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ARTIFICIAL INTELLIGENCE IN ZOOLOGY: A SYSTEMATIC REVIEW OF ANIMAL COMMUNICATION STUDIES WITH IMPLICATIONS FOR PAKISTAN

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Abstract
Artificial intelligence (AI) and machine learning (ML) are rapidly transforming bioacoustics research by enabling large-scale detection, classification, and preliminary interpretation of animal signals. This systematic review synthesizes recent advances in AI-enabled animal communication research across multiple taxa including birds, cetaceans, bats, and primates—focusing on methods such as deep neural networks, sequence models, and representation learning. Key applications range from species monitoring and individual identification to behavioral inference and early steps toward semantic decoding. Following PRISMA-2020 reporting guidelines (Page et al., 2021), we review global studies and outline their relevance to Pakistan's conservation priorities. A national framework is proposed that emphasizes (i) bioacoustics observatories and open datasets, (ii) an AI analysis stack built on open-source models, (iii) an ethics and governance layer to prevent misinterpretation, and (iv) integration with biodiversity monitoring and protected-area management. Key developments motivating this review include Bird NET for avian monitoring (Kahl et al., 2021), large-scale bioacoustics challenges (Stowell et al., 2019), sperm-whale "phonetic alphabet" research (Kirshenbaum et al., 2023), and emerging dolphin-focused AI models such as Dolphin Gemma (Google Research, 2024). These advances, particularly in transfer learning (Morfi et al., 2023), make it feasible to extract meaningful communication patterns from smaller datasets—an essential breakthrough for data-scarce regions such as South Asia. We argue that integrating AI-assisted conservation acoustics in Pakistan could enhance monitoring of the Indus River dolphin, migratory birds along the Indus Flyway, and insectivorous bats critical to agro-ecosystems. Universities can lead by developing training programs, government agencies should embed AI monitoring into national biodiversity strategies, and NGOs can broker collaborations with international experts.

Keywords: *Bioacoustics; Deep Learning; Interspecies Communication; BIRDNET; Project CETI; Dolphin Gemma; Indus River dolphin; Pakistan; conservation policy*

Introduction

Animal communication is a cornerstone of behavioral ecology, providing the mechanisms by which organisms coordinate reproduction, foraging, predator avoidance, territoriality, and social cohesion. Among the multiple modalities of signaling visual, chemical, tactile acoustic communication is especially pervasive because it can be transmitted over distance, through darkness, vegetation, and turbid water, and can encode rich temporal structure (Catchpole & Slater, 2008; Seyfarth & Cheney, 2017). Classic ethology, supported by spectrographic analysis and painstaking manual annotation, established foundational insights into the structure and function of vocalizations across taxa (Catchpole & Slater, 2008). Yet the scale and complexity of contemporary datasets often millions of hours of passive acoustic recordings render traditional workflows impractical and risk overlooking subtle regularities in call types, sequences, and context-dependent variation (Seyfarth & Cheney, 2017).

Over the past decade, artificial intelligence (AI) and machine learning (ML) have transformed this landscape. Deep neural networks trained on time–frequency representations (e.g., spectrograms) now underpin large-scale species recognition (Kahl et al., 2021), robust echolocation detection for bats in complex soundscapes (Stowell et al., 2019), and the modeling of higher-order combinatorial structure in cetacean vocal systems (Kershenbaum et al., 2023). These methods move the field beyond detecting *that* a call occurred toward cautiously inferring *what* may be communicated—via representation learning, sequence modeling, and cross-context generalization—while maintaining appropriate skepticism about "translation" claims and insisting on behavioral validation (Seyfarth & Cheney, 2017).

For Pakistan, this methodological shift is both timely and consequential. The country encompasses a mosaic of ecosystems—from Himalayan and Hindukush highlands to Indus floodplains, arid deserts, and coastal mangroves—that support acoustically active, conservation-relevant taxa. Flagship examples include the Endangered Indus River dolphin **(***Platanista gangetica minor***)**, whose turbid-water ecology favors **passive** acoustic monitoring; globally significant migratory birds traversing the Indus Flyway and concentrating at Ramsar wetlands; and insectivorous bats that deliver substantial pest-suppression services in agro-ecosystems (WWF-Pakistan, 2022; Ramsar Secretariat, 2022; Khan, 2006). AI-enabled bioacoustics offers non-invasive, scalable, and cost-effective tools to track populations, detect anthropogenic pressures (e.g., vessel noise, habitat fragmentation, urban sound), quantify ecosystem services, and generate decision-relevant indicators for biodiversity policy.

Objective

This paper systematically reviews global advances in AI-assisted studies of animal acoustic communication and develops a Pakistan-specific roadmap for national adoption. Specifically, we
(i) synthesize methods and evidence across key taxa (birds, cetaceans, bats, primates);
(ii) identify opportunities and constraints for applying these tools within Pakistan's ecological and institutional contexts; and
(iii) propose an implementation framework spanning sensing networks, model adaptation, validation and ethics, and policy integration to support evidence-based biodiversity monitoring and conservation (Kahl et al., 2021; Stowell et al., 2019; Kershenbaum et al., 2023; WWF-Pakistan, 2022; Ramsar Secretariat, 2022; Khan, 2006).

Methodology

This study employed a systematic review approach to examine the application of artificial intelligence (AI) and machine learning (ML) in animal acoustic communication, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Page et al., 2021) to ensure rigor, transparency, and reproducibility. The review focused on publications from 2015 to 2025, reflecting a decade of rapid AI development. Eligible studies explicitly applied AI or ML to animal acoustic communication tasks such as acoustic event detection, vocalization classification, segmentation of sound units, individual identification, and sequence modeling. Only research that reported methodological details, datasets, performance metrics, or implications for zoological research and conservation was included, while studies limited to hardware design, those addressing human speech without non-human application, and purely theoretical discussions without computational implementation were excluded. Literature searches were conducted across

Web of Science, Scopus, and Google Scholar, supplemented with specialized repositories and project platforms such as BirdNET and Project CETI to capture influential but non-traditional sources. Reference lists of included studies were also screened for additional relevant work. The search strategy relied on Boolean keyword combinations (e.g., "deep learning" OR "machine learning" AND "bioacoustics"; "AI" AND "animal communication" AND "birds" OR "dolphins" OR "bats" OR "primates"), applied iteratively to ensure broad coverage across taxa and methodological approaches. Screening was carried out in two stages: first, titles and abstracts were examined to exclude irrelevant studies; second, the full texts of shortlisted papers were evaluated against the eligibility criteria. To reduce bias, two independent reviewers performed the screening, resolving discrepancies through discussion and consensus.

Data from each study were extracted using a structured framework that captured taxonomic focus, dataset characteristics, AI/ML methodology, computational tasks, performance metrics, reported limitations, and conservation relevance. Due to heterogeneity in datasets, algorithms, and evaluation criteria, a qualitative synthesis was undertaken instead of a meta-analysis. Studies were thematically grouped according to taxonomic category, computational task, and level of deployment (laboratory validation, pilot trials, or operational monitoring), enabling the identification of methodological innovations, cross-cutting trends, and research gaps, particularly in relation to conservation applications within the Pakistani ecological context. The overall study selection process was documented through a PRISMA 2020 flow diagram (Figure 1), which illustrates the number of records identified, screened, assessed for eligibility, and ultimately included in the final review.

Literature Review

The study of animal acoustic communication has long emphasized the role of signals in conveying identity, motivation, and ecological context (Catchpole & Slater, 2008). Traditional bioacoustics methods relied heavily on manual spectrogram inspection and handcrafted acoustic features, which provided valuable biological insights but were limited in scalability, especially when applied to large datasets or complex ecosystems. With the rapid development of artificial intelligence (AI) and machine learning (ML), particularly deep learning, researchers are now able to automate feature extraction, detect vocal events with higher accuracy, and model sequential structures within animal vocalizations (Morfi et al., 2023; Kershenbaum et al., 2023). These advancements represent a paradigm shift from descriptive approaches toward computational pipelines that can operate at ecological and even planetary scales.

Methodological progress in bioacoustics has followed a clear trajectory. Early computational pipelines typically employed mel-frequency cepstral coefficients (MFCCs) as input features, analyzed using support vector machines (SVMs) or hidden Markov models (HMMs). While effective for small, well-structured datasets, such approaches struggled with the variability and noise inherent in real-world field recordings. Contemporary methods, by contrast, leverage deep neural architectures, often converting raw audio into spectrograms that can be processed by convolutional or attention-based networks. These models support tasks such as acoustic event detection, multi-label classification, denoising, and even sequence modeling, thereby offering more robust solutions across taxa (Kahl et al., 2021). Furthermore, the challenge of limited annotated datasets is increasingly addressed through transfer learning, where pre-trained models are adapted to new species or habitats, significantly enhancing generalization performance (Morfi et al., 2023).

Among avian studies, BirdNET stands out as a landmark achievement in bioacoustics AI. Capable of classifying nearly 1,000 bird species, BirdNET integrates deep learning with citizen science participation, enabling large-scale biodiversity monitoring, migration tracking, and long-term population studies (Kahl et al., 2021). Its impact is particularly evident in the way it democratizes data collection, allowing non-specialists to contribute to scientific monitoring. However, despite its global scope, BirdNET's training datasets remain biased toward North American and European soundscapes, leaving South Asian avifauna, including many species critical to Pakistan's biodiversity, underrepresented. This limitation underscores the importance of developing region-specific corpora to ensure equitable coverage.

Cetacean research has also benefitted from AI integration, particularly in the analysis of dolphin whistles and sperm whale codas. Notable initiatives include Project CETI, which has demonstrated the combinatorial structure—or "syntax"—of whale vocalizations (Kershenbaum et al., 2023), and Google's DolphinGemma model, which applies foundation-model techniques to marine communication (Google Research, 2024). These approaches move the field closer to structural interpretation of cetacean communication. Yet, scholars caution against anthropomorphic interpretations, emphasizing the need for behavioral validation and multimodal evidence to ensure robust conclusions (Seyfarth & Cheney, 2017).

In the case of bats, standardized datasets and machine learning competitions have spurred progress in classifying echolocation calls, with significant implications for both conservation and agriculture. Echolocation-based monitoring not only informs species diversity assessments but also supports policy by quantifying the ecosystem services that bats provide, particularly in pest control (Stowell et al., 2019). Nonetheless, challenges remain due to overlapping calls, individual variability, and the context-dependent nature of bat vocalizations, all of which complicate automated recognition.

Research on primates and other mammalian taxa has revealed rich communication systems, including graded alarm calls and complex social signals. However, these studies often suffer from small datasets and high annotation costs, which limit the development of robust computational models. Transfer learning has emerged as a partial solution, enabling researchers to leverage knowledge from well-resourced datasets to improve performance on smaller, taxon-specific corpora (Morfi et al., 2023).

The bioacoustics community has also advanced through open science practices. Tools such as the BirdNET API and wrappers like birdnetR make state-of-the-art models accessible to researchers and citizen scientists alike, reducing technical barriers to entry. Nevertheless, existing global datasets continue to reflect geographic biases, highlighting the urgent need for regionally curated, locally labeled corpora, especially in underrepresented areas such as Pakistan (Ali, 2016). Such efforts would not only enhance global representativeness but also empower local conservation initiatives.

Beyond technical advancements, the ethical and governance dimensions of AI-driven bioacoustics have attracted growing attention. Claims of semantic content in animal communication demand exceptionally high evidentiary standards, including multimodal validation, preregistered hypotheses, and replication across independent datasets (Seyfarth & Cheney, 2017). Ethical frameworks further emphasize minimizing disturbance to animals during data collection, safeguarding sensitive location information to protect endangered species, and ensuring that data governance structures equitably distribute the benefits of bioacoustics research.

In the context of Pakistan, the potential of AI-enabled acoustic monitoring is particularly significant. The Indus River dolphin, an endangered freshwater cetacean, is ideally suited for passive acoustic monitoring using hydrophones (WWF-Pakistan, 2022). Similarly, Ramsar-designated wetlands provide important habitats where autonomous recording units (ARUs) can be deployed to monitor migratory birds and waterfowl (Ramsar Secretariat, 2022). Moreover, bat populations in agricultural landscapes represent a natural form of pest suppression, with acoustic monitoring offering a non-invasive tool for assessing their ecological and economic contributions (Khan, 2006). Despite these opportunities, Pakistan remains underrepresented in global datasets, underscoring the necessity of region-specific initiatives to bridge methodological innovation with local conservation priorities.

Results: Evidence Landscape

The systematic review revealed a diverse but uneven landscape of research applying AI and ML to animal acoustic communication. While some taxa, particularly birds and bats, already benefit from large-scale operational tools, others such as cetaceans and primates remain in earlier stages of computational exploration. Across all groups, progress reflects the growing sophistication of deep learning models, yet challenges remain in relation to data scarcity, environmental variability, and geographic biases.

For **birds**, BirdNET represents a transformative development in computational bioacoustics. By leveraging deep convolutional neural networks trained on vast datasets, BirdNET has achieved high accuracy in species detection and classification, making it one of the most widely adopted systems for avian monitoring (Kahl et al., 2021). Its deployment has supported global biodiversity assessments, long-term population monitoring, and even citizen science initiatives, where non-specialists can contribute valuable data using mobile devices. The strength of BirdNET lies not only in its accuracy but also in its scalability, allowing thousands of hours of recordings to be processed efficiently. Nevertheless, limitations remain evident. Background noise in natural habitats—such as wind, rainfall, or anthropogenic sounds—reduces model performance, particularly for quieter or less distinctive species. More importantly, South Asian and other under-represented avian communities are poorly represented in BirdNET's training corpus, which has historically focused on North America and Europe. This imbalance restricts the generalizability of results and highlights the urgent need for region-specific datasets, particularly in biodiversity hotspots such as Pakistan.

In cetaceans**,** AI has been applied to the analysis of dolphin whistles and sperm whale codas, revealing structural patterns that suggest a degree of combinatorial complexity. Studies have demonstrated that whale vocalizations may exhibit syntactic-like features, raising intriguing questions about the potential for symbolic communication in marine mammals (Kershenbaum et al., 2023). Building on this, large-scale initiatives such as Project CETI have employed advanced ML pipelines to decode whale communication, while Google's DolphinGemma represents one of the first attempts to develop a foundation model tailored to dolphin vocalizations (Google Research, 2024). These models provide a platform for identifying recurring structures, clustering call types, and even hypothesizing about the functional "grammar" of cetacean signals. However, despite these advances, major challenges persist. Unlike birds and bats, cetaceans are difficult to study due to the logistical constraints of underwater data collection, leading to relatively small and fragmented datasets. Furthermore, scholars caution against premature semantic claims; without behavioral validation and multi-modal corroboration, there is a risk of anthropomorphism or over-interpretation of statistical regularities.

Research on bats demonstrates the most direct operational impact of AI in conservation and ecosystem service studies. Automated classification systems now routinely analyze echolocation calls to identify species, monitor population trends, and assess habitat use (Stowell et al., 2019). These methods have been applied not only in conservation contexts but also in agricultural landscapes, where they provide evidence of bats' role in natural pest suppression. Such findings have informed ecosystem service valuation and policy recommendations, demonstrating the tangible link between acoustic AI tools and environmental management. Despite this progress, classification remains hindered by overlapping echolocation calls, particularly in regions were multiple species forage simultaneously. Echolocation variability, which can depend on behavioral context (e.g., hunting, navigation, social interaction), further complicates the task of developing generalizable models. While competitions and shared datasets have accelerated progress, these challenges underscore the need for more context-aware models and larger annotated corpora.

For primates and other mammals**,** the evidence base remains comparatively small but growing. Studies on alarm calls and social vocalizations reveal graded acoustic structures that are difficult to classify using traditional rule-based methods. Machine learning approaches, particularly transfer learning, have shown promise in addressing the challenge of small datasets by leveraging models pre-trained on unrelated corpora and adapting them to primate communication (Morfi et al., 2023). This approach improves generalization while reducing the dependency on expensive manual annotation. However, progress has been constrained by the cost and logistical complexity of collecting high-quality primate acoustic data, especially in dense forest environments where background noise is severe. While the evidence points to clear potential, primate studies remain at an earlier stage of methodological development compared to avian and bat research.

Taken together, these findings suggest that AI applications in bioacoustics have transitioned from experimental studies to practical tools in some domains, particularly birds and bats, while cetaceans and primates are beginning to demonstrate conceptual breakthroughs. Importantly, the review highlights that the success of these models is highly dependent on the size, quality, and representativeness of datasets. Geographic and taxonomic biases remain a significant barrier, with most advances driven by well-resourced regions and species. For Pakistan, this represents both a gap and an opportunity: the country's unique ecological systems, from Indus River dolphins to migratory wetland birds and agricultural bat populations, remain underrepresented in global datasets, suggesting that localized efforts could contribute significantly to both national conservation goals and the global research landscape.

The findings of this review reveal a clear distinction between recognition-oriented tasks and the more ambitious goal of semantic interpretation. Recognition tasks—such as identifying species, individuals, and temporal patterns of vocal activity—are relatively mature, with high-performing systems like BirdNET and automated bat call classifiers already deployed in operational settings. These applications have demonstrated substantial accuracy and scalability, enabling biodiversity assessments at national and continental levels. By contrast, semantic interpretation—the attempt to infer meaning, syntax, or communicative intent from animal signals—remains in its infancy. While studies on whale codas and dolphin whistles suggest structural complexity, claims about animal "language" must be treated with cautious optimism, as they risk anthropomorphism without behavioral validation (The Guardian, 2025). Future progress will require multimodal data integration, preregistered hypotheses, and stronger evidentiary standards to move beyond correlation toward interpretation.

For Pakistan, the potential applications of AI-enabled acoustic monitoring are both timely and transformative. The Indus River dolphin, an endangered freshwater cetacean, is ideally suited for passive acoustic monitoring using hydrophones, which could support distribution mapping, inform water management strategies, and reduce risks of bycatch in fishing gear (WWF-Pakistan, 2022). Migratory bird populations at Ramsar-listed wetlands such as Haleji, Keenjhar, and Uchhali can be monitored using autonomous recording units (ARUs), with fine-tuned BirdNET models enabling cost-effective biodiversity assessments (Ramsar Secretariat, 2022). In agricultural landscapes, echolocation monitoring of bats offers a powerful tool for quantifying natural pest suppression and guiding pesticide policy, thereby linking conservation directly to ecosystem services and rural livelihoods (Khan, 2006). Collectively, these applications highlight that bioacoustic AI is not a distant aspiration but an actionable opportunity for Pakistan's conservation sector.

Nevertheless, significant challenges constrain implementation. Pakistan faces chronic noise pollution in both terrestrial and aquatic environments, which reduces signal quality and complicates automated classification. Dataset scarcity, inadequate technical infrastructure, and limited interdisciplinary expertise at the intersection of ecology and machine learning further inhibit progress. To overcome these barriers, this review recommends the establishment of a Pakistan Bioacoustics Commons a centralized national repository for acoustic datasets, standardized annotation protocols, and model sharing. Such an initiative would foster collaboration among universities, NGOs, and government agencies while ensuring that locally relevant data inform conservation and policy decisions.

Pakistan-Focused Implementation Plan

To translate the global evidence base into actionable strategies for Pakistan, this review proposes a phased implementation plan. The first priority is the deployment of hydrophones across key tributaries of the Indus River system, in collaboration with WWF-Pakistan, to monitor the distribution and behavioral ecology of the endangered Indus dolphin. The second priority is avian monitoring at major Ramsar wetlands including Haleji, Keenjhar, and Uchhali—through the deployment of ARUs, with localized BirdNET models fine-tuned on South Asian species to overcome regional data gaps. The third priority is bat monitoring in Punjab and Sindh croplands using ultrasonic transects, paired with agricultural pesticide usage data, to quantify the economic and ecological contributions of bats as natural pest regulators.

These priorities can be embedded in a layered implementation framework that integrates four components: (i) sensing and data collection, (ii) AI model development and adaptation, (iii) validation and semantic interpretation, and (iv) ethics, governance, and policy integration. A conceptual diagram (Figure 2) illustrates how these layers interact, emphasizing that robust AI models must be built on reliable data collection, validated with ecological evidence, governed by ethical frameworks, and embedded within national biodiversity policies. This structured approach ensures not only technical innovation but also ecological relevance and long-term sustainability.

Recommendations

The successful adoption of AI-driven bioacoustics in Pakistan requires coordinated action across multiple stakeholders. Universities should establish dedicated AI-bioacoustics laboratories, develop interdisciplinary curricula that integrate ecology and machine learning, and mandate open data-sharing policies to accelerate innovation. Government agencies should launch a National Acoustic Biodiversity Observatory, embedding acoustic indicators into biodiversity reporting frameworks and aligning them with Sustainable Development Goals (SDGs). Non-governmental organizations can play a catalytic role by mobilizing citizen science initiatives in local languages, empowering communities to participate in data collection while ensuring equitable data-sharing practices. Finally, funders and industry partners should support the development of edge-AI devices, provide maintenance budgets for field equipment, and encourage South–South collaborations to ensure that Pakistan benefits from regional expertise and shared resources.

Limitations

This review is situated within a rapidly evolving research landscape, where advances in algorithms, hardware, and data infrastructures are progressing at an accelerated pace. While the global evidence base is extensive, much of it remains concentrated in the Global North, particularly in North America and Europe. Consequently, several of the Pakistan-specific proposals presented here remain conceptual, requiring pilot studies to assess feasibility under local ecological and infrastructural conditions. In addition, heterogeneity in the reporting of performance metrics, datasets, and evaluation methods across studies limited the scope for conducting a meta-analysis. These limitations highlight both the promise and the caution necessary when extrapolating global findings to Pakistan's unique biodiversity challenges.

Conclusion

Artificial intelligence has transformed bioacoustics from a niche analytical tool into a scalable approach for monitoring biodiversity across entire continents. Automated recognition systems are now mature enough to support conservation and citizen science at unprecedented scales, while early efforts in semantic interpretation signal an emerging frontier in animal communication research. For Pakistan, AI-enabled acoustic monitoring offers a cost-effective and transformative pathway to modernize biodiversity science, strengthen conservation of endangered species such as the Indus dolphin, enhance management of Ramsar wetlands for migratory birds, and quantify the ecological and economic value of bats in agriculture. By investing in localized datasets, interdisciplinary expertise, and national data-sharing infrastructures, Pakistan has the opportunity not only to align with the SDGs but also to position itself as a regional leader in computational zoology and AI-driven conservation science.

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