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# Distribution patterns and conservation status of anurans in Kanga forest reserve, Eastern Arc Mountains, Tanzania

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**Abstract**

Understanding the ecological drivers of anuran assemblages is essential for biodiversity conservation in tropical montane ecosystems. This study assessed anuran diversity, distribution patterns, conservation status, and environmental determinants of species in Kanga Forest Reserve (KFR), an important component of the Eastern Arc Mountain Forests of Tanzania. Standardized surveys were conducted across four elevational categories and major habitat types to evaluate how habitat structure and environmental conditions influence anuran communities. A total of 455 individuals representing 22 species, 12 genera, and seven families were recorded. Species abundances were highest in lowland and sub-montane forests, whereas farmland and montane forests had fewer individuals. Similarly, diversity was highest in lowlands ($H'$ = 2.45) and lowest in farmland ($H'$ = 1.80), indicating anthropogenic impacts. Forest-restricted taxa, including *Callulina kanga* and *Probreviceps* cf. *durirostris*, were largely confined to structurally intact forest habitats, whereas species such as *Chiromantis rufescens* and *Ptychadena anchietae* exhibited broader ecological tolerances. Integrated analyses revealed that anuran distributions were influenced primarily by hydrological conditions and forest structural complexity. Water bodies, canopy cover, tree density, leaf litter, and mature trees emerged as the strongest predictor of species occurrence, closely associated with species persistence and community composition. The results therefore demonstrate that habitat complexity and moisture availability function as key ecological filters shaping community assembly within KFR. Conservation assessment revealed species spanning multiple IUCN Red List categories, including Critically Endangered, Endangered, Vulnerable, and Near Threatened taxa, highlighting the reserve's importance as a refuge for threatened anurans. This study provides a robust baseline for long-term monitoring and delivers testable ecological evidence to guide conservation planning, habitat restoration, and adaptive management within KFR and the broader Eastern Arc Mountain ecosystem.

**Key words**: abundance, amphibians, biodiversity, Eastern Arc Mountains, elevation gradient, environmental variables, Tanzania.
**Abbreviations:** EAMFs, Eastern Arc Mountain Forests; FL, farmland; KFR, Kanga Forest Reserve; LL, lowland; M, montane; SM, sub-montane.

## Introduction

Amphibians are currently recognized as the most threatened vertebrate group globally, making their conservation a major priority in biodiversity science and management (IUCN 2021; Bernabo et al. 2022; Kaur, Singh 2025). Approximately 41% of amphibian species are threatened with extinction, and Red List assessments continue to indicate a worsening conservation status for many taxa worldwide (IUCN 2021; Nneji et al. 2021; IUCN 2022; Tonelli 2023; Rodríguez et al. 2024). Population declines are driven by multiple interacting pressures, including habitat loss and fragmentation, agricultural intensification, pollution, invasive species, emerging infectious diseases, and climate change (Bernabo et al. 2022; Tonelli 2023; Rodríguez et al. 2024; Bassetto et al. 2024; Musubaho et al. 2024; Lyakurwa et al. 2025). Climate-induced shifts in habitat suitability and phenology have further intensified these threats across both tropical and temperate ecosystems (Nneji et al. 2021; Bernabo et al. 2022). Additional anthropogenic pressures such as illegal logging, charcoal production, fuelwood extraction, pole cutting, bushfires, and wildlife collection continue to degrade habitats critical for amphibian persistence (Mkonyi 2021).

The exceptional vulnerability of amphibians to environmental change is linked to their unique biological characteristics, including highly permeable skin, biphasic life cycles involving aquatic and terrestrial environments, limited dispersal capacity, and generally low vagility (Bernabo et al. 2022; Tonelli 2023; Rodríguez et al. 2024).

Consequently, amphibians are widely regarded as sensitive indicators of ecosystem integrity and environmental change, with population declines reported across diverse habitats (Li et al. 2025).

Within Africa, the Eastern Arc Mountain Forests (EAMFs) of Tanzania and Kenya represent one of the world's most important biodiversity hotspots, renowned for exceptional levels of endemism and evolutionary distinctiveness (Gereau et al. 2016; Bayliss et al. 2024; Lyakurwa et al. 2025). The mountain chain comprises a series of isolated forest blocks, including the Ukaguru, East and West Usambara, Uluguru, North Pare, South Nguru, Udzungwa, West Kilombero Scarp, Kindoroko, Minja, and Kanga Forest Reserve, extending across steep elevational gradients from approximately 500 to over 2000 m above sea level (Menegon et al. 2004; Poynton et al. 2007). These forests support approximately 96% indigenous vertebrate species and harbour at least 38 endemic amphibian species, many of which have highly restricted distributions and narrow ecological requirements (Gereau et al. 2016; Mkonyi 2021; Musubaho et al. 2024; Li et al. 2025). Such characteristics make Eastern Arc amphibians particularly susceptible to habitat disturbance.

Despite their global conservation importance, the EAMFs have undergone extensive habitat loss, fragmentation, and degradation over recent decades. Approximately 65 to 70% of the original forest cover has been lost, particularly in lowland and submontane areas, resulting in high reductions in habitat connectivity and ecological integrity (Newmark, McNeally 2018; Malhi et al. 2025; Siqueira et al. 2025). Similar patterns of biodiversity decline associated with habitat modification have been documented globally (Nneji et al. 2021; Bernabo et al. 2022; Kaur, Singh 2025). These trends underscore the need for strong ecological data to support conservation planning, biodiversity monitoring, and adaptive management within remaining forest refugia (Rija 2022; Lyakurwa et al. 2025).

Recognizing the global amphibian crisis, several conservation initiatives have been developed at both international and regional scales. The Amphibian Conservation Action Plan, coordinated by the IUCN Amphibian Specialist Group, provides a comprehensive framework addressing habitat protection, climate change, disease management, monitoring, conservation planning, taxonomy, policy, and public engagement (ASG 2021; IUCN 2022; Tonelli 2023). Within Tanzania, organizations such as the Eastern Arc Mountains Conservation Endowment Fund and the Tanzania Forest Conservation Group have supported forest conservation through ecological research, protected-area management, and community-based conservation initiatives (Channing et al. 2006; Burgess et al. 2007; Omoro et al. 2010; Rovero et al. 2014). Additional efforts coordinated by BirdLife International, Nature Kenya, the Wildlife Conservation Society of Tanzania, and the Critical Ecosystem Partnership Fund have promoted standardized biodiversity monitoring across the Eastern Arc and coastal forest ecosystems (Pius et al. 2008).

Previous investigations have largely focused on broad conservation assessments (Bernabo et al. 2022; Tonelli 2023), species discovery (Channing et al. 2006; Poynton et al. 2006), and impacts of habitat degradation and fragmentation on amphibian communities (CEPF 2003; Gardner et al. 2007; Newmark, McNeally 2018). More recently, studies have investigated amphibian diversity, distribution, and conservation within selected Eastern Arc landscapes, particularly the Uluguru, Udzungwa, and Ukaguru Mountains (Liedtke et al. 2022; Lyakurwa et al. 2025). Furthermore, growing evidence indicates that habitat complexity, and microhabitat conditions are important determinants of amphibian assemblage (Musubaho et al. 2024; Li et al. 2025; Musubaho et al. 2025; Siqueira et al. 2025).

Although amphibian research in the Eastern Arc Mountains has increased, important knowledge gaps remain, as most studies have predominantly focused on species inventories, taxonomic discoveries, and regional distribution patterns assessments. Little attention has been given on how ecological factors such as elevational gradients and habitat attributes shape local amphibian assemblages. The extent to which these ecological mechanisms operate within the Eastern Arc forests remains largely unknown. This knowledge gap is especially apparent in Kanga Forest Reserve (KFR), a biologically important yet poorly documented component of the Eastern Arc ecosystem. Given the scarcity of contemporary amphibian data for KFR, an integrated assessment of species diversity, distribution, and habitat associations across elevational is needed to improve ecological understanding and provide a baseline for conservation planning and long-term monitoring. The present study addresses this gap by moving beyond a conventional species inventory to examine multiple ecological dimensions of anuran assemblages within an underexplored Eastern Arc forest reserve. Specifically, the study integrates species diversity, abundance, conservation status, elevational distribution, and habitat associations within a single analytical framework. Unlike previous studies that primarily documented species abundances, this research quantitatively evaluates how local habitat characteristics and elevational variation shape anuran community structure in KFR. The study would provide site-specific ecological information necessary for understanding how habitat structure, and elevation features interact to influence amphibian diversity and distribution. The study is therefore novel in three principal respects. First, it provides an updated and comprehensive inventory of anuran species from a poorly documented Eastern Arc forest reserve; second, it examines the ecological structuring of amphibian assemblages across elevational categories while simultaneously evaluating the influence of habitat characteristics, thereby addressing an important gap identified in recent regional studies; and third, it establishes a contemporary ecological baseline for long-term monitoring of amphibian populations in Eastern Arc forest reserve, a prerequisite for detecting future biodiversity responses to habitat degradation, climate change, and conservation interventions as highlighted by Rija (2022) and Malhi et al. (2025). Specifically, this study hypothesized that (i) anuran assemblages would exhibit significant variation in diversity and abundance across elevational gradients, and (ii) habitat characteristics, particularly canopy cover, leaf litter, and water bodies, would significantly influence diversity, abundance, and distribution patterns.

## Materials and methods

### *Description of study site*

The present study was conducted in KFR, located at 6°8'49'S and 37°35'49'E (Fig. 1). The reserve forms part of the EAMFs, a globally recognized biodiversity hotspot characterized by exceptional plant and animal diversity, including numerous endemic and threatened species (Lyakurwa et al. 2025; Munishi, 2025). KFR was designated as a government forest reserve in 1954, primarily to conserve catchment forests and protect water resources and biodiversity. The reserve spans an elevational range of 500 to 2638 m above sea level, with annual rainfall varying between 1200 and 4000 mm (Mkonyi 2021). The rainfall regime is seasonal, with the rainy period extending from late November to June and peaking between March and April. Hydrologically, KFR is characterized by several permanent streams and numerous seasonal watercourses. The climate exhibits marked seasonality, with a dry season from June to October and a wet season from February to May. Mean annual temperatures range from 12.0 to 26.5 °C (Msalilwa et al. 2016; Tonelli 2023).

Like other forests within the EAMFs, KFR is notable for its high levels of species endemism. The reserve is defined by heterogeneous topography and diverse vegetation types associated with the mountain system, which generate complex microclimatic conditions. Environmental conditions vary considerably over short spatial scales along elevational gradients, resulting in a wide range of habitats and climatic zones. The surrounding landscape comprises a mosaic of natural montane grasslands, wetlands, and cultivated fields (Rija 2022; Tonelli 2023). Vegetation within KFR includes moist forests, forest patches, plantation forests, miombo woodlands, grasslands, and wetlands. KFR is surrounded by human settlements, encompassing around 25 villages. Among these, Kibatula, Mziha, Bwage, Difinga, and Dihinda are situated nearest to the reserve (Fig. 1). According to the 2022 Tanzania Population and Housing Census, the combined population of these communities is 51 037 (URT 2022). Local communities engage in various livelihood activities, including subsistence and commercial agriculture, with rice and sugarcane cultivation being predominant. In addition, communities depend on forest resources such as timber, fuelwood, and medicinal plants. These activities exert increasing anthropogenic pressure on the reserve's biodiversity and ecosystem services (Msalilwa et al. 2016). The selection of the study site was informed by preliminary reconnaissance surveys, which revealed a highly fragmented mountain block with unique ecological habitats and vegetation composition that remain poorly

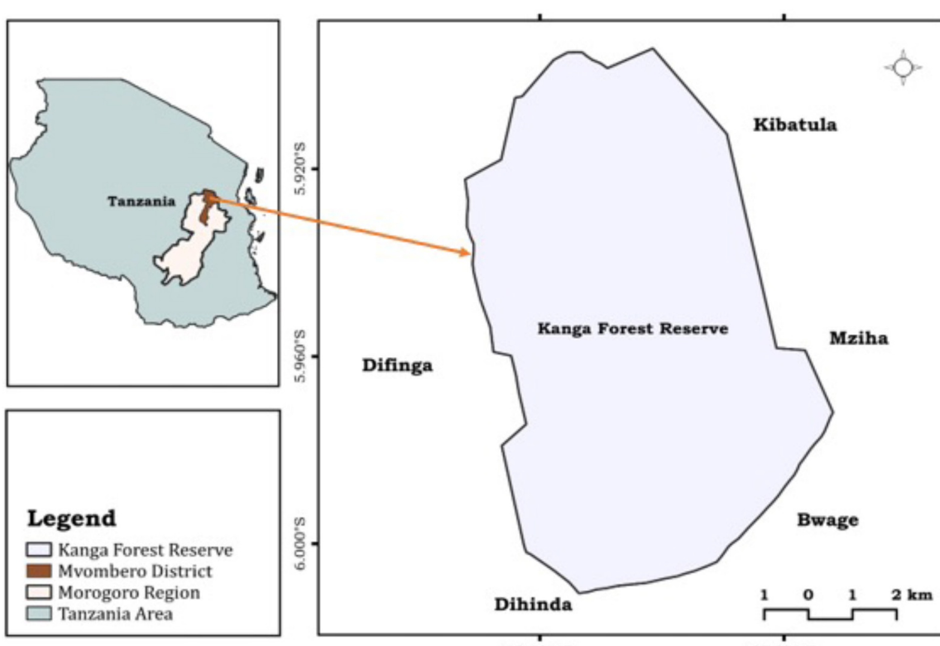


**Fig. 1.** Map of the Kanga Forest Reserve, showing its location and the surrounding villages.

studied. Such conditions are known to provide important opportunities for supporting high anuran diversity and distinct distribution patterns (Li et al. 2025).

*Sampling design and data collection methods*

A hierarchical stratified sampling design was employed to ensure representative Anuran assemblages across habitats and elevational gradients within KFR. First, the reserve was divided into four elevational categories based on altitude (m above sea leavel): farmland (FL; < 500 m), lowland (LL; 500 to 1000 m), sub-montane (SM; 1001 to 1500 m), and montane forest (M; > 1500 m), as per classifications proposed by Lyakurwa et al. (2019), Rodríguez et al. (2024), and Li et al. (2025). These elevational categories represented the broad ecological framework for assessing variation in amphibian assemblages along altitudinal gradients. Within each elevational category, environmentally relevant microhabitats known to influence amphibian occurrence, breeding, shelter, and foraging were identified and treated as ecological sampling strata. These included water bodies, canopy cover, leaf litter, tree trunks, tree density, woodland habitats, grasslands, and rocky habitats. The selection of these habitat strata was informed by previous studies demonstrating the importance of microhabitat conditions in determining amphibian distribution and assemblage structure (Mkonyi 2021; Musubaho et al. 2024; Li et al. 2025; Siqueira et al. 2025). Incorporating these habitat types within each elevational category, the design enabled simultaneous evaluation of both broad-scale elevational effects and local habitat influences on anuran communities. Within each environmental stratum, random plots were established and separated by a minimum distance of 10 m to reduce spatial autocorrelation and enhance sample independence (modified from Mkonyi 2021). The resulting design consisted of plots nested within environmental strata, environmental strata nested within elevational categories, and elevational categories nested within the KFR landscape. The plots constituted the primary sampling units used for all abundance, diversity, and habitat-association analyses.

Anuran surveys were conducted using standardized diurnal and nocturnal time-constrained visual encounter surveys, a widely applied approach for amphibian inventories and ecological studies (Mkonyi 2021; Musubaho et al. 2024; Siqueira et al. 2025). Each plot was surveyed repeatedly across three seasonal sampling periods corresponding to the onset of the rainy season (October – November 2024), peak rainfall (January – February 2025), and the end of the rainy season (April – May 2025). Repeated surveys were incorporated to maximize detection probability and account for temporal variation in anuran activity associated with rainfall and breeding cycles. During each sampling period, plots were surveyed during both diurnal (8:00 – 12:00 h) and nocturnal (20:00 – 23:00 h) periods by a team of three observers and one recorder. Each environmental stratum was surveyed over two consecutive days and revisited during each seasonal sampling period. Survey effort focused on systematically searching all potential anuran microhabitats within plots. Observers moved in parallel at a slow and standardized pace while visually inspecting vegetation, leaf litter, tree trunks, rock crevices, fallen logs, and other substrates likely to harbour anurans (Mkonyi 2021; Li et al. 2025). Nocturnal surveys employed torchlights and headlamps to enhance detectability of active individuals (Musubaho et al. 2024).

Visual observations were supplemented by acoustic encounter surveys and opportunistic observations, following established protocols (Mkonyi 2021; Siqueira et al. 2025), effective for detecting arboreal species and individuals calling from concealed locations. Calling males were located by tracing vocalizations to their source, and all detected individuals were counted and recorded using a microcassette recorder (Mkonyi 2021; Siqueira et al. 2025). The combined use of visual searches, acoustic detection, nocturnal sampling, and systematic habitat inspection is widely recognized as a cost-effective and robust approach for anurans surveys (Musubaho et al. 2024). To avoid inflating abundance estimates through repeated observations of the same individuals during successive visits, repeated counts from each plot were consolidated into a single plot-level abundance estimate (Bassetto et al. 2024). Specifically, the maximum number of individuals of each species recorded within a plot across all survey was used as a conservative measure of local abundance. This approach minimized the risk of double-counting highly mobile individuals while retaining information on species occurrence and peak detectability. Similar approaches have been employed in anuran inventory studies (Musubaho et al. 2024; Msalilwa et al. 2016; Tonelli 2023; Rija 2022), where repeated surveys are conducted primarily to maximize species detection rather than estimate demographic parameters.

*Species identification*

Anurans were initially identified using established regional field guide books and taxonomic references, including Amphibians of the Eastern Arc Mountains and Coastal Forests of Tanzania and Kenya (Harper et al. 2010), Mbije (2021), and Nneji et al. (2021). The identifications were based on a combination of external morphological characters, including body size, dorsal and ventral colour patterns, skin texture, snout shape, digital morphology, webbing extent, glandular structures, and other diagnostic features relevant to the taxa encountered. Taxonomic nomenclature followed the Amphibian Species of the World database (Mkonyi 2021; Musubaho et al. 2024; Lyakurwa et al. 2025). All visually detected individuals were photographed in situ using digital cameras prior to handling, and representative photographic records were subsequently used to verify field identifications. Particular attention was given to taxa exhibiting morphological similarity to closely related species.

Following identification, individuals were captured, examined, and released approximately 50 m from their point of capture to minimize the likelihood of immediate recapture and reduce disturbance to local populations (Bassetto et al. 2024). Temporary marking was undertaken using non-toxic dyes applied to the dorsal surface or head region following established capture–mark–recapture protocols (Musubaho et al. 2024). This procedure assisted field crews in recognizing previously encountered individuals during repeated surveys while minimizing handling stress. A subset of specimens representing all recorded taxa was retained as voucher material for taxonomic verification. Voucher specimens were anesthetized using chlorobutanol, fixed in 10% buffered formalin, and preserved in 70% ethanol. These specimens were deposited in the Department of Zoology, University of Dar es Salaam, Tanzania. The collection and preservation of voucher specimens were undertaken in accordance with ethical guidelines and with due consideration for conservation priorities and ecosystem integrity (Musubaho et al. 2024).

The designation "cf." (confer) was applied to species such as *Arthroleptides* cf. *yakusini*, *Probreviceps* cf. *durirostris*, and *Nectophrynoides* cf. *tornieri* because the examined specimens exhibited morphological characteristics consistent with these taxa but lacked sufficient diagnostic evidence for unequivocal species-level assignment. We adopted this conservative approach to avoid potential misidentification in a region characterized by high levels of endemism, cryptic diversity, and ongoing taxonomic revision (Tonelli 2023; Lyakurwa et al. 2025). Consequently, the use of "cf." reflects taxonomic caution rather than uncertainty arising from inadequate specimen examination. We acknowledge that, although species identifications were supported by detailed morphological examination, molecular and bioacoustic verification was not undertaken. The taxonomic status of the cf. taxa remains provisional, and future integrative studies incorporating morphology, vocalizations, and genetic analyses will be necessary to validate these identifications and explore the possibility of unrecognized species diversity.

### *Conservation status*

The conservation status of recorded species was evaluated using the IUCN Red List assessments, following approaches outlined by Nneji et al. (2021), Rija (2022), Kaur and Singh (2025), Li et al. (2025) and IUCN (2020, 2021, 2024). Species were classified into the following categories: Extinct, Extinct in the Wild, Critically Endangered, Endangered, Vulnerable, Near Threatened, Least Concern, and Data Deficient. Species that are recognized as valid but have not yet been assessed under the IUCN Red List criteria were categorized as Not Evaluated. Threats to species reported in this study were based on direct field observations during the survey period, rather than relying solely on generalized threat classifications from the IUCN Red List database (https://www.iucnredlist.org/).

### *Diversity assessment*

Anuran diversity was assessed using Simpson's diversity index (1–*D*) and the Shannon–Wiener index (*H*'). These indices provide robust measures of biodiversity, thereby offering a comprehensive characterization of community structure (Musubaho et al. 2024; Li et al. 2025). Relative abundance was calculated following the method described by Magurran (2004). To assess species complementarity across elevational categories, Bray–Curtis dissimilarity was applied as a measure of beta diversity that incorporates species abundance data (Musubaho et al. 2024).

### *Data analysis*

Species diversity was assessed using the Shannon–Wiener diversity index (*H*') (Shannon, Weaver 1949) and Simpson's diversity index (Simpson 1949). All diversity calculations were based on the consolidated plot-level abundance data described above, with each plot treated as an independent sampling unit. To examine patterns of species composition across habitat variables and elevational categories, a species × habitat abundance matrix was constructed from plot-level observations. In this matrix, rows represented anuran species and columns represented environmental variables (water bodies, canopy cover, leaf litter, tree trunks, tree density, woodland, grassland, and rocky habitats), while cell entries contained species abundance values. This matrix formed the basis for all multivariate analyses. Community similarity among habitat variables was quantified using the Bray–Curtis dissimilarity index, which is widely applied in ecological studies because of its suitability for abundance data and its reduced sensitivity to joint absences.

Hierarchical Cluster Analysis was subsequently performed on the Bray–Curtis dissimilarity matrix using the Unweighted Pair Group Method with Arithmetic Mean (average-linkage clustering). The resulting dendrogram was used to visualize ecological similarity among habitat variables based on shared species composition and abundance patterns. Cluster groupings were therefore interpreted as measures of relative ecological similarity rather than indicators of species richness. Heatmap visualization was generated from the same species × habitat abundance matrix to illustrate patterns of species occurrence and abundance across environmental variables. Prior to visualization, abundance values were standardized to reduce the influence of highly abundant species and facilitate comparisons among species exhibiting different abundance ranges. The heatmap therefore provided a graphical representation of relative species–habitat associations and abundance gradients.

Species–habitat relationships were further explored using

Bipartite Network Analysis. A species–habitat association matrix was constructed in which species constituted one set of nodes and habitat variables constituted the second set. Links between nodes represented observed occurrences of species within particular habitat categories, while link thickness was proportional to the relative abundance of each species–habitat association. The bipartite network was used as an exploratory visualization tool to identify dominant habitat associations and patterns of ecological connectivity and was not treated as an inferential statistical analysis. To evaluate relationships among environmental variables and identify the principal environmental gradients associated with variation in anuran assemblages, PCA was performed using standardized environmental variables. PCA was used to reduce data dimensionality and determine which habitat characteristics contributed most strongly to observed patterns of species abundance and distribution across elevational categories. Environmental variables exhibiting high loadings on the principal components were interpreted as the major drivers of assemblage variation. Heatmaps and bipartite network visualizations were generated from the standardized species–habitat matrices using the same dataset employed in the multivariate analyses.

The combined analytical framework enabled the assessment of diversity patterns, species–habitat associations, and environmental gradients influencing anuran assemblages in KFR, consistent with approaches recommended by Mkonyi (2021), Nessi et al. (2023), and Malunguja and Devi (2025). Differences in species diversity among elevational categories and environmental variables were tested using one-way ANOVA. Prior to analysis, data normality was evaluated using the Shapiro–Wilk test, while homogeneity of variances was assessed using Levene's test. When significant differences were detected, Tukey's Honest Significant Difference test was employed for pairwise comparisons among groups, following Nneji et al. (2021) and Musubaho et al. (2025). Statistical significance was assessed at $\alpha = 0.05$. All statistical analyses, including diversity calculations, ANOVA, PCA, Bray–Curtis dissimilarity, hierarchical clustering, and descriptive statistics, were performed using IBM SPSS Statistics version 26 (IBM Corp., Armonk, NY, USA).

## Results

### *Inventory of anuran species in KFR*

A total of 455 individual anurans representing 22 species, seven families, and 12 genera were recorded during the survey (Table 1). The recorded families were Arthroleptidae, Brevicipitidae, Bufonidae, Hyperoliidae, Phrynobatrachidae, Ptychadenidae, and Rhacophoridae. Hyperoliidae was the most species-rich family, comprising seven species (31.82%), namely *Afrixalus fornasini, Afrixalus uluguruensis, Hyperolius argus, Hyperolius cinnamomeoventris, Hyperolius mitchelli, Hyperolius substriatus*, and *Chiromantis rufescens*. Arthroleptidae was the second most species-rich family, represented by six species (27.27%), including *Arthroleptides* cf. *yakusini, Arthroleptis affinis, Leptopelis christyi, Leptopelis grandiceps, Leptopelis parkeri*, and *Leptopelis uluguruensis*. Bufonidae contributed three species (13.64%), namely *Mertensophryne lindneri, Nectophrynoides* cf. *tornieri*, and *Sclerophrys gutturalis*, while Brevicipitidae and Phrynobatrachidae each contributed two species (9.1%). Rhacophoridae and Ptychadenidae were represented by a single species each, accounting for 4.6% of the total species. Species abundance was highly uneven across the assemblage. *Ptychadena anchietae* was the most abundant species, accounting for 141 individuals (31.0% of all observations), followed by *Leptopelis uluguruensis* with 82 individuals (18.0%), *Chiromantis rufescens* with 34 individuals (7.5%), and *Leptopelis grandiceps* with 26 individuals (5.7%). Together, these four species comprised 62.2% of all recorded individuals. In contrast, several species were represented by fewer than five individuals, including *Callulina kanga* (0.9%), *Probreviceps* cf. *durirostris* (0.7%), and *Phrynobatrachus uzungwensis* (0.7%), indicating relatively low local abundance characterized by restricted habitat.

### *Diversity of anurans in KFR*

Anuran abundance showed modest variation across elevation categories, with the greatest number of individuals recorded in the lowland zone (LL, 500 – 1000 m above sea level), which supported 128 individuals (28.1% of the total abundance), followed closely by the sub-montane zone (SM, 1001 – 1500 m above sea level) with 126 individuals (27.7%). Montane forests (M, > 1500 m above sea level) accounted for 97 individuals (21.3%), while farmland habitats (FL, < 500 m above sea level) contained 91 individuals (20.0%).

In contrast to abundance patterns, species diversity differed significantly among elevation categories ($F = 18.762$, $p = 0.003$). The LL zone exhibited the highest diversity, with a Shannon diversity index ($H'$) of 2.45 and a Simpson's diversity index ($1-D$) of 0.889, reflecting both high diversity and a relatively even distribution of individuals among species (Fig. 2). Conversely, the FL zone recorded the lowest diversity ($H' = 1.80$; $1-D = 0.780$), indicating lower species richness and greater dominance by a few taxa. This reduced diversity is likely associated with habitat modification and disturbance resulting from anthropogenic activities. Although the SM zone supported nearly as many individuals as the LL zone, it exhibited comparatively lower diversity ($H' = 2.12$; $1-D = 0.774$), suggesting that the community was numerically dominated by a limited number of species. This pattern was largely driven by the high abundance of *Ptychadena anchietae*, which constituted a substantial proportion of all individuals recorded within this elevation category. The M zone displayed intermediate diversity values ($H' = 2.21$;

**Table 1.** Inventory of anuran species recorded in Kanga Forest Reserve and their abundance across different elevation categories. Names in parentheses mean the species was originally described in a different genus and later reassigned. "cf." (confer) means the specimen is similar to that species but not definitively identified. A cross mark (×) indicates that the species was not recorded within a given elevation category during the sampling. FL, farmland (< 500 m above sea level); LL, lowland (500 – 1000 m above sea level); SM, sub-montane (1001 – 1500 m above sea level); M, montane (> 1500 m above sea level)

| No. | Scientific name | Family | No. of individuals observed | Relative abundance | No. of individuals per elevation category | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | FL | LL | SM | M |
| 1 | *Arthroleptides* cf. *yakusini* (Channing, Moyer & Howell, 2002) | Arthroleptidae | 5 | 1.10 | × | × | 3 | 2 |
| 2 | *Arthroleptis affinis* Ahl, 1939 | | 10 | 2.20 | × | × | 5 | 5 |
| 3 | *Leptopelis christyi* Boulenger, 1912 | | 13 | 2.86 | 5 | 8 | × | × |
| 4 | *Leptopelis grandiceps* Ahl, 1929 | | 26 | 5.71 | 7 | 6 | 5 | 8 |
| 5 | *Leptopelis parkeri* Barbour & Loveridge, 1928 | | 12 | 2.64 | 1 | 3 | 4 | 4 |
| 6 | *Leptopelis uluguruensis* Barbour & Loveridge, 1928 | | 82 | 18.02 | 38 | 23 | 15 | 6 |
| 7 | *Callulina kanga* Loader, Gower, Müller & Menegon, 2009 | Brevicipitidae | 4 | 0.88 | × | × | 4 | × |
| 8 | *Probreviceps* cf. *durirostris* (Ahl, 1925) | | 3 | 0.66 | × | × | × | 3 |
| 9 | *Probreviceps macrodactylus* Nieden, 1926 | | 8 | 1.76 | × | 5 | 2 | 1 |
| 10 | *Mertensophryne lindneri* (Nieden, 1911) | Bufonidae | 23 | 5.05 | 10 | 13 | × | × |
| 11 | *Nectophrynoides* cf. *tornieri* (Roux, 1906) | | 5 | 1.10 | × | × | 2 | 3 |
| 12 | *Sclerophrys gutturalis* (Power, 1927) | | 11 | 2.42 | 4 | 4 | 3 | × |
| 13 | *Afrixalus fornasini* (Bianconi, 1849) | Hyperoliidae | 19 | 4.18 | × | 6 | 6 | 7 |
| 14 | *Afrixalus uluguruensis* (Barbour & Loveridge, 1928) | | 12 | 2.64 | × | 4 | 4 | 4 |
| 15 | *Chiromantis rufescens* (Günther, 1868) | Rhacophoridae | 34 | 7.47 | 16 | 7 | 5 | 6 |
| 16 | *Hyperolius argus* Peters, 1854 | | 9 | 1.98 | 3 | 6 | × | × |
| 17 | *Hyperolius cinnamomeoventris* Bocage, 1866 | | 16 | 3.52 | × | 7 | 4 | 5 |
| 18 | *Hyperolius mitchelli* Loveridge, 1953 | | 7 | 1.54 | × | × | 5 | 2 |
| 19 | *Hyperolius substriatus* (Ahl, 1931) | | 5 | 1.10 | × | × | 2 | 3 |
| 20 | *Phrynobatrachus natalensis* (Smith, 1849) | Phrynobatrachidae | 7 | 1.54 | × | 7 | × | × |
| 21 | *Phrynobatrachus uzungwensis* Menegon, Salvidio & Loader, 2011 | | 3 | 0.66 | × | 2 | 1 | × |
| 22 | *Ptychadena anchietae* (Bocage, 1868) | Ptychadenidae | 141 | 30.99 | 20 | 27 | 56 | 38 |
| | Total | | 455 | 100.00 | 91 | 128 | 126 | 97 |
| | Relative abundance | | | | 20.00 | 28.13 | 27.69 | 21.32 |
| | Simpson (1–*D*) | | | | 0.78 | 0.89 | 0.77 | 0.81 |
| | Shannon (*H*') | | | | 1.80 | 2.45 | 2.12 | 2.21 |

$1{-}D = 0.812$), indicating a moderately diverse assemblage with a more balanced distribution of individuals among species than observed in the FL and SM zones.

Patterns of community similarity further reflected elevational differences in species composition. Based on Bray–Curtis similarity indices, LL and SM shared the most similar assemblages (0.77), suggesting considerable overlap in species occurrence and abundance structure. In contrast, FL and M exhibited the lowest similarity (0.40), indicating pronounced differences in community composition between anthropogenically modified low-elevation habitats and relatively intact montane forests. Furthermore, several species demonstrated distinct elevational associations. *Ptychadena anchietae* was recorded across all elevation categories but reached its highest abundance in the SM zone,

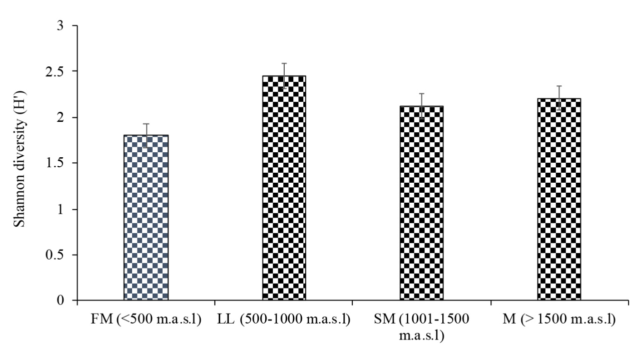


**Fig. 2.** Shannon diversity index of anuran species across different elevation categories in Kanga Forest Reserve. m.a.s.l., m above sea level; FM, farmland; LL, lowland; SM, sub-montane; M, montane.

where 56 individuals were observed. Likewise, *Leptopelis uluguruensis* occurred throughout the elevational gradient but was most abundant in FL and LL habitats (Table 1). On the other hand, *Callulina kanga, Arthroleptides* cf. *yakusini*, and *Nectophrynoides* cf. *tornieri* were largely restricted to SM and M habitats, indicating a preference for cooler, wetter, and less disturbed forest environments.

*Conservation status of anuran species in KFR*

Based on the IUCN Red List categories, the conservation assessment of the 22 anuran species recorded in KFR showed that species were distributed across five conservation categories (Fig. 3). The majority of the species were classified as Least Concern, comprising 10 species (45.5%) of the total assemblage, indicating that more than half of the recorded species currently face relatively low extinction risk. Species categorized as Endangered constituted four species (18.2%), while Near Threatened species accounted for three species (13.6%). Vulnerable species were represented by two species (9.1%), and Critically Endangered species were represented by one species (4.6%). Species such as *Arthroleptides* cf. *yakusini, Leptopelis parkeri, Probreviceps* cf. *durirostris*, and *Probreviceps macrodactylus* were classified as Endangered. Furthermore, *Afrixalus uluguruensis* and *Leptopelis grandiceps*, were listed as Vulnerable. Beyond the threatened categories, species such as *Leptopelis uluguruensis, Nectophrynoides* cf. *tornieri*, and *Phrynobatrachus uzungwensis* were classified as Near Threatened.

*Influence of environmental variables on anuran distribution patterns*

Principal component analysis revealed that the first two principal components explained 49.6% of the total variation in anuran–environment relationships, with PC1 accounting for 32.4% and PC2 accounting for 17.2% of the variance. The ordination identified two major environmental gradients influencing species distribution across the KFR. The first principal component (PC1) was strongly and positively associated with canopy cover (loading = 0.971), tree trunk (0.968), water bodies (0.947), and ground cover (0.892), all of which exhibited high vector magnitudes (> 0.89), indicating a strong contribution to species occurrence patterns (Table 2). This axis therefore represents a gradient of increasing habitat complexity and moisture availability. Species positioned towards the positive end of PC1, particularly *Ptychadena anchietae, Chiromantis rufescens, Hyperolius cinnamomeoventris*, and *Leptopelis grandiceps*, showed strong associations with aquatic habitats. The exceptionally high abundance of *Ptychadena anchietae* around water bodies further emphasizes the importance of semi-permanent aquatic habitats as key determinants of anuran distribution.

The second principal component (PC2) was primarily defined by tree density (loading = 0.956) and leaf litter cover (0.936), both exhibiting high vector magnitudes (> 0.96), indicating that these variables represent a distinct ecological gradient associated with forest-floor conditions and vegetation maturity. Species such as *Leptopelis uluguruensis, Leptopelis christyi*, and *Hyperolius argus* were closely aligned with this axis, suggesting a preference for habitats characterized by dense woody vegetation and well-developed litter layers. These habitat features likely provide favourable microclimatic conditions, shelter, and foraging opportunities necessary for the persistence of forest-dependent anuran species. In contrast, understory cover (loading = 0.013 on PC1 and −0.042 on PC2; magnitude = 0.044) contributed minimally to the observed variation and was located near the origin of the ordination space, indicating a weak influence on overall species distribution patterns. Similarly, woodland (magnitude = 0.153), dead trees (0.236), grassland (0.252), and rock habitats (0.252)

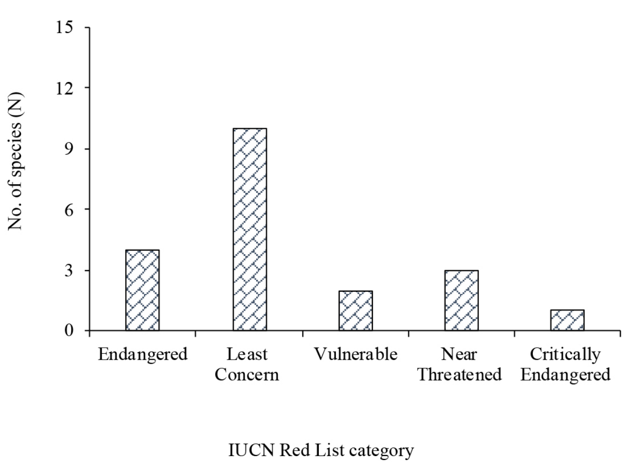


**Fig. 3.** The conservation status of anuran species in Kanga Forest Reserve using the IUCN Red List criteria.

**Table 2.** PCA loadings of environmental variables influencing anuran distribution in the Kanga Forest Reserve. Variables with higher absolute loading values and magnitudes contributed more strongly to the observed patterns of species distribution. Higher loading magnitudes indicate stronger contributions to community differentiation

| Environmental variable | PC1 | PC2 | Magnitude |
|---|---|---|---|
| Canopy cover | 0.971 | 0.091 | 0.976 |
| Dead tree | 0.008 | −0.236 | 0.236 |
| Grassland | −0.098 | −0.233 | 0.252 |
| Ground cover | 0.892 | 0.023 | 0.892 |
| Leaf litter | −0.242 | 0.936 | 0.967 |
| Rock | −0.193 | −0.163 | 0.252 |
| Tree density | −0.192 | 0.956 | 0.975 |
| Tree trunk | 0.968 | 0.098 | 0.973 |
| Understory cover | 0.013 | −0.042 | 0.044 |
| Water bodies | 0.947 | 0.169 | 0.962 |
| Woodland | −0.149 | 0.035 | 0.153 |

exhibited comparatively low loading magnitudes and weaker associations with the principal axes, suggesting that these habitat variables played a relatively minor role in structuring the anuran assemblage at the landscape scale. The PCA results closely mirrored patterns observed in the hierarchical cluster analysis. Environmental variables with the strongest positive loadings on PC1, namely water bodies, canopy cover, tree trunks, and ground cover, formed a closely related cluster, indicating that these habitat attributes collectively influence species occurrence. Likewise, tree density and leaf litter, which dominated PC2, clustered together and represented a separate ecological gradient associated with forest-floor specialization.

A hierarchical clustering analysis was performed to group environmental variables based on their influence on anuran species distribution (Fig. 4). The variables grouped into three major clusters with distinct contributions to overall anuran abundance. Cluster 1 was made up of variables such as water bodies, canopy cover, leaf litter and ground cover. This cluster supported the highest number of species (24 species) and individuals (279), representing 48.0% of the total individuals recorded. Water bodies were the dominant contributor (142 individuals, 24.0%), followed by canopy cover (70 individuals, 12.0%), leaf litter (40 individuals, 7.0%), and ground cover (27 individuals, 5.0%). Cluster 2 consisted of dead trees, tree trunks, tree density and understory cover. The cluster accounted for 25.0% of the total individuals. Dead trees (31 individuals, 5.0%) and tree trunks (37 individuals, 6.0%) provide oviposition and refuge sites, while tree density (66 individuals, 11.0%) and understory cover (13 individuals, 2.0%) enhance habitat structural complexity, especially in fragmented landscapes. The third cluster was made up of low influence variables such grassland, woodland and rock, with only 18 (3%) of total individuals. Although these habitats were less influential, they may serve as occasional refuge for generalist species.

The clustered heatmap further illustrated the distribution patterns of anuran species across environmental variables (Fig. 5). The most abundant species was *Ptychadena anchietae*, representing 30.9% of total records, largely associated with water bodies, canopy cover, ground cover, and tree trunks. Another dominant species was *Leptopelis uluguruensis*, contributing 17.9% of individuals, primarily associated with tree density, leaf litter, and water bodies. Chiromantis rufescens also showed substantial abundance (7.4%), commonly linked with trees, ground cover, and aquatic habitats. Moderately abundant species included *Mertensophryne lindneri* (5.0%) and *Leptopelis grandiceps* (5.7%), both strongly associated with forest habitats such as tree density, canopy cover, and understory cover. Some species such as *Phrynobatrachus uzungwensis, Arthroleptides* cf. *yakusini*, and *Probreviceps* cf. *durirostris* exhibited relatively low habitat associations, accounted for less than 2% of individuals. This reflecting either habitat specialization or lower detectability.

The bipartite network analysis revealed clear associations between anuran species and environmental variables across the study area (Fig. 6). Several species were linked to multiple habitat features, indicating varying degrees of habitat use and ecological flexibility. Aquatic habitats, particularly water bodies, supported the highest number of individuals (114 individuals; 24.9%), indicating their critical role as breeding and foraging habitats for amphibians, highlighting their importance as key microhabitats supporting anuran occurrence. Forest structural attributes

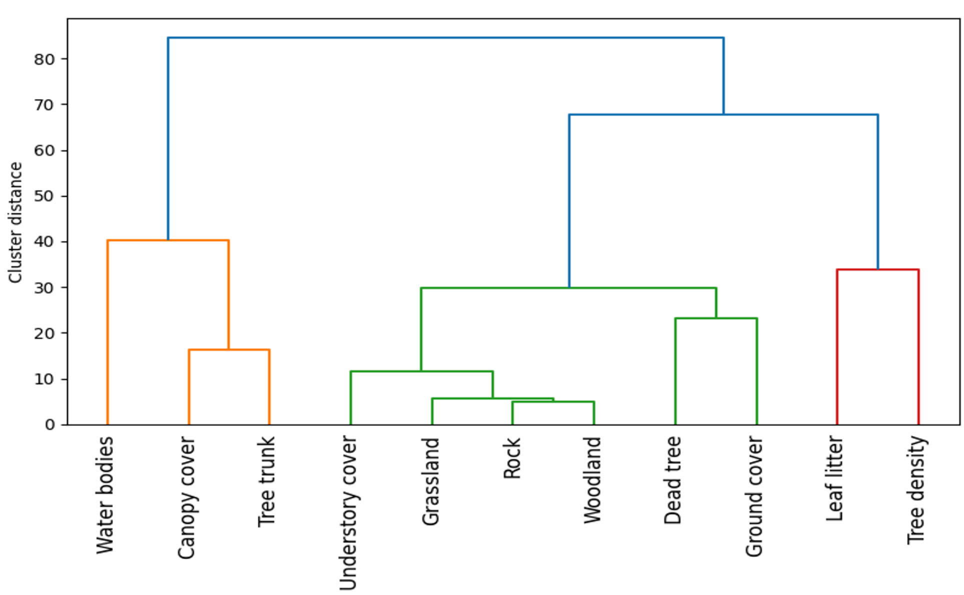


**Fig. 4.** Hierarchical clustering of environmental variables based on their influence on anuran species distribution.

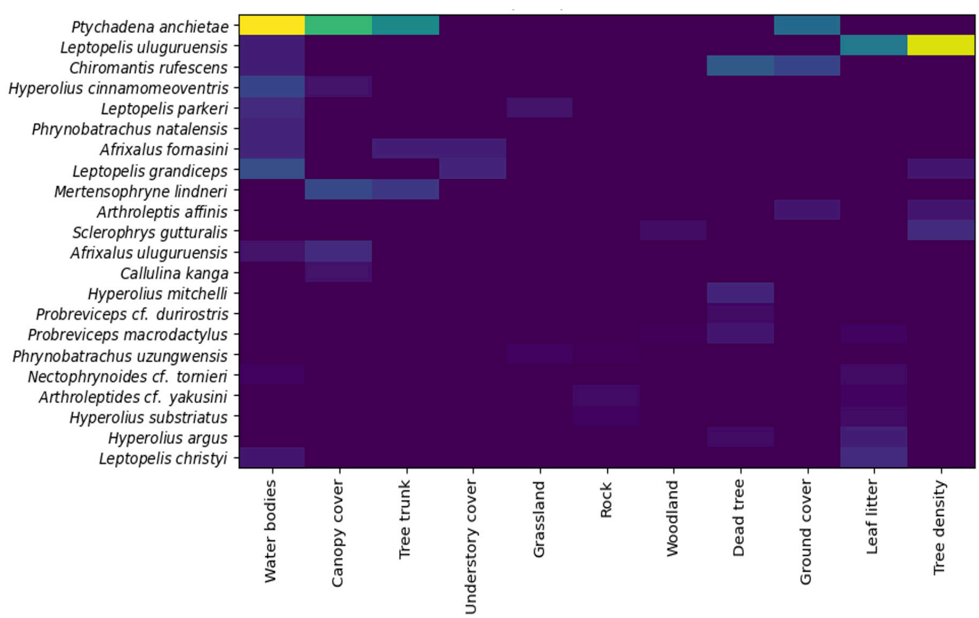


**Fig. 5.** Clustered heatmap showing the distribution patterns of anurans across environmental variables. The analysis highlights species-specific associations with key habitat features, illustrating how environmental heterogeneity shapes anuran community structure and abundance across the study area.

including canopy cover, tree density, and leaf litter also displayed numerous connections with species, indicating that forest-associated microhabitats contribute substantially to anuran distribution. Tree density accounted for 71 individuals (15.5%), followed by canopy cover with 63 individuals (13.8%), leaf litter with 47 individuals (10.3%), and tree trunks with 43 individuals (9.4%). These habitats were linked to several forest-associated species such as *Leptopelis uluguruensis, Mertensophryne lindneri*, and *Arthroleptis affinis*. Other environmental variables showed

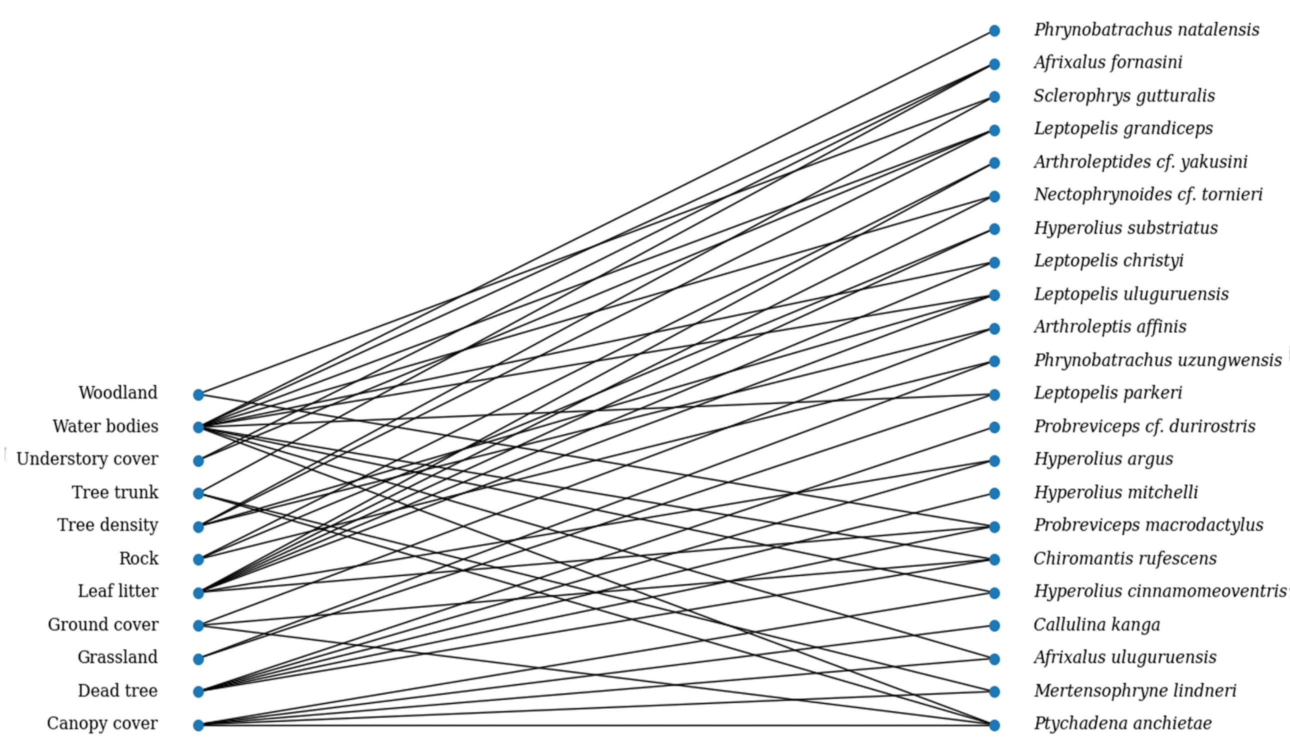


**Fig. 6.** Bipartite network illustrating associations between anurans and environmental variables across the study area. The analysis highlights species-specific habitat use and ecological flexibility, with several species linked to multiple habitat features.

relatively moderate associations with amphibian species. Ground cover contributed 37 individuals (8.1%), while dead trees supported 34 individuals (7.4%). Habitats with comparatively lower contributions included understory cover (13 individuals; 2.8%), rock habitats (6 individuals; 1.3%), grassland (six individuals; 1.3%), and woodland (four individuals; 0.9%). The network structure therefore highlights water bodies and forest structural components as the most important environmental features, collectively supporting more than 60% of all recorded individuals.

## Discussion

### *Inventory, abundance and diversity of anurans in KFR*

The anuran community documented in the KFR exhibits a clearly structured and ecologically heterogeneous assemblage distributed across farmland (FL), lowland (LL), sub-montane (SM), and montane (M) habitats. This pattern reflects the strong influence of habitat heterogeneity typical of Eastern Arc Mountain ecosystems, where variation in vegetation structure, moisture regimes, and microclimatic stability creates a mosaic of ecological niches that support both widespread and specialized amphibian taxa (Bassetto et al. 2024; Musubaho et al. 2024). The predominance of Hyperoliidae and Arthroleptidae aligns with regional observations indicating that these families are consistently successful in diverse East African forest systems due to their ecological plasticity, broad habitat tolerance, and reproductive versatility, which allow them to exploit both aquatic and terrestrial environments. In contrast, the comparatively low representation of Brevicipitidae, Phrynobatrachidae, and Rhacophoridae suggests stronger habitat specialization, particularly dependence on stable microclimatic conditions such as high humidity and well-developed leaf-litter layers, which are more characteristic of intact forested habitats than disturbed landscapes.

The overall assemblage structure, characterized by a small number of highly abundant species and a larger proportion of rare taxa, reflects a typical tropical anuran pattern driven by uneven resource partitioning, niche differentiation, and species-specific habitat requirements (Bassetto et al. 2024; Li et al. 2025). This indicates that although KFR sustains both generalist and specialist species, community composition is increasingly shaped by ecological filtering processes, particularly in areas influenced by anthropogenic disturbance. The occurrence of range-restricted and forest-dependent species further highlights the ecological importance of intact forest patches, which function as critical refugia by maintaining stable environmental conditions necessary for the persistence of sensitive amphibians (Liedtke et al. 2022; Lyakurwa et al. 2025). Variation in anuran diversity and assemblage composition across KFR is more strongly associated with habitat quality and microhabitat structure than with elevation alone. Forested environments, particularly lowland and sub-montane zones, support comparatively balanced communities because of their structural complexity, consistent moisture availability, and abundance of breeding microhabitats, all of which enhance niche availability and promote species coexistence (Malhi et al. 2025; Siqueira et al. 2025). These conditions create ecologically stable environments that facilitate both species persistence and reproductive success, thereby sustaining higher overall diversity. In contrast, farmland habitats display markedly simplified community structure, characterized by reduced evenness and the dominance of disturbance-tolerant species, a pattern indicative of biotic homogenization driven by land-use intensification and habitat fragmentation (Mkonyi 2021). Such environments filter out habitat specialists while favouring generalist taxa capable of tolerating altered microclimatic conditions, leading to reduced ecological complexity. Montane habitats, although relatively stable in terms of environmental conditions, show reduced diversity in part due to the dominance of a few well-adapted species, demonstrating how numerical dominance can obscure underlying declines in evenness. Nevertheless, montane forests maintain compositionally distinct assemblages, likely as a result of reduced anthropogenic pressure and stronger environmental filtering, which selectively excludes species lacking adaptations to cooler and wetter conditions while favouring specialized lineages adapted to high-elevation environments (Rija 2022; Bassetto et al. 2024; Kaur, Singh 2025; Li et al. 2025; Musubaho et al. 2025; Siqueira et al. 2025).

Patterns of community similarity further reinforce the role of habitat modification in shaping anuran assemblages. Forested habitats show greater compositional overlap, indicating ecological continuity and shared environmental conditions across elevational gradients, whereas farmland communities are markedly distinct, reflecting strong species turnover associated with anthropogenic disturbance. This highlights the disruptive effect of habitat conversion on community structure and emphasizes that changes in land use can alter not only species richness but also the fundamental composition of anuran assemblages. Environmental factors such as canopy cover, leaf-litter depth, and proximity to water bodies emerge as key determinants of species distribution, underscoring that amphibian assemblages in KFR are structured primarily by fine-scale habitat attributes rather than elevation alone (Li et al. 2025; Musubaho et al. 2025). These findings demonstrate that KFR operates as a spatially heterogeneous ecological mosaic in which species persistence depends heavily on habitat integrity and landscape connectivity. From a conservation standpoint, lowland and sub-montane forests emerge as priority management zones because they simultaneously support high species richness, habitat specialists, and threatened taxa. Maintaining ecological connectivity between these elevational belts is therefore essential for enabling dispersal processes and enhancing resilience under future environmental change.

Consequently, conservation strategies should prioritize the preservation of habitat heterogeneity and the protection of mid-elevation forests, where species richness, diversity, and community connectivity converge, making these habitats central to landscape-scale anuran conservation in KFR.

*Conservation status of anuran species in KFR*

The conservation assessment of the anuran assemblage in KFR demonstrates a heterogeneous distribution of species across IUCN Red List categories, reflecting a gradient of conservation risk within the anuran community. The predominance of Least Concern species indicates that a large portion of the assemblage currently maintains stable populations, likely supported by the relatively intact forest structure and heterogeneous habitats that characterize much of the reserve. These conditions provide essential ecological resources such as breeding sites, moisture retention, and microhabitat diversity, which collectively buffer common species against environmental fluctuations. However, the simultaneous presence of taxa classified as Near Threatened, Vulnerable, Endangered, and Critically Endangered highlights that KFR also functions as a refuge for species facing varying degrees of extinction risk. This dual conservation role underscores the ecological importance of the reserve, as it simultaneously supports widespread generalists and highly sensitive, range-restricted specialists whose persistence depends on specific habitat conditions that are increasingly rare outside protected areas.

Several species of high conservation concern, including *Callulina kanga, Arthroleptides* cf. *yakusini*, and *Probreviceps* spp., exemplify anurans with narrow geographic distributions and strong habitat specialization. These taxa are particularly vulnerable to environmental perturbations such as habitat loss, agricultural encroachment, and climate variability, which can rapidly degrade the moist, structurally complex environments they require for survival (Musubaho et al. 2024). Their distribution within KFR is not random but closely associated with relatively undisturbed forest patches and specific elevational zones, suggesting that fine-scale habitat integrity is a more important determinant of their persistence than reserve-level protection alone. This pattern emphasizes that conservation effectiveness depends not only on protected area designation but also on the maintenance of internal habitat quality, including forest structure, leaf-litter depth, and hydrological connectivity. Consequently, management strategies should prioritize safeguarding intact forest cores and maintaining ecological gradients that support species with narrow ecological niches.

Comparative evidence from regional and global studies provides further context for these findings. In line with observations by Nneji et al. (2021) in Tangjiahe National Nature Reserve, the majority of anuran species in KFR fall within the Least Concern category, while a smaller subset occupies higher threat categories, indicating that even relatively diverse ecosystems are shaped by habitat quality and anthropogenic pressures. Similarly, Musubaho et al. (2024) reported dominance of Least Concern species in East African forest reserves, reinforcing the idea that intact forest systems generally sustain stable populations of widespread anuran while simultaneously harbouring vulnerable endemic taxa. However, KFR differs from some regional systems in its relatively higher representation of threatened and elevation-restricted species, suggesting that its topographic heterogeneity and elevational isolation provide refugia for specialized anuran that may be less common elsewhere. This pattern is consistent with findings by Li et al. (2025), where effective habitat protection in structurally complex landscapes facilitated the persistence of highly sensitive taxa, including evolutionarily distinct species.

The presence of Near Threatened and Vulnerable species further underscores the importance of proactive conservation planning. Although these taxa are not currently at immediate risk of extinction, they are highly susceptible to ongoing environmental pressures such as deforestation, agricultural expansion, and localized hydrological disruption. As noted by Nneji et al. (2021), such species often function as early warning indicators of ecosystem degradation, declining before more resilient taxa show measurable population changes. Therefore, their continued presence in KFR highlights both the current conservation value of the reserve and the potential for future biodiversity loss if habitat degradation continues unchecked. The occurrence of multiple threat categories within a single assemblage also reflects varying species' responses to environmental gradients, where ecological specialists are disproportionately affected by habitat alteration compared to generalists. Importantly, the documented distribution of threatened taxa provides a critical baseline for long-term ecological monitoring in KFR. Targeted resampling of these species can serve as a sensitive indicator system for detecting early ecological change, allowing conservation managers to identify habitat degradation before it results in widespread biodiversity loss. Such baseline datasets are essential for adaptive conservation planning in tropical forest ecosystems, where environmental change can rapidly alter species composition and population viability. The findings reinforce the role of KFR as both a biodiversity reservoir and a conservation priority area, emphasizing the urgent need to maintain habitat integrity and strengthen long-term monitoring frameworks to safeguard its threatened amphibian fauna.

*Influence of environmental variables on anuran distribution patterns*

The integrated environmental analyses revealed that anuran distribution in KFR is governed primarily by habitat complexity and hydrological conditions rather than by elevation alone. The concordance among PCA, Hierarchical Cluster Analysis, Heatmap Analysis, and Bipartite Network Analysis provides strong evidence that anuran communities are structured by a combination of moisture availability, forest structural attributes, and habitat connectivity. Among all environmental variables examined, aquatic habitats emerged as the strongest determinant of anuran distribution. Water bodies, canopy cover, and tree trunks exhibited high ordination loadings within PCA and occupied central positions within the habitat network, indicating that these variables contribute disproportionately to species occurrence. Likewise, tree density and leaf litter formed a distinct ecological gradient associated with forest-floor specialization and were closely linked to species such as *Leptopelis uluguruensis, Leptopelis christyi*, and *Hyperolius argus*. The consistent prominence of water bodies across PCA ordination, hierarchical clustering, heatmap visualization, and bipartite network analyses demonstrates that moisture availability is the primary ecological driver shaping amphibian assemblages in KFR. This pattern reflects the fundamental dependence of anurans on aquatic environments for reproduction, larval development, and hydration, a relationship widely recognized across tropical ecosystems (Nneji et al. 2021; Nessi et al. 2023; Musubaho et al. 2024; Li et al. 2025; Siqueira et al. 2025).

These findings move beyond a descriptive inventory by identifying the ecological mechanisms that underpin community assembly and species persistence across the reserve. Elevational zonation reflects ecological specialization and differential habitat suitability among taxa. The concentration of species within lowland and sub-montane forests supports the widely recognized mid-elevation diversity pattern documented for tropical amphibian communities, where favourable climatic conditions, high habitat heterogeneity, and resource availability converge to support greater species coexistence (Carvalho-Rocha et al. 2021; Siqueira et al. 2025). Similar patterns have been reported for forest-dependent amphibians inhabiting undisturbed stream-associated forests where habitat specialization limits their distribution (Greenwood et al., 2020). The narrow habitat requirements of these species imply heightened sensitivity to habitat alteration and suggest that they may function as valuable bioindicators of forest ecosystem integrity within the reserve. The protection of streams, wetlands, and other aquatic habitats should be regarded as a primary conservation priority within KFR. On the other hand, leaf-litter accumulations provide shelter, breeding substrates, and foraging opportunities for terrestrial and semi-fossorial species, while mature trees and standing trunks increase habitat heterogeneity and create additional microhabitats. Similar relationships between forest structural complexity and amphibian diversity have been reported in tropical forests where litter depth and canopy cover strongly influence species richness and abundance (Greenwood et al. 2020; Mkonyi 2021).

The hierarchical clustering analyses provide additional insight into the functional organization of habitats within the reserve. The clustering of aquatic habitats with canopy cover and other forest structural variables suggests a high degree of ecological connectivity between breeding and terrestrial habitats. Such connectivity is particularly important for anurans because many species depend on multiple habitat types throughout their life cycles. The separation of grassland, woodland, and rock habitats into lower-influence clusters indicates that these environments provide comparatively limited resources for most species. Their reduced importance likely reflects lower moisture retention, and simplified structural conditions that constrain amphibian occupancy (Li et al. 2025). Nevertheless, these habitats may still provide occasional refuge for ecologically flexible species and should not be disregarded entirely within broader landscape conservation strategies. The heatmap analysis further revealed pronounced differences in habitat use among species, highlighting that habitat heterogeneity is essential for conserving both widespread species and narrowly distributed taxa. Habitat simplification, particularly in areas influenced by agricultural activities, is therefore likely to reduce niche availability and disproportionately affect specialist species. This provides a mechanistic explanation for the lower diversity frequently observed in disturbed landscapes and underscores the importance of preserving structurally complex habitats within KFR.

From a management perspective, these findings clearly indicate that conservation efforts should prioritize the protection of riparian habitats, maintenance of closed-canopy forest conditions, preservation of leaf-litter layers, and retention of mature trees. Furthermore, conservation planning should focus not only on species-rich locations but also on maintaining the full elevational gradient within the reserve to preserve both widespread generalists and environmentally sensitive specialists. Identifying the habitat features most strongly associated with anuran occurrence, provides a scientifically robust foundation for long-term monitoring, habitat restoration, and conservation prioritization and contributes valuable ecological insight into the mechanisms shaping anuran assemblages in the Eastern Arc Mountains.

## Conclusions

This study provides a comprehensive assessment of anuran diversity, conservation status, and environmental determinants of species distribution within KFR. A total of 22 anuran species were recorded, with lowland and sub-montane forests supporting the highest diversity and abundance, whereas farmland and montane habitats harboured comparatively less diverse assemblages. These patterns demonstrate that anuran communities in KFR are not distributed randomly across the landscape but are shaped by environmental gradients that influence habitat suitability and resource availability. A major contribution of this study is the identification of the ecological mechanisms underlying anuran community assembly. The integration of PCA, Hierarchical Cluster Analysis, Heatmap Analysis, and Bipartite Network Analysis consistently revealed that hydrological conditions and forest structural complexity are the primary drivers of species occurrence and distribution. Water bodies emerged as the most influential habitat component, highlighting the fundamental role of aquatic environments in supporting breeding, larval development, and population persistence. Forest structural attributes, particularly canopy cover, tree density, leaf-litter accumulation, and mature trees, further influenced species distributions. Maintaining habitat connectivity across the elevational gradient will be essential for preserving ecological processes, facilitating species persistence, and enhancing resilience to future environmental change. Moreover, the presence of species spanning multiple IUCN Red List categories, including Critically Endangered, Endangered, Vulnerable, and Near Threatened taxa, underscores the conservation significance of KFR as a refuge for species with differing ecological requirements and vulnerability levels. Therefore, identifying the habitat features and environmental processes most strongly associated with anuran assemblages, this study provides a robust baseline for long-term monitoring and delivers testable ecological evidence to guide conservation planning, habitat restoration, and adaptive management within KFR and the broader Eastern Arc Mountain ecosystem.

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