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Acoustic Communication Studies on Birds in India

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Abstract

The scientific study of acoustic signals and their ecological functions in birds is termed avian bioacoustics. This field has gained significant attention worldwide, as evident from the large volume of relevant research publications. However, despite the presence of more than 1,300 avian species in India, limited studies appear in this field. Moreover, the research made so far on bird models in India seems scattered and relatively underrepresented in the global literature. This review addresses this issue by compiling the studies dealing with acoustic communication in birds in India, with a focus on research trends, methodologies, and key discoveries made so far. Publications on the neural mechanisms of song production and automated species recognition or machine-learning classification in avian bioacoustics are not included in this review.

Keywords: Anthropogenic noise, avian bioacoustics, bird call, female song, geographic song variation, song repertoire, song sharing.

Introduction

Communication is a fundamental aspect of animal behavior, allowing individuals to exchange information essential for survival and reproduction (Garcia & Favaro, 2017). Vocal communication plays a crucial role in the behavioral ecology of animals, serving essential functions in mate attraction, territorial defense, and social interaction (Catchpole & Slater, 2008; Webster & Podos, 2018).

Birds are notable for their sophisticated vocalizations, which form a key part of the 'acoustic niche' in various ecosystems worldwide (Catchpole & Slater, 2008). Avian vocalizations range from simple calls to complex songs, each fulfilling distinct ecological and social functions (Andersson, 1994). The scientific study of these acoustic signals and their ecological functions in birds is termed avian bioacoustics. It has been identified as an increasingly important and useful tool in conservation with applications in monitoring threatened and endangered species, biodiversity, habitat health, noise pollution, impacts of climate change, and more (Laiolo, 2010; Kloepper & Simmons, 2014; Teixeira *et al.*, 2019; Penar *et al.*, 2020). This field bridges behavioral ecology, physiology, neurobiology, and computational sciences, thus making it highly interdisciplinary.

Avian acoustic communication has been extensively studied worldwide. Internationally, bioacoustics is a mature field with extensive empirical, theoretical and technological contributions, with research spanning song learning, species recognition, habitat acoustics and the impacts of anthropogenic noise (Baker, 2001; Slater, 2003; Beecher & Brenowitz, 2005; Catchpole & Slater, 2008). In contrast, Indian ornithology has historically emphasized taxonomy, distribution, and conservation, with bioacoustics studies only recently gaining momentum and recognition. With over 1,300 bird species available in India, this discrepancy highlights both a research gap and an opportunity for India to play an important role in avian bioacoustics.

This review article has a primary objective of consolidating and assessing the progress of avian acoustic communication research in India over the past few decades, which seems scattered and relatively underrepresented in the global literature. By bringing together the available findings, this review aims to provide a comprehensive overview of the research trends, methodologies, and key discoveries in this field. It also seeks to promote collaboration among researchers and encourage the use of bird species in India as model systems for addressing important questions in avian bioacoustics such as latitudinal and altitudinal influences on song, song dialect, effects of habitat on acoustic structure, song sharing, comparative bioacoustics among closely related species. This is because India constitutes a major part of the Oriental Realm, with wide latitudinal (08° 04' to 37° 06' N) and longitudinal (68° 07'to 97°25'E) extents,

and is situated within the tropical monsoon belt. Its varied topography, considerable isolation, and monsoon climate impart to it enormous complexity and habitat diversity.

Moreover, widely distributed bird species occurring across both peninsular India and the Himalayan foothills provide valuable model systems for comparative bioacoustics research. Species such as the black drongo (*Dicrurus macrocercus*), red-vented bulbul (*Pycnonotus cafer*), common myna (*Acridotheres tristis*), Oriental magpie robin (*Copsychus saularis*), purple sunbird (*Cinnyris asiaticus*), house sparrow (*Passer domesticus*) exhibit broad geographic and elevational ranges, occurring across diverse habitats from tropical lowlands to subtropical hill regions. Their widespread distribution, high vocal activity, and adaptability to varying environmental conditions make them particularly suitable for examining how ecological gradients, including altitude, habitat structure, and anthropogenic pressures, influence acoustic signal structure and communication dynamics. Such species thus offer a robust framework for generating insights with broader cross-regional relevance in avian bioacoustics.

Methodology

This study includes literature identification and review to assess and consolidate the research conducted on avian acoustic communication in India so far. A comprehensive literature search was conducted across multiple electronic databases, including Web of Science Core Collection, Scopus, PubMed/MEDLINE, Google Scholar, JSTOR, Science Direct, Springer Link and Wiley Online Library. The search strategy employed keywords such as avian acoustic communication, avian bioacoustics, bird songs and calls, acoustic communication in birds in India, pied bush chat (*Saxicola caprata*), using appropriate filters, and covered studies from 2000 to 2025.

The study selection followed a three-stage process: (i) Identification phase: Initial database searches identified 187 records in the form of research articles, with an additional 26 records from other sources, totaling 213 records. (ii) Screening phase: After removing 19 duplicates, 194 records underwent title and abstract screening, resulting in 87 exclusions due to geographic irrelevance and thematic mismatch, and 107 articles proceeding to full-text assessment. (iii) Eligibility phase: Full-text assessment of 107 articles led to the exclusion of 37 articles for various reasons, such as inappropriate focus, studies conducted outside India, research on the neural mechanism of song production and automated species recognition or machine-learning classification in avian bioacoustics, methodology issues, and language barriers. Finally, a total of 70 studies were included in this review.

Avian acoustic communication studies from India

India's first systematic and data-driven research paper in the field of avian bioacoustics was published in the year 2000 (Bhatt *et al.*, 2000). This research paper dealt with the structure and biological significance of songs of a well-known songbird in India, the Oriental magpie robin (*Copsychus saularis*). Bhatt *et al.*, (2000), in this detailed investigation, focused on the territorial songs and calls of the Oriental magpie robin. They recorded the vocalizations of males within their territories and found that the territorial song was most prominent during territory establishment and throughout the breeding season. However, calls were mostly given in the non-breeding season, when males defended food resources. Songs and calls showed clear differences: songs tended to have lower frequencies and faster pulse rates, features that are likely to help them travel longer distances. This not only makes the males more noticeable but also serves to advertise their presence to rivals and attract potential mates during the breeding season. With the publication of this research paper, a series of research papers in the field of avian bioacoustics, albeit insufficient, began to be published from India.

A subsequent research paper focused on the structure and biological significance of the call repertoire of the Oriental magpie robin. This study, conducted by Kumar & Bhatt (2001), was based on the physical features of the calls and the social contexts under which they were delivered. They identified six primary call types in the call repertoire of this species: territorial, emergence/roosting, threat, submissive, begging, and distress calls.

In a further study on the singing behavior of the Oriental magpie robin, Singh *et al.* (2019a) focused on its two main song categories: discrete songs and continuous songs. They demonstrated that discrete songs are delivered throughout the breeding season at different times of the day, while continuous songs are used more selectively, often during courtship, male–male rivalry, and mate attraction by this species. Song bouts ranged from just a few minutes to nearly an hour. Cumulative curves of distinct song types against the number of songs recorded for each individual showed no clear asymptote, suggesting that the full repertoire was not exhausted. Moreover, repertoire composition shifted across years due to the addition or loss of song types, indicating that the Oriental magpie robin could be an open-ended song learner.

Bird song has been assumed to be the primary trait of males only. However, female song is believed to be widespread across bird species and ancestral (Garamszegi *et al.*, 2007; Odom *et al.*, 2014). Unfortunately, studies on the structure and function of female song have remained almost untouched in India. However, Indian ornithologists have attempted to address this rarely reported behavior using Indian bird models (Kumar & Bhatt, 2002; Sethi *et al.*, 2012a). Kumar & Bhatt (2002) studied the structure and context of female song in the Oriental magpie robin. Unlike males, the females, in their study, sang occasionally and for a short period in the presence of the male. The basic structure of the songs did not vary between sexes, and female song appeared to stimulate males to sing during the breeding season.

Female song has also been documented in the pied bush chat from India. Sethi *et al.* (2012a) studied the structure and context of female song in this species. All females in the study were found to sing. Like males, their songs were found to be varied and complex. They did not find a significant difference in any of the song type characteristics of the female song when compared with males. However, mean song repertoire size for males and females differed significantly. They observed females singing occasionally under the following two circumstances. First, females sang during aggressive interactions with floater or neighboring females. Second, females used song to answer to their mate. They did not observe females choosing any specific song type for delivery under these two contexts. They also observed song answering in the pied bush chat, where females responded immediately to the song of their mate with their own songs.

Dealing with the structure and functions of various call types used by birds, another research paper was published on the vocal repertoires of the red-vented bulbul from India. In this study, Kumar & Bhatt (2000) examined and characterized the vocal signals by their acoustic properties. The possible significance of these call types was inferred from the contexts under which they were produced. They identified six main types of vocalizations: contact, roosting, alarm, twittering, distress, and begging signals. Two acoustically distinct alarm calls were produced in response to different levels of predation threat. These calls differed significantly in most acoustic parameters, including minimum frequency, maximum frequency, frequency range, duration, interval, and call rate, while dominant frequency remained relatively unchanged.

In another study, Sethi & Bhatt (2008) studied the call repertoire of the Indian Chat (*Cercomela fusca*) and examined both the structure and role of its various call types. They identified eight

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distinct call types: territorial calls, begging calls, feeding calls, alarm calls, threat calls, contact calls, distress calls, and roosting or emergence calls. Similarly, Sethi *et al.* (2012b) examined the acoustic structure and sociobiological relevance of different call types in a tropical songbird, the pied bush chat. This species produced five distinct call types, namely territorial, begging, alarm, contact, and distress calls. Of these, three were produced by young ones, while the remaining two were restricted to adults. The sociobiological functions of each call type were inferred from the behavioral and ecological contexts in which they were observed.

Song repertoire size varies greatly among bird species. Some species have only one song per individual, whereas others have several hundred or even thousands of songs per individual. The structure and use of song repertoires are believed to be traits to understand proximate and functional issues in animal communication. Additionally, studies on song repertoires can provide insights into the circumstances under which the repertoire was acquired and possibly provide information on a male's quality (Catchpole & Slater, 2008). To understand the role and evolution of repertoire sizes in species, it becomes a pre-requisite that one should know the accurate repertoire size of the species to be studied. To address this issue, Sethi *et al.* (2011a) estimated the song repertoire size of the pied bush chat in India, which ranged from 13 to 29 song types with a mean repertoire of 22.2 ± 6.6 (SD) song types. Since plots of the number of newer song types versus the total number of songs uttered approached an asymptote for all the males studied, they were able to determine complete song repertoire sizes of the study species.

Vocal repertoire size and complexity in birds are strongly shaped by their social systems. Species that live in social groups often exhibit larger and more diverse vocal repertoires, reflecting the need to mediate complex social interactions, coordinate group activities, and maintain cohesion (Freeberg *et al.*, 2012). While this relationship is well established in many mammalian systems, evidence from birds remains comparatively limited. Yambem *et al.*, (2021) presented evidence for complex vocal communication in a cooperatively breeding passerine, the jungle babbler (*Turdoides striata*) from India. They found that jungle babblers possess a rich vocal repertoire of 15 distinct call types that play a key role in coordinating social behaviors such as group movement, foraging, brood care, aggression, and vigilance. Notably, more than half of the vocalizations were associated with acoustic vigilance, a feature commonly observed in cooperatively breeding birds. Overall, their findings highlighted the relationship between sociality and communicative complexity and set the stage for future work on the combinatorial rules underlying avian vocal systems.

It is well known that birds employ vocal signals as key mechanisms for territory establishment, mate attraction, and pair-bond maintenance during the breeding season (Catchpole & Slater, 2008). However, they also serve important functions during the non-breeding season. This interesting aspect of avian bioacoustics was first addressed in India by Katti (2001). He examined vocal communication and territoriality during the non-breeding season in the greenish leaf warbler (*Phylloscopus trochiloides*). The important feature of this study was the selection of a migrant warbler as a study model, as migratory species provide insight into how vocal behavior functions when birds are no longer competing directly for mates but may still compete for resources such as food and space. This study revealed that the greenish leaf warbler defends territories using simple calls to announce ownership and more complex songs during prolonged boundary negotiations.

Kumar (2011) provided detailed documentation of the physical characteristics and biological significance of song in an endemic bird species, the Indian robin (*Saxicoloides fulicata*). Two categories of songs were identified on the basis of their acoustical features and context of production. Type-A songs were simple, stereotyped, and common vocalizations that served primarily in male-male competition for territory and mates, representing the basic territorial advertisement system of the species. In contrast, Type-B songs were rare, female-oriented, and more complex than Type-A. These specialized vocalizations were found to be associated with courtship and mate attraction contexts.

Kumar (2012) further investigated the acoustic characteristics of vocalizations in some bird species in India and discussed their significance in studies on behavior, systematics, and conservation. He touched on the current state of knowledge on avian acoustic communication across the Indian subcontinent and its application to multiple research disciplines. He further emphasized the importance of systematic documentation of birdsong and illustrated how acoustic research can contribute to the understanding of behaviour, taxonomic work, and conservation in one of the world's most biodiverse regions.

Sethi *et al.* (2012c) presented a detailed account of the singing behavior of the pied bush chat. Results revealed that the songs of this species were composed of different song types, with each song type being made up of different types of elements. During dawn, males started their dawn chorus in quite darkness (about an hour before sun rise) and sang continuously for about 30 min (median= 30.5 min, range= 15-46 min). Dadwal & Bhatt (2017a) studied how astronomical (lunar) and meteorological factors influence the onset of the dawn song chorus in this species. Results demonstrated that light levels were the primary determinant of dawn song onset. Individuals tended to initiate singing earlier when ambient light levels were higher, which was strongly influenced by lunar phases. Cloud cover delayed the onset of singing by reducing available light before sunrise. Temperature had a weaker effect than lunar illumination and cloudiness.

Dadwal & Bhatt (2017b) further studied how and why the singing behavior of the pied bush chat varies over multiple years and, more specifically, through the different stages of its annual nesting cycle. They found that the males' singing was at its most intense and complex during the pre-nesting period. Both the song rate and the song bout length were significantly higher during this time compared to the later stages. An interesting finding was the stability of the birds' song repertoire size across the years of the study. This indicates that the pied bush chat is likely a closed-ended learner.

To investigate the function and social influence of dawn singing behavior in the pied bush chat, Sethi *et al.* (2011b) conducted a mate removal experiment. They removed a focal male's mate from different territories to determine any change in his dawn singing behavior. Results of this experiment did not detect any significant difference in the dawn song of males, suggesting that the presence or absence of a mate does not influence male dawn singing behavior. In fact, their dawn chorus appears to function primarily for close-range communication among neighboring males. Neighboring males used perches consistently to interact vocally, often performing counter-singing at high rates for extended periods throughout the breeding season. Such observations are consistent with the social dynamics hypothesis for the functional significance of dawn singing, which suggests that this behavior functions in the maintenance and adjustment of social relationships among neighboring males (Staicer *et al.*, 1996; Liu & Kroodsma, 2007).

To gain a deeper understanding of the singing behavior of the pied bush chat, Dadwal & Bhatt (2017c) examined song variations in this species with respect to different breeding stages. Results revealed that the singing behaviour of the males was found to be continuous until the later stages of the nesting cycle. Song bout length, song complexity, song rate, phrase gap, and percentage performance time differed significantly across the stages of the nesting cycle. They further investigated the complex relationships between males' song repertoire size and key aspects of their life such as the success in raising young, the size of the territory and the frequency of conflicts with other males. Results revealed a positive correlation between a male's

song repertoire size and his nesting success. Interestingly, the study found no direct relationship between the size of a male's song repertoire and the size of his territory.

Avian bioacoustics has increasingly been recognized internationally as a critical tool for the conservation of endangered birds. It provides insights into a wide range of birds' lives, which are crucial for developing specific conservation measures (Celis-Murillo *et al.*, 2012; Campos-Cerqueira & Aide, 2016). Indian ornithologists have also contributed to this area. For instance, Jeganathan & Wotton (2004) reported the first-ever recordings of the vocalizations of the Jerdon's courser (*Rhinoptilus bitorquatus*), a critically endangered nocturnal bird. They detailed and compared the calls of this species as recorded in the natural habitat. This discovery was a significant step for the scientific study of this elusive creature, which till then was regarded as a former occupant of this planet, till its rediscovery in Andhra Pradesh, India, in 1986. Similarly, Ishtiaq & Rahmani (2005) worked on the vocalization of then critically endangered species, the forest owlet (*Heteroglaux blewitti*). The most striking feature about this species was also its rediscovery in 1997 in central India, calling for urgency on conservation. The fact may be stated that in India, where sustained monitoring and evidence-based measures are imperative for the conservation of avian biodiversity and preventing further declines, the application of avian bioacoustics is still at a nascent stage and needs to be strengthened.

Research implies that noise obscures acoustic signals such that the effectiveness of the songs, as well as the communication calls that facilitate mate attraction, territory defense, as well as parental care, is lowered (Slabbekoorn & Peet, 2003). Birds can compensate for this with vocal plasticity, such as raising the frequency of the song, amplitude, or adjusting timing, but such compensation can involve energetic costs as well as diminishing signal honesty (Brumm & Zollinger, 2013). Likewise, habitat alteration greatly affects birdsong by changing the selective forces acting on communication as well as the acoustic environment (Slabbekoorn & Ripmeester, 2008).

In such a situation, research on the effects of anthropogenic noise pollution and habitat manipulation on birds' acoustic communication appears indispensable for comprehending how human activities modify natural ecosystems. Extensive work has been accomplished globally along this line, and Indian ornithologists have also started their contributions to this area. For example, Singh *et al.* (2019b) examined how ambient noise in urban environments influences the song structure of the purple sunbird (*Cinnyris asiaticus*). Using recordings from noisy urban and quiet sites, this study compared spectral and temporal song parameters. Results revealed weak and statistically non-significant relationships between background noise and most spectral parameters. In contrast, song amplitude showed a significant positive correlation with ambient noise, indicating the presence of a Lombard effect.

Some researchers from India, such as Kotian *et al.* (2024), demonstrated how altered habitats affect the communication pattern of birds. This research filled one substantial gap in restoration ecology research by examining how restorations are affecting the pattern of vocalization of species rather than noting the incidence or absence of the species. They assessed the change in vocal attributes of red-vented bulbuls at sites with varying densities of *Lantana camara*. The acoustic parameters of the bulbul, such as note length and bandwidth, varied considerably across the sites, but a random forest classifier showed that density of *Lantana camara* was not a substantial predictor of vocal attributes.

Sengupta & Gameti (2025) also investigated the effects of urbanization and weather on the spectral and temporal characteristics of common myna (*Acridotheres tristis*) calls across habitat types. The findings of this investigation illustrated a clear urban-rural contrast in call structure, *i.e.*, urban birds had higher minimum and maximum frequencies and shorter syllables compared to semirural conspecifics. But no notable influence was shown by temperature and humidity on vocal parameters.

Avian vocal mimicry is a fascinating and intriguing feature of avian bioacoustics that refers to the capability of specific bird species to mimic the vocalizations of heterospecifics, other animals, or even anthropogenic noises, far beyond the limit of species-specific song learning. Theoretically, this behavior serves various ecological and evolutionary functions, such as predator avoidance, mate attraction, territorial maintenance, and social cohesion within multispecies flocks (Dalziell *et al.*, 2015). The necessity to explore vocal mimicry in birds arises from its unique role in advancing our understanding of vocal learning, a distinct feature in the animal kingdom with direct parallels to human language acquisition (Naguib & Riebel, 2026). Nonetheless, although vocal mimicry is a crucial topic in the area of avian bioacoustics, Indian studies on this aspect are almost negligible. To address this gap, Crisologo *et al.* (2017) provided a detailed description of the repertoire of mimetic vocalizations produced by the tawny lark (*Galerida deva*). In their study, they evaluated the accuracy of mimicry at an acoustic level and peer-based evaluation. By describing the diversity and accuracy of mimetic vocal skills, this study offers a basis for future studies on the ecological and functional significance of mimicry in birds.

Recently, acoustic monitoring has been identified as a valuable tool for long-term ecosystem assessment and monitoring. It addresses a fundamental question of acoustic ecology, *i.e.*, how do tropical bird communities maintain their acoustic structure when faced with the influx of winter migrants from temperate regions? Krishnan (2019) has provided remarkable insights into this area of research. This study revealed that the arrival of migrants altered species composition, but the community remained over-dispersed in acoustic niche space. However, migrants tended to occupy similar acoustic regions as resident species and were phylogenetically closer to them, resulting in greater clustering and reduced phylogenetic diversity in winter. In a further study from India, Lahiri *et al.* (2021) advanced our understanding of how ecological constraints shape animal communication communities and underscored the power of acoustic methods for conservation monitoring in imperiled ecosystems. Their study compared the composition, signal space, and phylogenetic diversity of bird acoustic communities from dry semiarid grasslands of northwest India and wet floodplain grasslands of northeast India. Results revealed that despite differences in species composition, both communities exhibited convergent, over-dispersed distributions in acoustic signal space. A convincing suggestion given in their study was that the role of passive acoustic monitoring protocols developed for one habitat type could be effectively transferred to the other, enhancing scalable biodiversity assessments.

Researchers worldwide have employed song playback experiments to investigate interspecific aggression as a potential mechanism shaping avian distribution patterns (Robinson & Terborgh, 1995; Jankowski *et al.*, 2010). However, such studies have remained largely unexplored in India. Addressing this gap, Singh & Rawat (2014) conducted a study to investigate the role of interspecific aggression in shaping the distribution of closely related leaf warblers (*Phylloscopus* spp.) in the Indian Himalayas. Their results showed that interspecific aggression was observed in only one out of four species pairs tested, indicating that such aggression has a limited role, while environmental factors and ecotones are likely more important in determining the distribution of Himalayan bird species.

To further highlight the importance of playback experiments in avian field surveys, Kumar & Singh (2010) conducted a study in northern India within sal (*Shorea robusta*) dominated forests to compare playback surveys with visual/aural transects for detecting woodpeckers. They recorded a total of 11 woodpecker species and concluded that playback is a more efficient and reliable method for assessing woodpecker diversity, as their surveys recorded more species and over twice as many

individuals as visual/aural methods and also detected species more quickly.

During the review of the literature, vocal individuality proved to be a peculiar feature of avian bioacoustics, in which each bird generates specific vocal traits that can be exploited to recognize individuals as well as play a pivotal role in avian communication. Individual signatures contained within acoustic parameters facilitate recognition by mates as well as neighbors, reinforcing stable social systems through phenomena such as the 'dear enemy effect' during song sharing (Beecher & Brenowitz, 2005). A perusal of avian bioacoustics in the Indian context shows that Indian ornithologists are making significant contributions toward such crucial domains too. For example, Sethi *et al.* (2014) studied song sharing in the pied bush chat, where neighboring males shared significantly more song types than did non-neighboring males. The highest and the lowest similarities of song repertoires were observed in neighboring and non-neighboring pairs, respectively. Nevertheless, no two males shared all song types in their repertoires, and all males shared some song types. They found a significant negative correlation between the number of song types shared between two males and their distance.

Adding to the singing behavior of the pied bush chat, Dadwal & Bhatt (2017d) explored how males distinguish between familiar neighbors and unknown strangers, a crucial social skill in the competitive world of territory defense. Males, in their study, demonstrated a significantly more aggressive and pronounced response to the songs of strangers compared to the songs of their neighbors. Such results demonstrate that male pied bush chats can recognize individuals by their songs alone and can adjust their defensive behavior based on the level of threat posed by the singer.

In the field of song sharing studies in birds, significant contributions have also been made by Sawant *et al.*, (2022a). They put forward new measures for estimating song sharing within complex avian repertoires as well as showcased the cultural as well as behavioral dynamics of variation in songs within a range-restricted, endemic and highly territorial species, the white-bellied sholakili (*Sholicola albiventris*). They examined individual-level variation in the vocal repertoires as well as constancy in individual repertoire across years. Also, they compared songs of neighboring individuals versus stranger individuals. Results exhibited shared note-types among neighbors, substantial inter-individual variations within the song parameters, as well as temporal variations in individual repertoires, indicating a dynamic structure of the song.

Kumar *et al.* (2023) also investigated individual variation and distinctness in the songs of a highly vocal passerine from India, white-rumped shama (*Copsychus malabaricus*). They demonstrated that the songs of this species exhibit strong individual-level variation. Acoustic parameters, particularly frequency range, peak frequency and note duration, differed consistently between individuals. They further highlighted that despite the species' natural tendency toward vocal mimicry and improvisation, individuals maintained stable acoustic features, in their most frequently used song type, which could serve as unique identifiers.

Quantifying birdsong complexity is a central challenge in avian bioacoustics. Traditional approaches often rely on manual classification of song types, motifs, or syllables, which are time-intensive, subjective, and constrained by observer bias (Kroodsma, 2004). Therefore, robust and flexible frameworks are needed for quantifying birdsong complexity, emphasizing spectral diversity over manual classification. Indian ornithologists have been making remarkable contributions in this regard too. For example, Sawant *et al.* (2022b) proposed a novel metric, the Note Variability Index (NVI), which quantifies immediate song complexity by incorporating both spectral and temporal variation among notes using spectrogram cross-correlation (SPCC). They highlighted that unlike conventional approaches, NVI does not require manual note classification, thereby reducing subjectivity and improving reproducibility. They further emphasized that by avoiding manual note categorization, NVI can be rapidly applied to large datasets with existing sound analysis software.

Geographical variation in bird song structure is a widely documented phenomenon in avian bioacoustics. Globally, numerous studies have examined the mechanisms driving such variation (Marler & Tamura, 1964; Slabbekoorn & Smith, 2002; Beecher & Brenowitz, 2005). However, despite India's exceptional avian diversity and heterogeneous habitats, which make it a natural laboratory for investigating song variation, limited research studies were encountered during the literature survey in this regard. For example, Singh & Price (2015) investigated geographical variation in song structure of two Himalayan warblers and found greater complexity in the northwest compared to the southeast. In the grey-hooded warbler (*Phylloscopus xanthoschistos*), higher complexity arose from increased note diversity within song types and a broader frequency bandwidth, whereas in Blyth's leaf warbler (*Phylloscopus reguloides*), it resulted from greater variation among song types. Their results support the hypothesis that complex songs evolve in species-poor, acoustically less cluttered environments, where signal detection is enhanced. They further argued that sexual selection drives these patterns, but that complexity is resolved differently across species, as it can manifest through diverse traits such as repertoire size, bandwidth, and song switching.

In a study, Kathait *et al.* (2016) suggested that birds have a distinct call signature tied to their specific population, indicating localized vocal patterns. For this study, they analyzed the spotted munia's (*Lonchura punctulata*) morning calls. Results revealed that these calls had no spectrographic variation across locations. However, parametric comparisons revealed significant differences among populations from different geographic regions. Another study by Singh & Price (2024) investigated the evolution of species recognition signals in birds by exploring the paradox between the need for divergence in these signals to avoid maladaptive interactions and the strong stabilizing forces that maintain signal similarity due to environmental constraints and sexual selection. They studied four Cyanoderma babbler species distributed along an elevational gradient in the Himalayas and adjacent regions, where they are largely segregated by elevation but come into contact in narrow zones. They suggested that transmission constraints act similarly on note shape across habitats, but divergence driven by species interactions spreads throughout species ranges. These findings indicate that reproductive character displacement may be widespread and emphasize the interplay of ecological and sexual selection in shaping avian song.

An important feature of avian bioacoustics is that genetically similar bird populations isolated by human-caused habitat fragmentation provide a natural experiment to study cultural drift in vocal variation. In order to contribute to this field, Robin *et al.* (2011) showed strong evidence that both local habitat structure and ancient isolation cause song variation among birds. Using the white-bellied shortwing (*Brachypteryx major*), an endangered endemic passerine, they investigated the impact of genetic distinction across populations on the song on different islands of the Sky Island system and found differences in songs among three populations.

In a further study on the same species and in the same study area, Purushotham & Robin (2016) explored geographic variation in song structure across six populations of the white-bellied shortwing. The researchers highlighted the value of song analysis in reconstructing phylogenetic relationships and detecting the impacts of both historical and contemporary isolation. They identified three major song clusters and demonstrated that bird vocalizations can capture layers of divergence often missed by genetic data alone.

Chitnis *et al.* (2020) also investigated four sympatric species of wren-warblers (genus *Prinia*, family Cisticolidae) in the dry deciduous scrub-grasslands. They found evidence that these species divided up acoustic signal space, creating structured community organization. Within each species, they observed different strategies for managing note diversity: two species used multiple distinct note types, while the other two varied note repetition rates to different degrees. In addition, the species sang from different perch heights, further separating their acoustic niches along multiple dimensions.

Modern ornithology has seen avian bioacoustics as a significant force to re-evaluate and update the taxonomic status of birds as well. This field has become a necessary part of avian taxonomy over the past years around the world. Similarly, significant contributions to the same can be seen from Indian ornithologists. For instance, Singh *et al.* (2019c) re-evaluated the taxonomic status of the blue-throated flycatcher (*Cyornis rubeculoides*) complex throughout the Indian subcontinent by combining molecular, morphological, and bioacoustic data. Traditionally treated as one species with various subspecies recognized primarily on the basis of slight plumage variations as well as geographic range, the *C. rubeculoides* complex represented a classic 'cryptic species' dilemma. Besides studying other parameters, the authors made thorough song analyses to check if such phenotypically subtle entities deserve to be recognized as distinct species and concluded that molecular divergence times far exceed those of traditionally recognized flycatcher species and, therefore, vocal characteristics may not reflect reproductive isolation reliably.

Chethana *et al.* (2021) also presented a comprehensive analysis of greater flameback (*Chrysocolaptes guttacristatus*) vocalizations by examining three taxa: *C. g. socialis* (Western Ghats), *C. stricklandi* (Sri Lanka) and *C. guttacristatus sensu stricto* (Himalayas and Southeast Asia). This study analyzed contact calls, flight calls, and drumrolls. Results revealed that *C. g. socialis* exhibited strikingly different contact and flight calls compared to *C. guttacristatus sensu stricto*, with differences in some cases even greater than those observed between *C. stricklandi* and *C. guttacristatus*. Preliminary examination of available drumrolls further indicated that *C. g. socialis* is highly distinct in its acoustic characteristics. Based on their results, they argued that *C. guttacristatus socialis* merits elevation to full species status (*C. socialis*), under the common name Malabar flameback.

Conclusion

From the above review, it is evident that research on avian acoustic communication in India has progressed commendably over the past 25 years, with Indian ornithologists contributing valuable insights into various aspects of bird vocal behavior. However, there remains a strong need to further strengthen this field in India. Keeping India's remarkable avian diversity and vast habitat heterogeneity in view, ornithologists from India, especially young researchers, need to pursue this fascinating field by integrating behavioural ecology, technology, and conservation perspectives. If Indian researchers extend efforts to diverse avian models inhabiting different altitudinal and latitudinal gradients, India can make remarkable contributions to the global science of bioacoustics. We would like to add that this review has attempted to compile the relevant work conducted so far in India, though a few studies may inadvertently have remained unacknowledged. If this is the case, we welcome inputs from the readers in this regard.

CONFLICT OF INTEREST

The authors declare no competing interests.

DATA AVAILABILITY

No additional data is used in this article.

AUTHOR CONTRIBUTIONS

Both authors contributed equally to the conceptualization, review of literature, writing the review, editing, and validation.

USE OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

The authors used ChatGPT tool [ChatGPT-6 developed by Open AI.] for language consistency and paraphrasing in the preparation of this manuscript. We have thoroughly reviewed and edited the content generated and take responsibility for the content of the publication.

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