International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Current Status of Amphibian Research in Meghalaya (2020–2025): A Systematic Review of Diversity, Reproductive Ecology, Bioacoustics, Taxonomy, and Conservation

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Abstract
Meghalaya, situated within the Indo-Burma biodiversity hotspot of Northeast India, supports one of the richest amphibian assemblages in the Indian subcontinent. Characterized by exceptionally high rainfall, varied altitudinal gradients, dense forest ecosystems, limestone caves, and numerous temporary wetlands, the state provides highly suitable habitats for diverse amphibian communities. During the period from 2020 to 2025, amphibian research in Meghalaya expanded considerably, particularly in the fields of reproductive ecology, developmental biology, taxonomy, bioacoustics, ecotoxicology, and conservation biology. The present review synthesizes recent scientific investigations conducted in Meghalaya with special emphasis on anuran amphibians. Studies revealed remarkable reproductive diversity, unique breeding adaptations, developmental plasticity, cryptic species diversity, and the ecological significance of community-managed forests and freshwater habitats. Several new species and distributional records were documented using integrative approaches combining morphology, molecular phylogenetics, and bioacoustics. Research also highlighted the growing threats posed by habitat destruction, agricultural contaminants, urbanization, and climate variability. The review identifies major research gaps including limited long-term monitoring, inadequate ecological modelling, insufficient disease surveillance, and poor understanding of climate change impacts on amphibian populations. Future research directions are proposed, including the integration of molecular ecology, acoustic monitoring, conservation genomics, ecotoxicology, and community-based conservation strategies. This review serves as a comprehensive synthesis of amphibian studies in Meghalaya from 2020–2025 and provides a baseline for future herpetological research and conservation planning in Northeast India.

Keywords: Amphibians, Meghalaya, reproductive ecology, bioacoustics, taxonomy, conservation, Northeast India, anurans, ecotoxicology, systematic review.

1. INTRODUCTION

Amphibians represent one of the most ecologically sensitive vertebrate groups and are widely recognized as important bioindicators of environmental health due to their permeable skin, biphasic life cycle, and sensitivity to environmental changes. Globally, amphibians are facing severe declines as a result of habitat destruction, pollution, climate change, emerging diseases, invasive species, and

anthropogenic disturbances. In tropical regions such as Northeast India, amphibian diversity remains comparatively underexplored despite the region being recognized as part of the Indo-Burma biodiversity hotspot.

Among the northeastern states of India, Meghalaya is particularly important because of its unique climatic and ecological conditions. The state experiences some of the highest rainfall levels in the world, especially in regions such as Mawsynram and Cherrapunjee. Meghalaya comprises the Khasi Hills, Jaintia Hills, and Garo Hills, each characterized by diverse vegetation types, altitudinal variation, limestone caves, sacred groves, temporary wetlands, forest streams, and community reserve forests. These habitats support a rich diversity of amphibians, many of which are endemic, cryptic, or poorly studied.

From 2020 to 2025, amphibian research in Meghalaya witnessed significant advancement. Investigations focused on reproductive ecology, embryonic development, ecotoxicology, bioacoustics, taxonomy, phylogenetics, and conservation biology. The use of integrative approaches involving molecular techniques, acoustic analyses, and ecological observations contributed substantially to the discovery of new species and a deeper understanding of amphibian ecology.

The present review aims to synthesize the major amphibian studies conducted in Meghalaya from 2020 to 2025. It focuses on reproductive ecology, developmental biology, bioacoustics, taxonomy, ecotoxicology, conservation significance, and emerging research trends. The review also identifies knowledge gaps and predicts future directions necessary for effective amphibian conservation and research in Meghalaya.

2. METHODOLOGY OF REVIEW

This systematic review is based on published peer-reviewed research articles, book chapters, review papers, and scientific reports related to amphibian studies conducted in Meghalaya between 2020 and 2025. Relevant literature was collected from scientific databases, journals, conference proceedings, and published books using keywords such as “Amphibians of Meghalaya,” “anuran ecology,” “bioacoustics,” “taxonomy,” “reproductive ecology,” “ecotoxicology,” and “Northeast India.”

The studies included in this review were categorized into the following thematic areas:

1. Reproductive ecology and breeding biology
2. Developmental biology and embryology
3. Ecotoxicology and environmental stress
4. Bioacoustics and acoustic diversity
5. Taxonomy and species discovery
6. Conservation biology and habitat management
7. Distributional records and biodiversity documentation

Only studies conducted within Meghalaya or directly related to Meghalaya’s amphibian fauna were included (Table 1).

3. REPRODUCTIVE ECOLOGY AND BREEDING BIOLOGY

3.1 Reproductive Diversity in Meghalaya Amphibians

Research conducted between 2020 and 2025 revealed remarkable reproductive diversity among amphibians inhabiting Meghalaya. Early investigations focused on the breeding ecology of Kurixalus naso in Mawsynram. Shangpliang et al. (2020a) documented the unique reproductive strategy of the

species, which deposits eggs in moist soil burrows and open ground without foam nest formation. The species was identified as an explosive breeder, with reproductive activity triggered by pre-monsoon rainfall during February and March. Interestingly, males exhibited parental care by guarding exposed egg masses, demonstrating behavioural adaptation to highly moist environments.

Subsequent studies by Shangpliang et al. (2020b) documented seven distinct reproductive modes among eight anuran species including *Rhacophorus maximus, Rhacophorus bipunctatus, Polypedates himalayensis, Polypedates teraiensis, Kurixalus naso, Duttaphrynus melanostictus, Hyla annectans,* and *Fejervarya nepalensis*. Members of the family Rhacophoridae displayed the highest reproductive diversity through foam nest construction and terrestrial oviposition. The study highlighted the ecological role of temporary rain-fed habitats, dense vegetation, and high humidity in promoting breeding success.

These investigations collectively demonstrated that Meghalaya's climatic conditions strongly influence amphibian reproductive behaviour. Seasonal rainfall, humidity, and microhabitat availability were identified as major determinants of breeding success.

3.2 Breeding Ecology of *Hyla annectans*

Shangpliang et al. (2023) provided the first detailed account of the breeding biology of *Hyla annectans* in temporary rain-fed pools of Meghalaya. The study reported that breeding activity occurred during April and May and was strongly associated with rainfall, humidity, and temperature. Males formed large breeding choruses and emitted advertisement calls for mate attraction.

Egg deposition occurred on half-submerged aquatic vegetation in clear temporary pools. The study further demonstrated a positive relationship between female body size and clutch size, indicating reproductive fitness advantages associated with larger body size. The research highlighted the importance of undisturbed temporary wetlands for successful larval development and population persistence.

3.3 Reproductive Behaviour of *Boulenophrys parva*

Research conducted by Shangpliang et al. (2024a) investigated the reproductive ecology of *Boulenophrys parva* in stream ecosystems located on the southern slopes of Meghalaya. The study demonstrated that heavy rainfall and humidity strongly influenced reproductive activity. Males utilized advertisement calls for attracting females, while females selected suitable oviposition sites to maximize larval survival.

The findings emphasized the ecological importance of stream microhabitats and intact riparian ecosystems. Since stream-breeding amphibians are highly sensitive to environmental disturbances, the study highlighted the necessity of conserving freshwater ecosystems for amphibian survival.

3.4 Reproductive Ecology of *Polypedates himalayensis*

Rangad et al. (2022) documented the reproductive activity and terrestrial oviposition behaviour of *Polypedates himalayensis* from Riat Laban Reserve Forest in Meghalaya. The species constructed foam nests in moist burrows, vegetation, and pine leaf litter near temporary ponds.

The study documented sexual dimorphism, clutch size variation, parental care, and advertisement calls. Environmental factors such as pre-monsoon rainfall, humidity, and vegetation cover were found to significantly influence reproductive success. This study further demonstrated the importance of community-protected habitats and temporary wetlands in amphibian breeding ecology.

3.5 Reproductive Ecology of *Minervarya nepalensis*

The recent study by P. Wankitlang Shangpliang and colleagues provides a significant contribution to amphibian biology by documenting the breeding behaviour and developmental stages of *Minervarya*

nepalensis in Meghalaya, Northeast India. The detailed observations on reproductive ecology, courtship behaviour, and larval development enrich the understanding of the species' natural history (Shangpliang et. al., 2025).

4. EMBRYONIC DEVELOPMENT AND DEVELOPMENTAL PLASTICITY

4.1 Embryonic and Larval Development of *Kurixalus naso* and *Minervarya nepalensis*

Shangpliang et al. (2021) conducted the first comprehensive study on the embryonic and larval development of *Kurixalus naso*. The research documented 46 developmental stages from fertilization to metamorphosis over a period of 62 days. Further, the identification of 37 developmental stages of *Minervarya nepalensis* (Shangpliang et al., 2025), offers valuable baseline data for future taxonomic, ecological, and conservation studies. This work highlights the ecological importance of Meghalaya's amphibian diversity and emphasizes the need for continued research and conservation of freshwater habitats in the Indo-Burma biodiversity hotspot.

4.2 Altitudinal Effects on Embryonic Development

Shangpliang et al. (2024b) investigated the influence of altitude on the embryonic development of *Hyla annectans*. The study compared developmental patterns between high-altitude and low-altitude breeding habitats.

Embryos from low-altitude habitats developed more rapidly and completed metamorphosis earlier than those from high-altitude environments. Environmental variables such as water temperature, dissolved oxygen, pH, and carbon dioxide concentration significantly influenced developmental duration and larval growth.

This research demonstrated developmental plasticity in response to environmental gradients and emphasized the importance of altitude in shaping amphibian adaptation and survival.

5. ECOTOXICOLOGY AND ENVIRONMENTAL STRESS

5.1 Effects of Urea Fertilizer on Amphibians

Ecotoxicological investigations in Meghalaya focused primarily on the effects of agricultural contaminants on amphibian larvae. Nongkynrih et al. (2022) examined the effects of urea fertilizer on the embryonic and larval stages of *Duttaphrynus melanostictus.*

The study demonstrated concentration-dependent toxicity, with hatchlings being particularly vulnerable. Exposure to high urea concentrations caused severe morphological deformities including curved bodies, bent tails, swollen heads, depigmentation, and abnormal mucus secretion. Behavioural abnormalities such as sluggish movement and impaired swimming were also documented.

The findings highlighted the ecological risks posed by agricultural runoff in amphibian breeding habitats and reinforced the significance of amphibians as bioindicators of environmental contamination.

5.2 Erythrocyte Abnormalities in Tadpoles

Further ecotoxicological research by Nongkynrih et al. (2025) investigated the effects of sublethal urea exposure on erythrocyte morphology in *Rhacophorus maximus* tadpoles. Tadpoles exposed to varying concentrations of urea exhibited severe red blood cell abnormalities including membrane disintegration, crenulation, rupture, contraction, and lobopodial projections.

The study confirmed that fertilizer-induced stress alters physiological processes in amphibians and may negatively affect survival, growth, and reproductive fitness.

5.3 Organophosphate Pesticides and Amphibian Health

Lyngkhoi et al. (2025) comprehensively reviewed the impacts of organophosphate pesticides on anuran amphibians. The review highlighted that exposure to organophosphate compounds disrupts neural transmission through acetylcholinesterase inhibition.

The consequences included behavioural abnormalities, impaired predator avoidance, developmental deformities, delayed metamorphosis, and suppressed immune responses. Histopathological changes in liver and muscle tissues demonstrated systemic toxicity.

The review emphasized the urgent need for long-term ecotoxicological investigations in Meghalaya and Northeast India to assess the cumulative impacts of agricultural contaminants on amphibian populations.

6. BIOACOUSTICS AND ACOUSTIC DIVERSITY

Bioacoustic research emerged as an important field of amphibian study in Meghalaya during 2025. Warjri et al. (2025a) conducted a comprehensive acoustic analysis of nine anuran species representing six families.

The study investigated temporal and spectral call characteristics of species including *Hyla annectans, Hylarana leptoglossa, Clinotarsus alticola, Microhyla mymensinghensis, Kaloula pulchra, Rhacophorus bipunctatus, Raorchestes shillongensis, Minervarya pierrei,* and *Leptobrachium smithi.*

Importantly, advertisement calls of *Hylarana leptoglossa, Clinotarsus alticola, Microhyla mymensinghensis,* and *Rhacophorus bipunctatus* were documented for the first time. Bioacoustic analyses provided critical information for species identification, taxonomy, ecological behaviour, and conservation.

The study demonstrated that acoustic diversity in Meghalaya amphibians remains poorly explored and highlighted the potential of bioacoustics as a non-invasive monitoring tool for amphibian populations.

7. TAXONOMY, SPECIES DISCOVERY, AND CRYPTIC DIVERSITY

7.1 Discovery of New *Amolops* Species

Recent taxonomic studies revealed substantial hidden amphibian diversity in Meghalaya. Saikia et al. (2025a) documented the discovery of *Amolops shillong* from urban freshwater habitats in Shillong. Using integrative taxonomic approaches involving molecular phylogenetics and morphological analyses, the authors identified a shallow divergent lineage distinct from other congeners.

The species was found within urban landscapes and faced threats from habitat disturbance and harvesting for consumption. The study highlighted the ecological importance of urban freshwater habitats and demonstrated that urban ecosystems can support cryptic amphibian diversity.

Another important taxonomic contribution was the description of a new species of *Amolops* from Siju Cave in South Garo Hills (Saikia et al., 2025b). Unlike most members of the *Amolops marmoratus* group that inhabit cascade environments, the newly described species was adapted to a cave ecosystem.

Morphological and genetic analyses confirmed the distinctiveness of the species and highlighted the importance of cave ecosystems in amphibian diversification.

7.2 Discovery of New *Raorchestes* Species

Warjri et al. (2025b) described two new bush frog species, *Raorchestes jakoid and Raorchestes jadoh,* from the Khasi Hills of Meghalaya. The study used integrative approaches combining morphology, molecular phylogenetics, and bioacoustics.

Phylogenetic analyses confirmed the placement of the new species within the Raorchestes parvulus species complex. The findings emphasized the remarkable cryptic diversity of Meghalaya amphibians and suggested that many additional undescribed species may still exist in Northeast India.

7.3 Distributional Records and Biodiversity Expansion

Das et al. (2025) reported the first distributional record of *Minervarya asmati* from Meghalaya based on morphological examination and molecular analyses using 16S rRNA sequences.

The discovery extended the species distribution by approximately 260 km northward and increased the known amphibian diversity of Meghalaya to 62 species. The study highlighted the importance of systematic field surveys and molecular tools in documenting amphibian diversity.

8. CONSERVATION BIOLOGY AND COMMUNITY FORESTS

8.1 Role of Community Reserved Forests

Conservation-oriented studies emphasized the ecological significance of community-managed forests in Meghalaya. Tron et al. (2022) highlighted the role of community reserve forests in conserving amphibian diversity.

Managed traditionally by Khasi, Jaintia, and Garo tribal communities, these forests provide stable breeding habitats, oviposition sites, and suitable microclimatic conditions for amphibians. The study demonstrated that many newly discovered amphibian species have been documented from such forests.

Community reserve forests were identified as critical refugia for amphibian populations in the face of increasing urbanization, deforestation, mining, and habitat fragmentation.

8.2 Amphibians of Meghalaya: A Documentation Milestone

The publication “Amphibians of Meghalaya” by Saikia et al. (2025) represented a major milestone in documenting the amphibian diversity of the state.

The book documented 60 amphibian species with detailed descriptions, colour photographs, diagnostic characters, and distributional information. The publication also resolved historical taxonomic ambiguities and served as a valuable resource for researchers, conservationists, forest officers, and students.

9. CURRENT RESEARCH TRENDS IN MEGHALAYA AMPHIBIAN STUDIES

The review of amphibian studies conducted between 2020 and 2025 reveals several important research trends:

1. Increased use of integrative taxonomy combining morphology, molecular data, and bioacoustics.
2. Growing interest in reproductive ecology and breeding behaviour.
3. Expansion of ecotoxicological investigations involving agricultural contaminants.
4. Increased focus on developmental plasticity and embryology.
5. Recognition of community forests and urban freshwater habitats as important conservation areas.
6. Rapid discovery of cryptic and previously undescribed amphibian species.

The integration of molecular phylogenetics and acoustic analyses has significantly improved species identification and understanding of amphibian diversity in Meghalaya.

10. RESEARCH GAPS

Although amphibian research in Meghalaya has progressed considerably in recent years, several important gaps still remain. Most studies conducted so far are short-term and restricted to specific

localities, making it difficult to understand long-term population trends, seasonal fluctuations, and the impacts of climate change on amphibian diversity. Information on amphibian diseases such as chytridiomycosis and ranavirus infections is also extremely limited, despite their global role in amphibian declines.

In addition, very few studies have examined how changing rainfall patterns, temperature variation, and other climatic factors influence breeding behaviour, distribution, and survival of amphibians in the region. Many habitats, particularly limestone caves, high-altitude forests, and remote stream ecosystems, remain poorly explored and may still harbor undiscovered or endemic species. Furthermore, studies involving conservation genetics, population connectivity, and genomic diversity are largely absent, limiting our understanding of species adaptation and evolutionary relationships. Ecotoxicological research in Meghalaya has mainly focused on urea fertilizers, while the effects of pesticides, heavy metals, pharmaceutical pollutants, and microplastics on amphibian health and development remain insufficiently studied. These gaps highlight the urgent need for long-term, multidisciplinary, and conservation-oriented research on the amphibians of Meghalaya.

11. FUTURE PREDICTIONS AND DIRECTIONS

The future of amphibian research in Meghalaya appears highly promising due to rapid advancements in molecular biology, bioacoustics, ecological modelling, and modern conservation technologies (Fig. 1). Recent discoveries of new and cryptic amphibian species suggest that many more undescribed species may still exist in the forests, streams, caves, and high-altitude habitats of the region. In the coming years, automated acoustic monitoring and machine learning-based call recognition systems are expected to become valuable tools for monitoring amphibian populations and assessing biodiversity. Future studies will also likely focus on understanding the impacts of climate change on breeding phenology, larval development, altitudinal distribution, and habitat suitability of amphibians. The growing field of conservation genomics may help identify genetically vulnerable populations and support effective conservation planning. Equally important will be the role of traditional community reserve forests, where collaborative efforts between local communities, researchers, and government agencies can strengthen amphibian conservation initiatives. In addition, ecotoxicological research is expected to expand beyond fertilizer studies to include pesticides, pharmaceutical pollutants, heavy metals, and emerging contaminants that may affect amphibian physiology, reproduction, and survival. Together, these approaches will significantly enhance our understanding and conservation of Meghalaya's rich amphibian diversity.

12. NOVELTY OF THE PRESENT REVIEW

The present review represents one of the first comprehensive syntheses of amphibian research conducted in Meghalaya from 2020 to 2025. Unlike previous isolated studies focusing on individual species or ecological aspects, this review integrates findings from reproductive ecology, developmental biology, bioacoustics, taxonomy, ecotoxicology, and conservation biology.

The review highlights recent discoveries of cryptic species, the ecological significance of temporary wetlands and community reserve forests, and emerging conservation challenges in Meghalaya. Furthermore, it identifies major research gaps and proposes future directions including climate change research, disease surveillance, conservation genomics, and long-term ecological monitoring.

By synthesizing recent scientific progress, the review provides a consolidated baseline for future amphibian research and conservation planning in Northeast India.

13. CONCLUSION

Amphibian research in Meghalaya from 2020 to 2025 has significantly improved understanding of the state's rich anuran diversity, reproductive ecology, developmental adaptations, bioacoustics, and conservation challenges. The discovery of new species, novel reproductive modes, unique developmental patterns, and cryptic diversity demonstrates that Meghalaya remains an important center of amphibian diversification in Northeast India.

Research also revealed the ecological significance of temporary wetlands, stream ecosystems, cave habitats, urban freshwater systems, and community reserve forests in supporting amphibian populations. However, increasing anthropogenic pressures including habitat destruction, agricultural contamination, urbanization, and climate variability pose serious threats to amphibian survival.

Future studies integrating molecular ecology, bioacoustics, ecotoxicology, conservation genomics, and climate modelling are essential for understanding and conserving Meghalaya's amphibian diversity. Long-term ecological monitoring and community-based conservation approaches will be critical for ensuring the persistence of amphibian populations in this globally significant biodiversity hotspot.

14. ACKNOWLEDGEMENT

The authors sincerely thank the Department of Zoology, St. Edmund's College, for providing academic support. We are grateful to Dr. Jenniefer Dkhar, Saffishisha Sawkmie and Jason Andrew Shangpliang and for their valuable inputs and constructive suggestions that significantly improved the manuscript's quality.

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Figure 1: Future predictions and directions (AI generated)

Table 1. Major amphibian studies conducted in Meghalaya (2020–2025)

	Focus	s/Topic	Major Findings
	eproductive ecology	*lus naso*	Explosive breeding and parental care
	eproductive modes	le species	Seven reproductive modes documented
	evelopmental biology	*lus naso*	46 developmental stages described
	cotoxicology	*hrynus melanostictus*	Urea-induced deformities
	onservation	unity forests	Importance of reserved forests
	reeding ecology	*nnectans*	Chorus formation and clutch variation
	ream ecology	*ophrys parva*	Rainfall-dependent breeding
	evelopmental plasticity	*nnectans*	Altitudinal developmental variation
	ioacoustics	nuran species	First acoustic records
	axonomy	*ps shillong*	New species discovery
	axonomy	*estes jakoid* and *R. jadoh*	Cryptic diversity documented
	eproductive ecology	*arya nepalensis*	Explosive breeding and parental care