assessed in a 1:2.5 soil–water suspension. Organic carbon (OC) was estimated using the method of Walkley and Black (1934), while available nitrogen was quantified through the alkaline $KMnO_4$ method (Subbiah and Asija, 1956), phosphorus was measured as per Olsen et al. (1954), and potassium was determined using the flame photometric technique (Merwin and Peech, 1951). All parameters were analyzed in triplicate, with data presented as mean ± SD.

Cyanobacterial isolation and identification

Soil and water samples were cultured on BG-11 medium under controlled conditions (28 ± 2 °C; 12:12 h light:dark photoperiod). Morphological identification was performed microscopically using the taxonomic keys of Desikachary (1959) and Komárek & Anagnostidis (1998, 2005). Only coccoid (non-filamentous) taxa were considered, characterized by colony form, pigmentation, and mucilage.

Diversity assessment

Cyanobacterial diversity was quantified using the Shannon-Wiener (H′) (Shannon and Weaver, 1949), Simpson (1-D) (Simpson, 1949), Pielou's evenness (J′) (Pielou, 1966), Berger-Parker dominance (D) (Berger and Parker, 1970), and species richness (S) indices. Alpha (α), beta (β), and gamma (γ) diversities were computed following Whittaker (1972). Inter-district similarity was evaluated using Jaccard's coefficient.

Statistical analysis

Significant differences among districts were tested using one-way ANOVA followed by Duncan's Multiple Range Test (DMRT) ($p < 0.05$). Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) (Ward's method, Euclidean distance) were applied to examine relationships between soil and biodiversity variables. The Cophenetic correlation coefficient (CPCC) was used to verify clustering accuracy. Analyses were conducted using SPSS v26.0 and OriginPro 2024.

RESULTS

Soil physicochemical properties

The physicochemical properties of the coastal paddy soils varied significantly among the three districts of Karnataka (Table 1). Soil pH ranged from 5.05 ± 0.13 to 5.26 ± 0.05, showing no significant difference ($p > 0.05$), indicating slightly acidic conditions across all regions. Electrical conductivity (EC) exhibited highly significant variation (F = 863.395, $p < 0.001$), with the highest value recorded in Uttara Kannada (0.61 ± 0.02 dS m^{-1}), followed by Dakshina Kannada (0.19 ± 0.01 dS m^{-1}), and the lowest in Udupi (0.15 ± 0.00 dS m^{-1}). Organic carbon (OC) also differed significantly (F = 31.241, $p < 0.01$), being highest in Dakshina Kannada (1.20 ± 0.04 %) and lowest in Udupi (0.97 ± 0.03 %). Similar trends were observed for nitrogen (N), which ranged from 302.53 ± 12.21 mg kg^{-1} (Udupi) to 354.91 ± 5.97 mg kg^{-1} (Dakshina Kannada), showing significant regional differences (F = 23.218, $p < 0.01$). Phosphorus (P) content showed no significant variation among the districts ($p > 0.05$). Potassium (K), however, exhibited strong spatial variability (F = 96.784, $p < 0.001$), with the highest mean value in Dakshina Kannada (241.55 ± 5.34 mg kg^{-1}). Overall, the nutrient profile followed the order Dakshina Kannada > Uttara Kannada > Udupi, reflecting the progressive enrichment of macronutrients toward the southern coastal zone.

Table 1: Mean ± SD, one-way ANOVA, and Duncan's Multiple Range Test results for soil parameters across the districts of Coastal Karnataka, India

Parameter	Region	Mean ± SD	F-value	*p*-value
pH	UK	5.13 ± 0.20^{a}	1.598	0.2778
	Udupi	5.26 ± 0.05^{a}	1.598	0.2778
	DK	5.05 ± 0.13^{a}	1.598	0.2778
EC	UK	0.61 ± 0.02^{d}	863.395	0.0000
	Udupi	0.15 ± 0.00^{a}	863.395	0.0000
	DK	0.19 ± 0.01^{b}	863.395	0.0000
OC	UK	1.08 ± 0.03^{b}	31.241	0.0007
	Udupi	0.97 ± 0.03^{a}	31.241	0.0007
	DK	1.20 ± 0.04^{d}	31.241	0.0007
N	UK	334.89 ± 9.27^{b}	23.218	0.0015
	Udupi	302.53 ± 12.21^{a}	23.218	0.0015
	DK	354.91 ± 5.97^{c}	23.218	0.0015
P	UK	14.33 ± 0.21^{a}	1.190	0.3671
	Udupi	14.70 ± 0.49^{a}	1.190	0.3671
	DK	14.12 ± 0.61^{a}	1.190	0.3671
K	UK	164.82 ± 6.68^{a}	96.784	0.0000
	Udupi	207.70 ± 8.02^{b}	96.784	0.0000
	DK	241.55 ± 5.34^{d}	96.784	0.0000

Values are Mean ± SD (n = 3). Different letters within a row indicate significant differences among districts at $p < 0.05$ (Duncan's test). F- and *p*-values derived from one-way ANOVA. UK = Uttara Kannada; Udupi = Udupi; DK = Dakshina Kannada.

Composition and distribution of cyanobacteria

Morphological identification revealed 46 species of coccoid (non-filamentous) cyanobacteria distributed among 20 genera belonging to the orders Chroococcales and Chroococcidiopsidales (Table 2). The dominant genera included *Aphanothece*, *Merismopedia*, *Gloeocapsa*, *Chroococcus*, and *Microcystis*, which were commonly encountered across the sites. A diverse array of coccoid cyanobacteria was documented throughout the coastal districts of Karnataka, revealing significant differences in their distribution and abundance. Species such as

Aphanothece nidulans, *Merismopedia glauca*, *Gloeocapsa punctata*, and *Chroococcus minutus* were prevalent and widely spread, found in various locations within Uttara Kannada, Udupi, and Dakshina Kannada. These taxa, along with other related genera within *Aphanothece*, *Merismopedia*, and *Chroococcus*, exhibited a wide ecological tolerance, flourishing under the varying nutrient and soil conditions present in the paddy ecosystems. At the genus level, *Aphanothece*, *Merismopedia*, and *Gloeocapsa* were consistently represented across all districts, indicating their adaptability to both moderately acidic and nutrient-rich soils. Conversely, genera such as *Johannesbaptistia*, *Myxosarcina*, and *Chlorogloea* displayed localized distributions, with *Johannesbaptistia* sp. and *Myxosarcina spectabilis* being limited to Dakshina Kannada. Their restricted presence and low abundance suggest a narrow ecological range and potential specialization to specific microhabitats that are characterized by higher organic carbon and nutrient levels. In summary, the observed distribution patterns imply that widespread taxa play a crucial role in maintaining the structural stability of cyanobacterial communities across the coastal paddy fields, while rare and localized species highlight the environmental variability within the region.

Table 2: The enumeration of cyanobacteria identified in the paddy fields of Coastal Karnataka*

Phylum	**Class**	**Sub-class**	**Order**	**Family**	**Genus**	**Species**
Cyanophyta	Cyanophyceae	Oscillatoriophycidae	Chroococcales	Chroococcaceae	*Chroococcus*	*C. macrococcus* (Kützing) Rabenhorst, 1863
						C. montanus var. *hyalinus* C.B.Rao, 1937
						C. minutus (Kützing) Nägeli, 1849
						C. turgidus (Kützing) Nägeli, 1849
						C. turgidus var. *maximus* Nygaard, 1926
					Cyanosarcina	*Cyanosarcina* sp.
					Entophysalis	*Entophysalis* sp.
						E. arboriformis Kaštovský, Fucíková, Hauer & Bohunická, 2011
						E. granulosa Kützing, 1843
						E. samoensis Wille, 1913
					Johanseninema	*J. constrictum* (Szafer) Hasler, Dvorák & Poulícková, 2014
				Cyanothrichaceae	*Johannesbaptistia*	*Johannesbaptistia* sp.
				Gomphosphaeriaceae	*Gomphosphaeria*	*G. aponina* Kützing, 1836
				Microcystaceae	*Aphanocapsa*	*Aphanocapsa* sp.
						A. benaresensis Bharadwaja, 1935
						A. grevillei (Berkeley) Rabenhorst, 1865

			A. montana C.E.Cramer, nom. inval., 1862
		Aphanothece	*A. clathrata* West & G.S.West, 1906
			A. microscopica (West) J.Komárková-Legnerová & G.Cronberg, 1994
			A. minutissima (West) J.Komárková-Legnerová & G.Cronberg, 1994
			A. nidulans P.Richter, 1884
			A. smithii Komárková-Legnerová & G.Cronberg, 1994
			A. saxicola Nägeli, 1849
			A. stagnina (Sprengel) A.Braun, 1863
		Asterocapsa	*A. divina* Komárek, 1993
		Eucapsis	*Eucapsis* sp.
			E. minor (Skuja) Elenkin, 1933
		Gloeothece	*G. fuscolutea* (Nägeli ex Kützing) Nägeli, 1849
		Merismopedia	*M. elegans* A.Braun ex Kützing, 1849
			M. glauca (Ehrenberg) Kützing, 1845
			M. glauca f. *mediterranea* (Nägeli) Collins, 1910
			M. marssonii Lemmermann, 1900
			M. minima G.Beck, 1897
			M. punctata Meyen, nom. illeg. 1839
		Microcystis	*M. pseudofilamentosa* Crow, 1923
			M. wesenbergii (Komárek) Komárek ex Komárek, 2006
		Synechocystis	*S. aquatilis* Sauvageau, 1892
		Woronichinia	*W. compacta* (Lemmermann) Komárek & Hindák, 1988
			W. delicatula (Skuja) Komárek & Hindák, 1988
			W. naegeliana (Unger) Elenkin, 1933
	Pleurocapsaceae	*Myxosarcina*	*M. burmensis* Skuja, 1949
			M. spectabilis Geitler, 1933
		Pleurocapsa	*Pleurocapsa* sp.
Chroococcidiopsidales	Gloeocapsaceae	*Chlorogloea*	*C. fritschii* A.K.Mitra, 1950
			C. microcystoides Geitler, 1925
			C. novacekii Komárek and Montejano, 1994
		Gloeocapsa	*Gloeocapsa* sp.
			G. atrata Kützing, nom. illeg., 1843
			G. kuetzingiana Nägeli ex Kützing, 1849
			G. punctata Nägeli, 1849
			G. rupestris Kützing, 1847
		Gloeocapsopsis	*Gloeocapsopsis* sp.

*The morphological identification of cyanobacteria is performed based on cell morphology. Here, these cyanobacteria are of the coccoid, colonial and non-filamentous types.

Biodiversity indices and similarity patterns

The diversity assessment (Table 3) showed that Uttara Kannada exhibited the highest alpha diversity (α = 31 species) and Shannon–Wiener index (H′ = 3.434), followed by Dakshina Kannada (α = 22, H′ = 3.091) and Udupi (α = 12, H′ = 2.485). Simpson's diversity index (1-D) ranged from 0.917 to 0.968, indicating a highly even species distribution across all districts (J′ = 1.000). The Berger–Parker dominance index (D) was lowest in Uttara Kannada (0.032), suggesting minimal dominance by a single species. The regional gamma diversity (γ = 46) and Whittaker's beta diversity (β = 1.12) highlighted moderate species turnover among districts. Jaccard's similarity coefficients indicated low species overlap, with the highest similarity between Dakshina Kannada and Uttara Kannada (J = 0.233), reflecting distinct yet overlapping community compositions.

Table 3: Overall biodiversity assessment of coccoid cyanobacteria across Coastal Karnataka

Parameter	Uttara Kannada	Udupi	Dakshina Kannada	Regional (γ/β)
No. of sampling sites	30	18	25	–
No. of genera	14	10	12	–
No. of species (α)	31	12	22	γ = 46
Shannon-Wiener diversity index (H′)	3.434	2.485	3.091	–
Simpson's diversity index (1-D)	0.968	0.917	0.955	–
Pielou's evenness (J′)	1.000	1.000	1.000	–
Berger-Parker dominance (D)	0.032	0.083	0.045	–
Species richness index (S)	2.21	1.20	1.83	–
Jaccard's similarity (Inter-district)	Uttara Kannada-Udupi = 0.132	Uttara Kannada-Dakshina Kannada = 0.233	Udupi-Dakshina Kannada = 0.214	β = 1.12

H′ - Shannon-Wiener diversity index; 1-D - Simpson's diversity index; α - Alpha diversity (local species richness); γ - Gamma diversity (regional species pool); β - Whittaker's beta diversity (species turnover among districts); J′ - Pielou's evenness index; D - Berger-Parker dominance index; S - Species richness index. Jaccard's similarity (J) values indicate the proportion of shared species between districts, with higher values signifying greater compositional similarity.

Principal Component and Cluster Analyses

Principal Component Analysis (PCA) (Table 4; Fig. 1) revealed that soil nutrients and biodiversity variables were strongly correlated. The first two components (PC1 and PC2) explained most of the total variance, with high negative loadings of EC, OC, nitrogen (N), and diversity indices (H′, 1-D, S), suggesting their joint influence on cyanobacterial richness. Potassium (K) and phosphorus (P) loaded positively on PC2, indicating their secondary contribution. Hierarchical Cluster Analysis (HCA) (Fig. 2) grouped Uttara Kannada and Udupi together, while Dakshina Kannada formed a separate cluster, corresponding to its higher nutrient status and diversity values. The cophenetic correlation coefficient (r = 0.856) indicated a good fit between the clustering pattern and the observed data structure.

Table 4: Component loadings and communalities of soil and diversity variables derived from Principal Component Analysis (PCA). Loadings represent the correlation between variables and the respective principal components

Properties	PC1	PC2	PC3	Communality
pH	1.069772	-0.59631	-5.07E-17	1.5
EC	-0.81098	-0.91778	-3.51E-16	1.5
OC	-0.95981	0.760767	1.14E-18	1.5
N	-1.06892	0.597833	-1.04E-16	1.5
P	1.082249	-0.57336	6.44E-17	1.5
K	0.230549	1.20285	-1.15E-16	1.5
Shannon-Wiener (H)	-1.18864	-0.29518	3.00E-17	1.5
Simpson-(1-D)	-1.21499	-0.15423	3.87E-17	1.5
Berger-Parker (D)	1.214995	0.154232	-2.70E-17	1.5
Species richness S	-1.18354	-0.315	5.33E-17	1.5
α species count	-1.14111	-0.44482	1.80E-16	1.5

Bold values (|r| ≥ 0.70) indicate strong loadings. Communality denotes the proportion of variance explained per variable. EC - electrical conductivity; OC - organic carbon; N - nitrogen; P - phosphorus; K - potassium; H′ - Shannon-Wiener index; 1-D - Simpson index; D - Berger-Parker dominance; S - species richness.

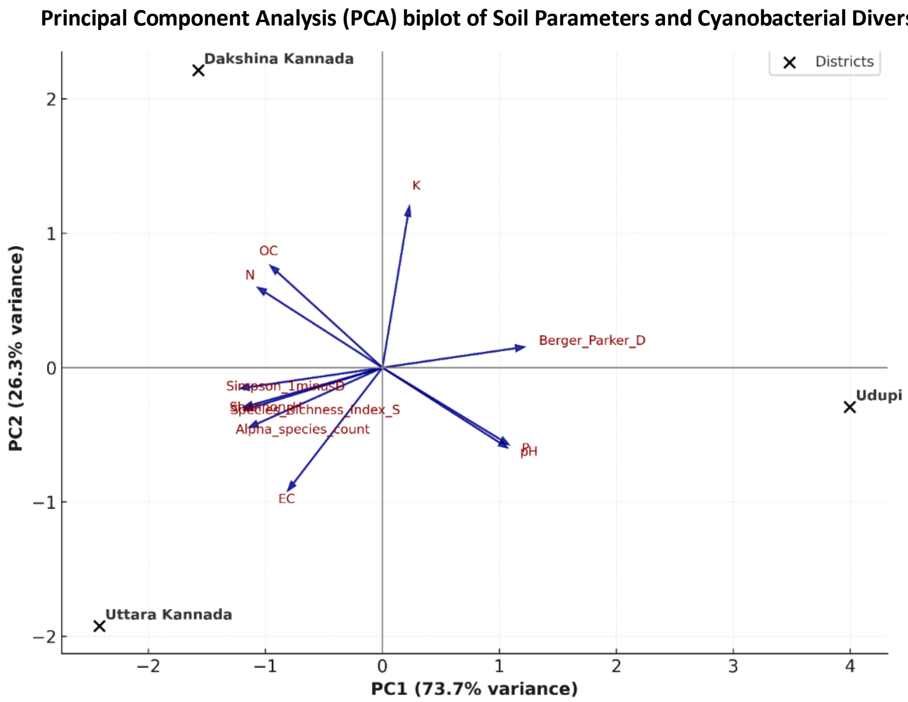

Figure 1: Principal Component Analysis (PCA) biplot showing the relationship between soil physicochemical parameters and cyanobacterial diversity indices across the coastal districts of Karnataka, India

Summary of trends

Overall, the results demonstrate that soil nutrient gradients, particularly pH, EC, OC, N, and K, play a major role in shaping the cyanobacterial diversity in the coastal paddy ecosystems of Karnataka. Dakshina Kannada's elevated nutrient content supports a more enriched and diverse cyanobacterial community, whereas Udupi's relatively nutrient-poor soils sustain lower diversity and richness.

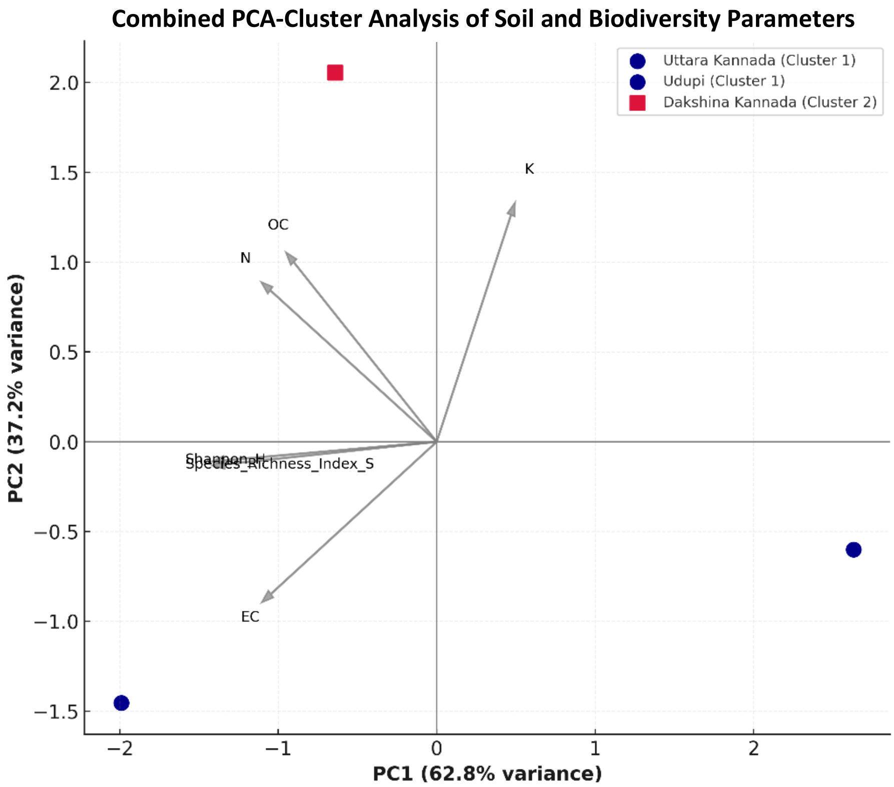

Figure 2: Combined Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) of soil physicochemical and biodiversity variables across the coastal districts of Karnataka

DISCUSSION

The spatial variation in cyanobacterial diversity across the paddy fields of Coastal Karnataka reflects strong edaphic control, particularly by soil nutrient status. The uniformly acidic pH (≈5.0-5.3) supports the proliferation of coccoid cyanobacteria typical of wetland environments (Brock, 1973). Significant differences in EC, OC, N, and K, especially the enrichment in Dakshina Kannada, correspond to higher diversity indices, suggesting that nutrient availability and organic matter enhance cyanobacterial abundance and community complexity (Hakkoum et al., 2021; Bhardwaj et al., 2025). A total of 46 coccoid species from 20 genera were recorded, with *Aphanothece*, *Chroococcus*, *Merismopedia*, and *Gloeocapsa* dominating across districts. The higher Shannon-Wiener and Simpson's indices in Uttara Kannada and Dakshina Kannada indicate stable, evenly distributed assemblages, while the lower values in Udupi reflect nutrient limitation. Low Jaccard's similarity (0.13-0.23) and moderate β-diversity (1.12) denote distinct but overlapping communities, driven by local soil and microclimatic conditions. Principal component and cluster analyses confirmed strong associations between diversity and soil variables (EC, OC, N, and K). Dakshina Kannada formed a distinct cluster, signifying its nutrient-rich and biologically diverse status. These results emphasize that soil fertility gradients are key determinants of cyanobacterial distribution and diversity in coastal rice ecosystems

(Saleem et al., 2025). The dominance of non-heterocystous and coccoid taxa further suggests their ecological role in nutrient cycling and soil fertility maintenance in submerged paddy environments (Dommergues and Diem, 1982).

CONCLUSION

This study highlights the rich cyanobacterial diversity in coastal paddy fields of Karnataka, India, with 46 species from 20 genera, predominantly under Chroococcales and Chroococcidiopsidales. Slightly acidic, nutrient-rich soils supported abundant coccoid and non-filamentous forms. Multivariate analyses identified organic carbon and available nitrogen as key drivers of species composition, while pH and salinity had secondary effects. The highest diversity in Uttara Kannada reflected favorable soil fertility and hydrological conditions. Overall, coastal paddy fields serve as important reservoirs of cyanobacterial diversity and potential biofertilizer resources for enhancing soil fertility and promoting sustainable rice cultivation.

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