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Journal of Threatened Taxa

Open Access

10.11609/jott.2026.18.8.29375-29558
www.threatenedtaxa.org

26 August 2026 (Online & Print)
18(8): 29375-29558
ISSN 0974-7907 (Online)
ISSN 0974-7893 (Print)

ISSN 0974-7907 (Online); ISSN 0974-7893 (Print)

Publisher
Wildlife Information Liaison Development Society
www.wild.zooreach.org

Host
Zoo Outreach Organization
www.zooreach.org

Srivari Illam, No. 61, Karthik Nagar, 10th Street, Saravanampatti, Coimbatore, Tamil Nadu 641035, India
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Cover: *Minervarya cepfi* & *Nyctibatrachus petraeus*—mix media. © P Kritika

Journal of Threatened Taxa | www.threatenedtaxa.org | 26 August 2026 | 18(8): 29459–29469

ISSN 0974-7907 (Online) | ISSN 0974-7893 (Print)

https://doi.org/10.11609/jott.10360.18.8.29459-29469

#10360 | Received 02 January 2026 | Final received 22 July 2026 | Finally accepted 04 August 2026

OPEN ACCESS

ARTICLE

Community structure and environmental determinants of amphibians in the Western Ghats watersheds of eastern Goa, India

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Abstract: We studied the amphibian diversity and the influence of abiotic factors across 12 watershed zones in the Western Ghats region of Goa, India. Surveys conducted at 102 sampling sites recorded 22 amphibian species, including eight Western Ghats endemics. Species richness and diversity were highest in watersheds with intermediate canopy cover and deeper leaf litter. Pearson correlation analysis identified leaf litter depth, humidity, and temperature as key factors influencing amphibian diversity. The findings highlight the importance of forest floor microhabitats and microclimatic conditions in shaping amphibian communities and emphasize the need to conserve structurally diverse forest habitats in the Western Ghats.

Keywords: Abiotic factors, alpha diversity, canopy cover, ecology, leaf litter depth, microclimate, species richness.

Editor: Anonymity requested.

Date of publication: 26 August 2026 (online & print)

Citation: Gawas, M.M., S.S. Sawal & N.S. Sawant (2026). Community structure and environmental determinants of amphibians in the Western Ghats watersheds of eastern Goa, India. *Journal of Threatened Taxa* 18(8): 29459–29469. https://doi.org/10.11609/jott.10360.18.8.29459-29469

Funding: None.

Competing interests: The authors declare no competing interests.

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Author contributions: MG—field data collection, data analysis, manuscript preparation and writing. SS—field data collection. NSS—conceptualization of the research, research methodology and study design, manuscript preparation, review, proofreading and supervision.

Acknowledgements: We sincerely thank the Goa Forest Department for granting necessary permissions, Honourable MLA Smt. Deviya Rane for support in facilitating permissions, and our fellow colleagues for their valuable assistance during fieldwork.

INTRODUCTION

The Western Ghats is recognised as one of the world's 34 biodiversity hotspots and supports high amphibian diversity and endemism (Myers et al. 2000). Goa forms part of the Goa Gap, a bioclimatic and vegetational transition zone within the Western Ghats (Pascal 1988; Qureshi 1965; Barboni et al. 2003; Reddy et al. 2016; Ramachandran et al. 2017; Biswas & Karanth 2021; Chaitanya & Meiri 2022). Despite the rich amphibian diversity of the Western Ghats, Goa remained comparatively understudied for many decades because the state was under Portuguese rule during the period when extensive faunal surveys were being conducted in British India (Kulkarni et al. 2013).

The earliest published accounts of amphibians from Goa were provided by Abdulali & Sekar (1988), followed by studies by Sekar (1991, 1992), Das & Whitaker (1997, 1998), Bhat & Desai (1998), and Sarkar & Ray (2004). Kamble (2008) carried out one of the last detailed taxonomic studies on Goan amphibians. Later, Kulkarni et al. (2013) reported 36 species from Goa, while Dinesh et al. (2015) updated the checklist and reported 34 species from the state. Although these studies contributed significantly to the knowledge of amphibians in Goa, information regarding amphibian community structure, spatial distribution, and the influence of abiotic factors on amphibian assemblages remains limited.

Understanding amphibian diversity, habitat associations, and community structure is therefore essential for developing effective conservation strategies (Sawant & Jadhav 2013; Bowalkar & Sawant, in press). Therefore, the present study was conducted to document amphibian species from the forests in the study area, examine their community structure, and assess the influence of selected abiotic factors on their communities.

METHODS

The study was carried out in the Western Ghat region of Goa covering Mhadei Wildlife Sanctuary, Bhagwan Mahavir Wildlife Sanctuary, Mollem National Park, Netravali Wildlife Sanctuary, Cotigao Wildlife Sanctuary, and parts outside these sanctuaries amounting to a total geographical area of 1335.95 km^2 (Image 1). The surveys were conducted across watersheds associated with Valvanti river (W1), Kotrachi nadi (W2), Madhei river – Satrem tributary (W3), Madhei river (Main) (W4), Ragada river (W5), Dudhsagar river (W6), Uguem river (W7), Netravali river (W8), Kushawati river (W9), Agonda river (W10), Talpona river (W11), and Kali river tributary (W12) (Table 1). The study was carried out during the monsoon season from June–September in dense forested areas, defined as regions having tree canopy cover greater than 40% (Forest Survey of India 2023). The entire study area is divided into 12 watershed zones (W1–W12) using QGIS software and SRTM data from U.S. Department of the Interior (Image 2). Each watershed zone was further subdivided into three elevational zone low (0–200 m), mid (200–400 m), and high (above 400 m) and sampling was conducted uniformly in each of the elevational zone to minimize sampling bias. In total, 102 sampling sites were established (three sites per elevation in each watershed) (Image 1, table 1). At each site, three replicate line transects (30 × 20 m; 10 m on either side) were laid. Amphibians were surveyed using standardized visual and acoustic encounter surveys for 30 minutes per observer, covering all available microhabitats (Crump 1994; Rödel & Ernst 2004). Surveys were conducted at night between 2000 h and 0300 h, coinciding with peak amphibian activity.

Along with species data, environmental, climatic, and habitat-related variables were collected to understand the relationship between amphibian communities and environmental factors. Seven key abiotic variables were recorded: tree cover (%) using a densitometer, leaf litter temperature (^{0}C) using an infrared thermometer, leaf litter depth (cm) using a scale, leaf litter ratio by counting number of leaves, twigs and fruits in 1 m^2, understory vegetation (count in 5 m^2), ambient temperature (^{0}C) using a thermometer, and relative humidity (%) using a hygrometer.

RESULTS

A total of 22 amphibian species were recorded from the study area. Of these, two species are classified as 'Endangered', two as 'Vulnerable', one as 'Near Threatened', one as 'Data Deficient', and 16 species as 'Least Concern' according to the IUCN Red List of Threatened Species. Eight of the recorded species are endemic to the Western Ghats of India, highlighting the region's unique and irreplaceable biodiversity (Image 2; Table 2).

Alpha diversity

Species richness ranged from 9–19 species, with least species in W12 (9 species) and highest species in W3 (19 species) (Image 3A; Table 3). The Shannon diversity

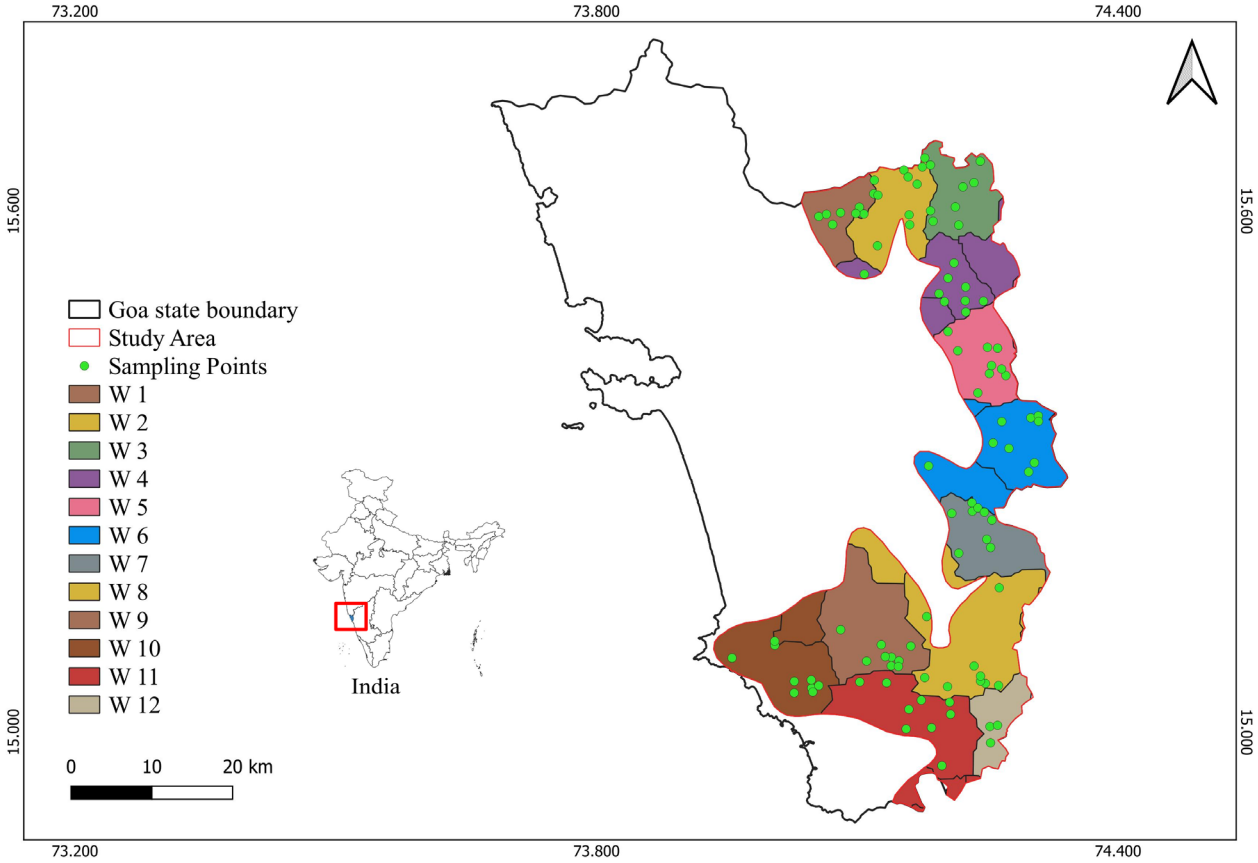


Image 1. Watershed zones (W1–W12) and sampling sites in the study area.

Table 1. Details of sampling sites, elevation categories, associated watersheds, and hill ranges surveyed in the Western Ghats region of Goa.

Watershed code	Site names			Watershed/river basin	Hill range
	Low elevation (0–200 m)	Mid elevation (200–400 m)	High elevation (above 400 m)		
W1	1_A1, 1_A2, 1_A3	1_B1, 1_B2, 1_B3	1_C1, 1_C2, 1_C3	Valvanti river basin	Morlegad and vagheri hill range
W2	2_A1, 2_A2, 2_A3	2_B1, 2_B2, 2_B3	2_C1, 2_C2, 2_C3	Kotrachi Nadi river basin	Chorla ghat range
W3	3_A1, 3_A2, 3_A3	3_B1, 3_B2, 3_B3	3_C1, 3_C2, 3_C3	Madhei river – Satrem tributary basin	Surla ghat range
W4	4_A1, 4_A2, 4_A3	4_B1, 4_B2, 4_B3	4_C1, 4_C2, 4_C3	Madhei river basin	Sosogad hill range
W5	5_A1, 5_A2, 5_A3	5_B1, 5_B2, 5_B3	5_C1, 5_C2, 5_C3	Ragada river basin	Anmod ghat range
W6	6_A1, 6_A2, 6_A3	6_B1, 6_B2, 6_B3	6_C1, 6_C2, 6_C3	Dudhsagar river basin	Dudhsagar-Kuveshi hill range
W7	7_A1, 7_A2, 7_A3	7_B1, 7_B2, 7_B3	7_C1, 7_C2, 7_C3	Uguem river basin	Dhargini-Patiem hill range
W8	8_A1, 8_A2, 8_A3	8_B1, 8_B2, 8_B3	8_C1, 8_C2, 8_C3	Netravali river basin	Netravali-Ravon dongor Hill range
W9	9_A1, 9_A2, 9_A3	9_B1, 9_B2, 9_B3	9_C1, 9_C2, 9_C3	Kushawati river basin	Corla hill range
W10	10_A1, 10_A2, 10_A3	10_B1, 10_B2, 10_B3	10_C1, 10_C2, 10_C3	Agonda river basin	Karmal ghat range
W11	11_A1, 11_A2, 11_A3	11_B1, 11_B2, 11_B3	11_C1, 11_C2, 11_C3	Talpona river basin	Cotigao-Ravon dongor hill range
W12	Nil	Nil	12_C1, 12_C2, 12_C3	Kali river tributary basin	Netravali-Ravon dongor Hill range

index (H') was highest at W1 1 (2.35) and lowest at W12 (1.82), with elevated H' values at Sites 1 and 11 indicating a diverse and well-distributed amphibian community in these watersheds (Image 3B; Table 3). Simpson Index (1−D) ranged from 0.79 in W12 to 0.89 in W11, watersheds such as W5 and W11 which exhibited high

Table 2. Table showing presence (1) absence (0) of species across watersheds, * Endemic to Western Ghats of India.

	Species	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12
1	*Duttaphrynus melanostictus*	1	1	1	1	1	1	1	1	1	1	1	0
2	*Pedostibes tuberculosus**	0	0	1	1	0	1	0	0	1	0	0	0
3	*Euphlyctis cyanophlyctis*	0	0	1	1	0	1	1	1	1	1	1	1
4	*Minervarya gomantaki*	1	1	1	1	1	1	1	1	1	1	1	0
5	*Minervarya goemchi*	0	1	1	0	0	0	0	0	0	0	0	1
6	*Minervarya cepfi*	1	1	1	1	1	1	0	1	1	1	1	1
7	*Hoplobatrachus crassus*	1	1	1	1	0	1	1	1	1	1	1	1
8	*Sphaerotheca maskeyi*	1	1	1	1	1	1	1	1	1	1	1	1
9	*Microhyla ornata*	1	0	1	0	1	0	0	1	0	1	1	0
10	*Uperodon globulosus*	1	0	0	0	0	0	0	0	0	0	0	0
11	*Uperodon mormorata*	1	1	1	1	1	1	1	1	0	1	1	0
12	*Nyctibatrachus petraeus**	1	0	1	0	1	0	1	1	1	0	1	1
13	*Clinotarsus curtipes**	0	0	1	0	0	0	0	0	0	0	0	0
14	*Hydrophylax bahuvistara*	0	1	1	0	0	0	0	1	0	1	1	0
15	*Indosylvirana caesari**	1	0	1	0	0	0	1	0	0	0	0	0
16	*Indirana salelkari**	1	1	1	0	1	0	1	1	1	1	1	1
17	*Polypedates maculatus*	1	1	1	1	1	1	1	1	1	1	1	0
18	*Pseudophilautus amboli**	1	1	1	1	1	1	1	1	1	1	1	1
19	*Raorchestes bombayensis**	1	1	1	1	1	1	1	1	1	1	1	1
20	*Rhacophorus malabaricus**	1	1	1	0	1	0	1	0	1	0	1	0
21	*Ichthyophis davidi*	0	0	0	0	0	1	0	0	0	0	0	0
22	*Ichthyophis bombayensis*	0	0	0	0	0	0	0	0	1	0	0	0

Simpson values, indicates low dominance and higher probability of encountering different species (Image 3C; Table 3). Evenness (J') was highest at W5 (0.92), showing a balanced species distribution, while W3 (0.74) had lower evenness despite high richness possible due to dominance by few species (Image 3D; Table 3).

Environmental Variation

Tree cover: Tree canopy cover was generally high across all watersheds, ranging from 71.11% SE = 6.33 at W10 to 100% at W5 and W12. Watersheds in the northern and central regions (W1–W7) consistently exhibited dense canopy cover (>90%), whereas southern watersheds showed variable tree canopy cover between 71% in W10 to 100% in W12, indicating canopy openness or disturbance in south (Image 4A; Table 4).

Leaf Litter Temperature: This was relatively stable across the sites, ranging from 22.70 ^{0}C SE = 0.65 in W8 to 24.76 ^{0}C SE = 0.19 (W11) (Image 4B; Table 4).

Leaf litter depth: It varied across the gradients, with W3 recording the highest mean depth (3.50 cm SE = 0.54), followed by W2 (3.22 cm SE = 0.67), and W9 (3.11 cm SE = 0.46) (Image 4C; Table 4).

Leaf Litter Ratio: ratio remained consistent across watersheds, generally ranging between 0.73 and 0.80, except in W10 (0.67 SE = 0.05), which had the lowest value. Most northern and central watersheds had a ratio of 0.76–0.80, indicating high-quality litter habitats (Image 4D; Table 4).

Understory Vegetation: This showed high spatial variability. The densest vegetation was observed in W6 (173.33 SE = 12.69), and W3 (160 SE = 17.16), while W10 had the sparsest understory (82.78 SE = 14.89). Northern watersheds such as W1–W6 also had moderate to dense understory with an average of 140.04, contributing to microhabitat complexity (Image 4E; Table 4).

Ambient Temperature: This varied significantly along the gradient. The coolest site was W8 (23.53 ^{0}C, SE = 0.49), while the warmest was W7 (28.90 ^{0}C, SE = 1.08), and W10 (28.14 ^{0}C, SE = 0.30). Southern watersheds, particularly W7–W12, exhibited higher temperatures compared to northern ones (Image 4F; Table 4).

Humidity: This was generally high across the watersheds. W4 and W9 recorded the highest mean humidity (92.33% SE = 1.48 and 91.11% SE = 1.44) while W7 recorded the lowest (74.56% SE = 5.40) (Image 4G;

Image 2. Amphibians recorded in the study area. A—*Duttaphrynus melanostictus* | B—*Pedostibes tuberculosus* | C—*Euphlyctis cyanophlyctis* | D—*Minervarya gomantaki* | E—*Minervarya goemchi* | F—*Minervarya cepfi* | G—*Hoplobatrachus crassus* | H—*Sphaerotheca maskeyi* | I—*Microhyla ornata* | J—*Uperodon globulosus* | K—*Uperodon mormorata* | L—*Nyctibatrachus petraeus* | M—*Clinotarsus curtipes* | N—*Hydrophylax bahuvistara* | O—*Indosylvirana caesari*. © Mayur Gawas.

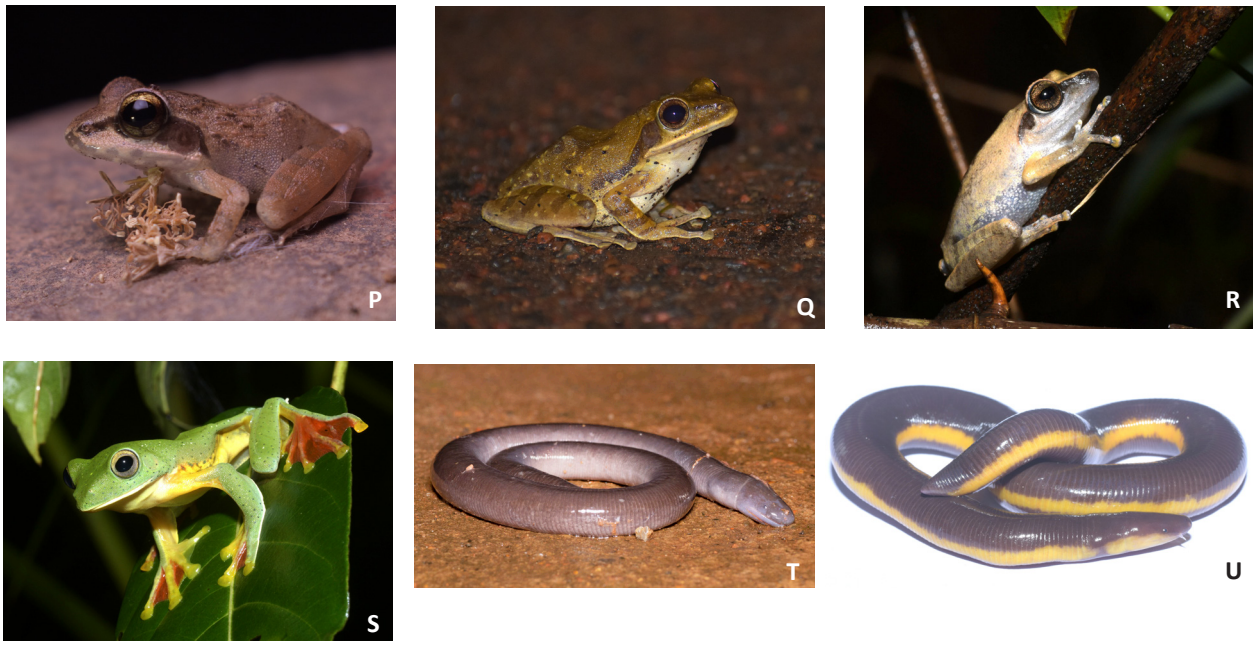


Image 2 continued. Amphibians recorded in the study area. P—*Indirana salelkari* | Q—*Polypedates maculatus* | R—*Pseudophilautus amboli* | S—*Rhacophorus malabaricus* | T—*Ichthyophis bombayensis* | U—*Ichthyophis davidi.* © Mayur Gawas.

Table 3. Table showing alpha diversity indices across watersheds.

Site	Richness	Shannon	Simpson	Evenness
W1	15	2.35	0.88	0.87
W2	13	2.10	0.85	0.82
W3	19	2.19	0.85	0.74
W4	11	1.92	0.81	0.80
W5	12	2.28	0.88	0.92
W6	12	1.98	0.81	0.80
W7	13	2.07	0.85	0.81
W8	14	2.32	0.88	0.88
W9	14	2.17	0.86	0.82
W10	13	2.09	0.85	0.81
W11	15	2.32	0.89	0.86
W12	9	1.82	0.79	0.83

Table 4).

Overall, southern watersheds were characterized by higher ambient temperatures, variable humidity, and relatively sparse vegetation, whereas northern and central watersheds exhibited denser canopy cover, cooler microclimates, and deeper litter layers. These environmental gradients likely influence the observed patterns in amphibian community composition and beta diversity.

Pearson correlation

Pearson correlation analysis revealed leaf litter depth as the strongest driver of amphibian alpha diversity across 12 Western Ghats watersheds (Image 5). Species richness was strongly positively correlated with leaf litter depth (r = 0.65) and humidity (r = 0.37), but negatively with temperature (r = -0.35) and tree cover (r = -0.27). Shannon and Simpson indices were highly intercorrelated (r = 0.97) and moderately tied to richness (r = 0.67, 0.57), with weak negative links to temperature and understory vegetation. Pielou's evenness showed a strong negative correlation with leaf litter depth (r = -0.47), indicating dominance in deeper litter, and weak positive ties to tree cover (r = 0.21) and leaf litter ratio (r = 0.21). Environmental variables were tightly linked: tree cover & leaf litter ratio (r = 0.82), understory & leaf litter ratio (r = 0.63), and temperature & humidity (r = -0.54). Overall, leaf litter depth, humidity, and temperature were the primary predictors, with depth exerting opposing effects on richness (+ve) and pielou's evenness (-ve).

Intermediate canopy cover (80–95 %) and deeper leaf litter emerge as key drivers of amphibian alpha diversity across Western Ghats watersheds, with peak richness occurring where microclimatic conditions optimize the litter–forest floor interface. While full canopy closure maintains evenness through generalist dominance, it reduces habitat suitability via litter compression and

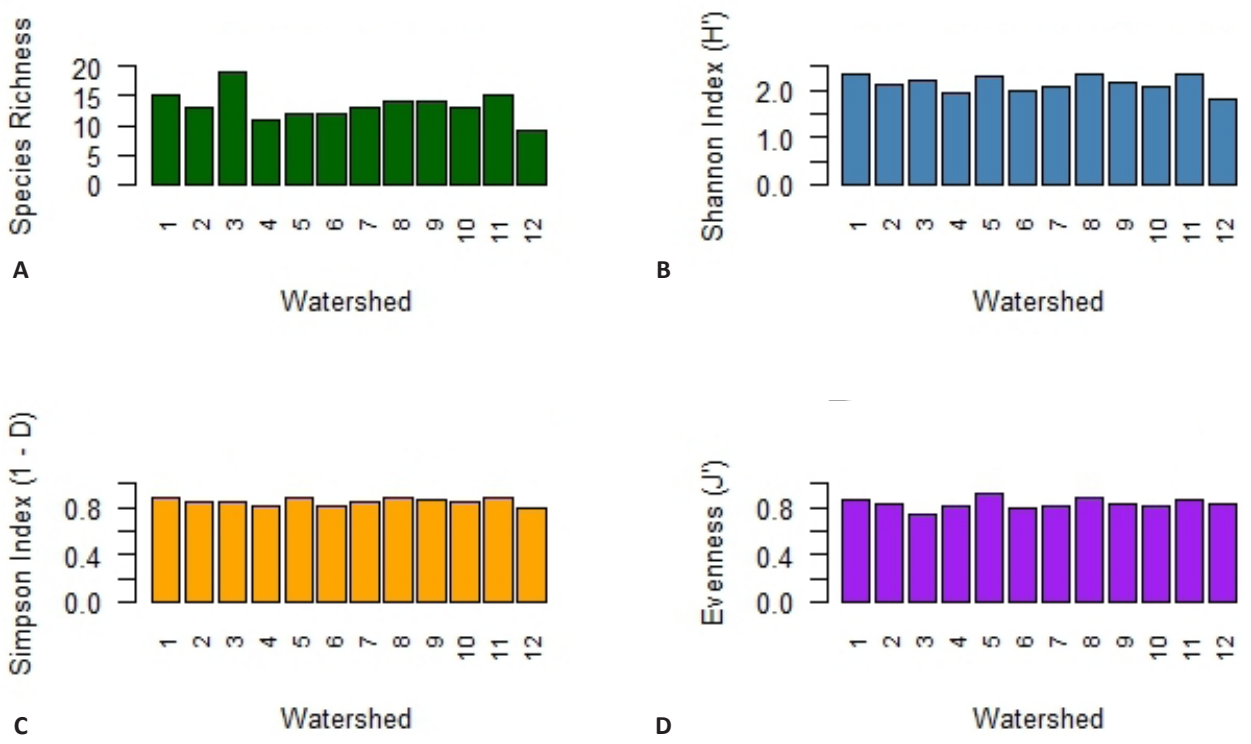


Image 3. Alpha diversity indices: A—Species richness | B—Shanon diversity index | C—Simpson diversity index | D—Pielou's evenness.

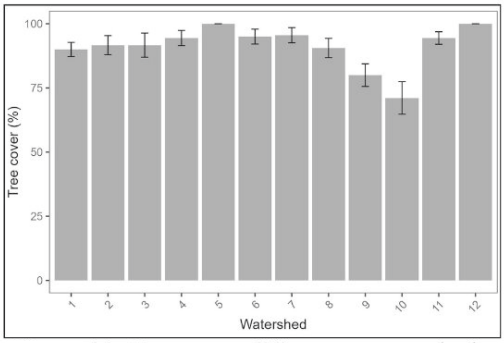
thermal stress. These findings highlight the value of mid-successional forest patches for conserving anuran biodiversity amidst ongoing habitat alteration in this global biodiversity hotspot. To safeguard anuran biodiversity amid escalating climate change and habitat fragmentation, conservation priorities must emphasize preserving undisturbed leaf litter layers and intermediate vegetation structure in tropical montane streams, ensuring both species coexistence and long-term community stability.

DISCUSSION

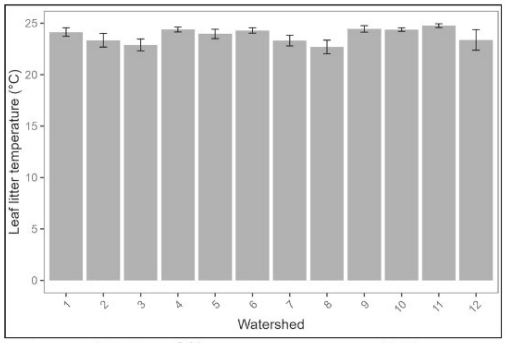
Amphibian alpha diversity across the 12 Western Ghats watersheds exhibited moderate variation, with species richness ranging from 9 (W12) to 19 (W3) and Shannon diversity from 1.82 (W12) to 2.35 (W1). Highest richness and Shannon values occurred in watersheds with intermediate canopy cover (80–95 %) and deeper leaf litter (W1, W9, W3, W8, W11), consistent with studies showing that canopy closure and litter depth are key predictors of anuran diversity in Western Ghats forests (Katwate et al. 2013) and that amphibian richness tends to decline under very dense canopy in forested wetlands (Skelly et al. 2005).

In contrast, full-canopy, shallow-litter sites (W5, W12) supported lower richness despite occasionally high Pielou's evenness (W5 = 0.92), a pattern similar to sites with low richness but evenly distributed abundances reported from Phansad Wildlife Sanctuary (Katwate et al. 2013). Simpson diversity remained consistently high across watersheds (0.79–0.89), indicating low dominance and relatively even assemblages; this is in line with work showing that elevated local alpha diversity and evenness can persist across habitat conditions while masking underlying shifts in species composition and regional diversity (Dehling & Dehling 2023). Together, these results suggest that fine-scale variation in canopy structure and forest-floor litter depth modulates local richness within broadly forested catchments, whereas community evenness remains high, as expected for assemblages dominated by a mix of habitat generalists and a smaller set of specialists.

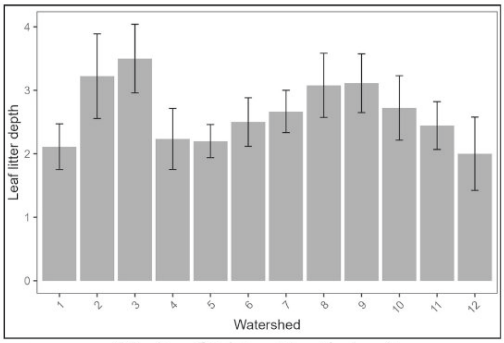
Pearson correlation analysis confirmed leaf litter depth as the strongest predictor, positively driving richness (r = 0.65) but reducing evenness (r = −0.47), indicating that greater forest-floor microhabitat complexity promotes species accumulation while fostering dominance by leaf-litter specialists (Scott 1976; Kouamé et al. 2018).



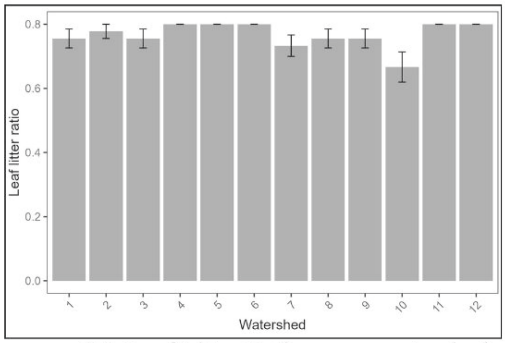
4A: Tree cover (%) across watersheds



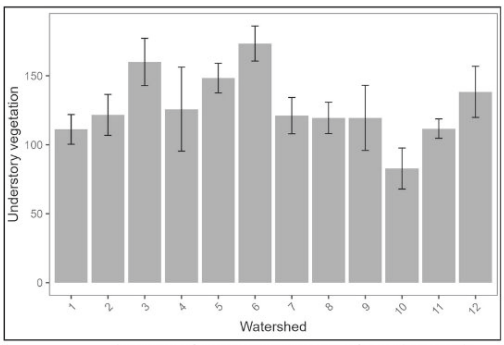
4B: Leaf litter temperature (°C) across watersheds



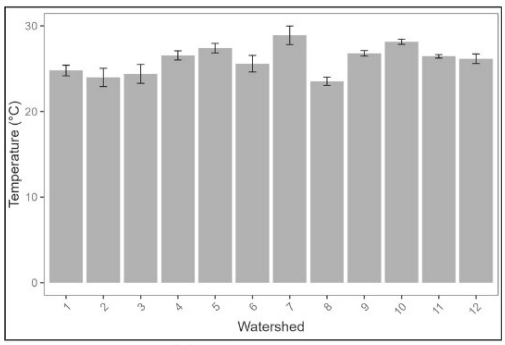
4C: Leaf Litter Depth (cm) across watersheds



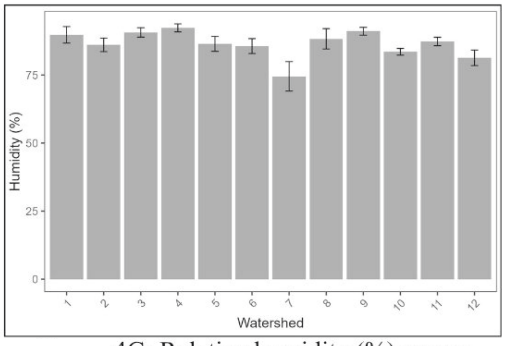
4D: Leaf Litter Ratio across watersheds



4E: Understory Vegetation (count) across watersheds



4F: Ambient Temperature (°C) across watersheds



4G: Relative humidity (%) across watersheds

Image 4. Environmental variables across watersheds.

Table 4. Environmental variables across watersheds.

watershed	Tree Cover			Leaf Litter Temperature			Leaf Litter Depth			Leaf Litter Ratio			Understory Vegetation			Temperature			Humidity		
	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE
1	90	8.29	2.76	24.14	1.25	0.42	2.11	1.08	0.36	0.76	0.09	0.03	111.11	32.29	10.76	24.79	1.85	0.62	89.78	9.11	3.04
2	91.67	11.18	3.73	23.35	1.98	0.66	3.22	2.00	0.67	0.78	0.07	0.02	121.67	44.51	14.84	23.98	3.20	1.07	86.11	7.49	2.50
3	91.67	14.14	4.71	22.89	1.72	0.57	3.50	1.62	0.54	0.76	0.09	0.03	160.00	51.48	17.16	24.40	3.29	1.10	90.67	5.17	1.72
4	94.44	8.82	2.94	24.39	0.73	0.24	2.23	1.45	0.48	0.80	0.00	0.00	125.78	91.36	30.45	26.56	1.61	0.54	92.33	4.44	1.48
5	100	0.00	0.00	23.96	1.36	0.45	2.20	0.78	0.26	0.80	0.00	0.00	148.33	32.21	10.74	27.40	1.69	0.56	86.44	8.22	2.74
6	95	8.66	2.89	24.29	0.79	0.26	2.50	1.15	0.38	0.80	0.00	0.00	173.33	38.08	12.69	25.59	2.89	0.96	85.67	8.19	2.73
7	95.56	8.82	2.94	23.31	1.57	0.52	2.67	1.00	0.33	0.73	0.10	0.03	121.11	39.43	13.14	28.90	3.25	1.08	74.56	16.19	5.40
8	90.56	11.30	3.77	22.70	1.96	0.65	3.08	1.52	0.51	0.76	0.09	0.03	119.44	33.95	11.32	23.53	1.46	0.49	88.33	11.24	3.75
9	80	13.23	4.41	24.45	0.95	0.32	3.11	1.39	0.46	0.76	0.09	0.03	119.44	70.73	23.58	26.80	0.96	0.32	91.11	4.31	1.44
10	71.11	19.00	6.33	24.38	0.50	0.17	2.72	1.52	0.51	0.67	0.14	0.05	82.78	44.66	14.89	28.14	0.90	0.30	83.56	3.68	1.23
11	94.44	7.26	2.42	24.76	0.57	0.19	2.44	1.13	0.38	0.80	0.00	0.00	111.67	21.07	7.02	26.44	0.61	0.20	87.33	4.66	1.55
12	100	0.00	0.00	23.38	1.74	1.00	2.00	1.00	0.58	0.80	0.00	0.00	138.33	32.15	18.56	26.17	0.96	0.55	81.33	4.93	2.85

Humidity positively influenced richness and Shannon indices (r = 0.37, 0.32), and temperature showed negative associations (r = −0.35, −0.26), consistent with amphibians' reliance on cool, moist microclimates, and narrow physiological tolerances to desiccation and heat (Wells 2007). The strong inverse relationship between temperature and humidity (r = −0.54) therefore highlights a key microclimatic trade-off, where drier, warmer conditions are likely to restrict activity and occupancy of many forest-floor anurans despite otherwise suitable structural habitat (Wells 2007).

Environmental variables show some distinct patterns. Tree cover ranged from 71.11% (W10) to 100% (W5, W12), with leaf litter depth peaking (3.0–3.5 cm) under moderate canopy and declining under dense closure (~2.2 cm) due to compression and reduced litterfall (Wells 2007; Cardelús 2010). Understory vegetation was densest in closed-canopy sites (W6, W5, W12), potentially impeding amphibian movement or prey access as reported from Western Ghats forests. Ambient temperature was elevated (>27 ^{0}C) in high-canopy watersheds, likely from reduced ventilation and heat trapping (Spranger et al. 2024), while humidity dipped lowest in W7 and W5, coinciding with moderate canopy and high thermal stress (Wells 2007; Seshadri 2014).

Despite structural roles in habitat provision, tree cover, and understory vegetation showed weak or negative correlations with amphibian diversity metrics, as dense canopies suppressed leaf litter depth (r = -0.40) and elevated temperature, indirectly constraining occupancy. This pattern supports tropical studies documenting peak anuran diversity in mid-successional habitats rather than closed-canopy forests, where intermediate structural complexity optimizes microclimate, litter accumulation, and foraging opportunities (Skelly et al. 2005; Wells, 2007). The near-perfect correlation between Shannon and Simpson indices (r = 0.97) across watersheds confirms their redundancy for characterizing these assemblages, with Pielou's evenness contributing only modestly to overall diversity variation (Magurran 2003). These integrated findings demonstrate that intermediate canopy cover optimizes the litter–microclimate interface, maximizing species richness and functional stability (Skelly et al. 2005). Full canopy closure, while enhancing evenness in some cases, reduces habitat suitability through litter compression and thermal elevation (Wells 2007; Rödel & Ernst 2004).

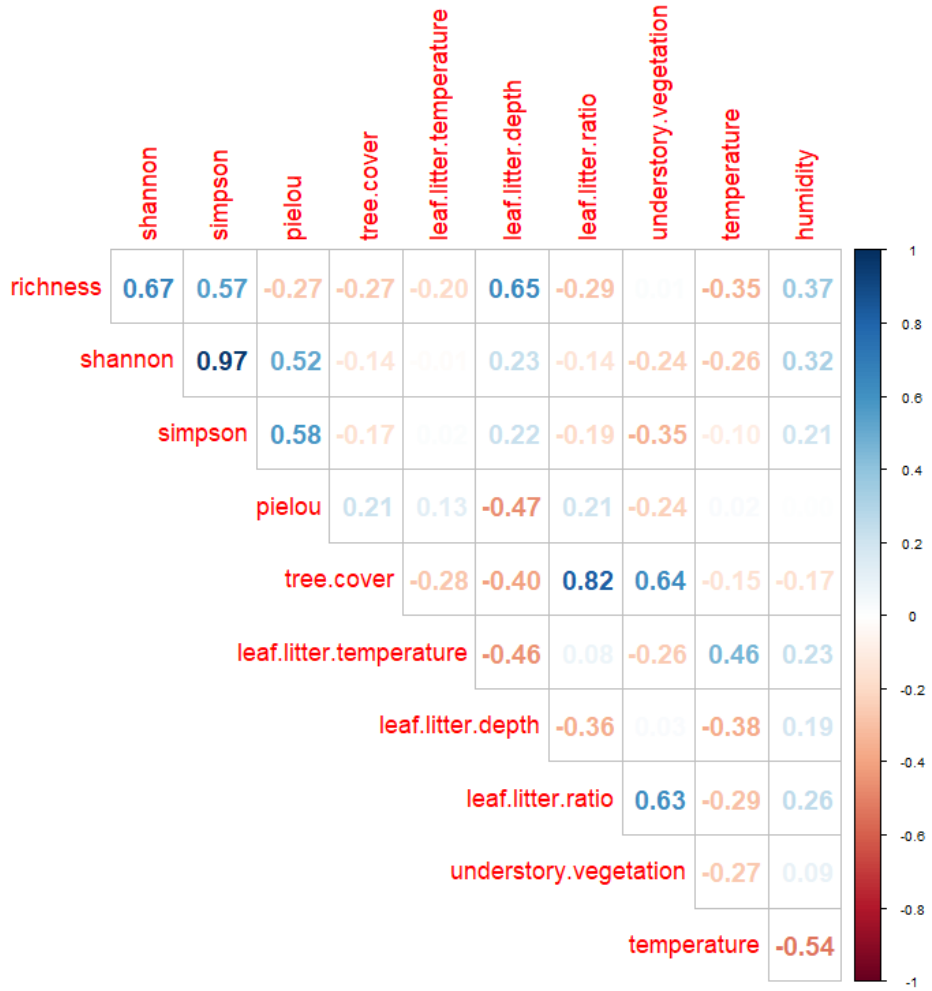


Image 5. Correlation matrix of alpha diversity and environmental variables.

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Journal of Threatened Taxa is indexed/abstracted in Bibliography of Systematic Mycology, Biological Abstracts, BIOSIS Previews, CAB Abstracts, EBSCO, Google Scholar, Index Copernicus, Index Fungorum, JournalSeek, National Academy of Agricultural Sciences, NewJour, OCLC WorldCat, SCOPUS, Stanford University Libraries, Virtual Library of Biology, Zoological Records.

NAAS rating (India) 5.64

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Journal of Threatened Taxa

www.threatenedtaxa.org

ISSN 0974-7907 (Online) | ISSN 0974-7893 (Print)

August 2026 | Vol. 18 | No. 8 | Pages: 29375–29558
Date of Publication: 26 August 2026 (Online & Print)
DOI: 10.11609/jott.2026.18.8.29375-29558

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