

Bird diversity and spatial distribution in agroforestry landscapes of Kalibawang, Central Java, Indonesia

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Manuscript received: 24 November 2024. Revision accepted: 7 December 2025.

Abstract. Nursami F, Ardelia F, Nuraini FL, Aliyazzahra F, Sholiqin M, Sugiyarto, Indrawan M, Iskandar J, Iskandar B, Md Naim D, Setyawan AD. 2025. Bird diversity and spatial distribution in agroforestry landscapes of Kalibawang, Central Java, Indonesia. *Asian J For* 9: 390-409. Agroforestry landscapes play an increasingly important role in sustaining biodiversity within human-modified regions of Java. This study assessed bird diversity across four villages in Kalibawang, Central Java—Dempel, Karangsembung, Kalialang, and Margolangu—representing a mosaic of agroforests, mixed-fruit gardens, riparian vegetation, and open agricultural fields. Standardized point counts complemented by opportunistic observations recorded 71 bird species representing 32 families, dominated by insectivores, frugivores, and nectarivores, reflecting the structural and trophic complexity of traditional agroforestry systems. Several conservation-priority taxa were documented, including *Nisaetus bartelsi*, *Myophonus glaucinus*, *Brachypteryx montana crassa*, and *Zosterops flavus*, underscoring the ecological significance of forest-agroforest interfaces. Species richness varied among villages, with higher richness associated with stronger forest connectivity and more heterogeneous agroforestry structure, particularly in upland villages adjacent to the Kalibawang foothill forests. Beta-diversity analysis indicated substantial species turnover among villages (Whittaker's $\beta_w \approx 0.95$), demonstrating that each village contributes distinct components to the regional species pool rather than representing redundant assemblages. Functional guild analysis further highlighted the ecological roles of insectivores in natural pest regulation and of frugivores and nectarivores in seed dispersal and pollination processes, while omnivorous species reflected gradients of anthropogenic disturbance across the landscape. Overall, these findings demonstrate that traditional agroforestry systems function as critical biodiversity reservoirs and ecological connectors within a fragmented agricultural matrix. Conservation efforts should therefore prioritize the maintenance of vegetation connectivity between agroforests and remnant forest patches, protection of riparian buffers, and long-term, community-supported monitoring of sensitive and conservation-priority species to ensure the continued ecological integrity of Kalibawang's avifauna.

Keywords: Agroforestry, beta diversity, bird diversity, Central Java, functional guilds

INTRODUCTION

Agroforestry landscapes play an increasingly important role in conserving avian diversity, particularly in tropical regions where deforestation and land-use intensification have reduced the extent of natural habitats. Birds constitute one of the most ecologically significant vertebrate groups, contributing to pollination, seed dispersal, insect regulation, and ecosystem monitoring across a wide range of environments (Sekercioglu 2006; Sodhi et al. 2010; Bibby et al. 2000). Their behavioral diversity and ecological sensitivity further enhance their role as indicators in landscape-level studies (Gill 2007). Their sensitivity to habitat structure and environmental change makes them useful indicators of biodiversity patterns in human-modified landscapes, including agricultural mosaics, forest edges,

and mixed-crop systems (Danielsen and Heegaard 1995; Gregory et al. 2004; Gaston 2010). In many parts of tropical Asia, agroforestry has been recognized for its ability to maintain structural complexity and provide resources—such as fruiting trees, nectar sources, nesting substrates, and microhabitats—that support diverse bird communities (Marsden 1998; Waltert et al. 2004; Harvey et al. 2006; Perfecto and Vandermeer 2010). As a multifunctional land-use system, agroforestry can act as a semi-natural refuge for wildlife while simultaneously sustaining rural livelihoods, particularly where traditional land-use systems retain ecologically valuable components (Kehlenbeck and Maass 2004; FAO 2017).

Java, one of the world's most densely populated islands, presents an important case study for understanding how birds persist in anthropogenic habitats. The island's landscapes

have been heavily transformed through agriculture, settlements, and plantation forestry, resulting in a patchwork of small forest remnants embedded within expansive agroforestry and agricultural matrices (Whitten et al. 1996). These processes of fragmentation have profound ecological consequences, altering species composition, reducing habitat connectivity, and increasing the vulnerability of forest-dependent birds (Nijman 2010; Nijman et al. 2018; Withaningsih et al. 2025). Despite these pressures, Java still hosts substantial avian richness, with more than 500 species recorded and numerous endemics restricted to upland or forest-margin habitats (MacKinnon and Phillipps 1993; BirdLife International 2023). In many upland areas, agroforestry systems composed of fruit trees, coffee shrubs, bamboos, and shade vegetation form ecotones that allow the coexistence of generalist and forest-associated species, offering opportunities to examine how birds respond to human-managed landscapes.

The northern part of the Southern Serayu Mountains, including parts of Kalibawang Sub-district in Central Java, Indonesia, represents such a mosaic where agroforestry plots border pine plantations, secondary forests, and irrigated and non-irrigated rice fields. Although these areas are known to support diverse bird assemblages, scientific documentation of avifauna in agroforestry-dominated landscapes of southern Java remains limited. Most ornithological studies on the island have focused on protected forests, wetland habitats, or lowland agricultural regions, while upland agroforests—particularly those adjacent to Kalibawang—are comparatively understudied. This gap is noteworthy because agroforestry in these regions retains multi-strata vegetation and provides important ecological functions that may mitigate the effects of fragmentation. Understanding how bird species are distributed across villages with differing habitat compositions can offer insights into the ecological value of traditional agroforestry management and its potential role in biodiversity conservation.

Moreover, little is known about spatial variation in bird communities within small administrative units such as villages, even though differences in elevation, canopy cover, crop types, and proximity to forest patches may lead to distinct assemblage patterns. Such fine-scale analyses are

essential for identifying priority species, assessing habitat complementarity, and formulating localized conservation strategies. Beyond species richness, examining functional aspects—such as feeding guilds—can improve understanding of ecological processes operating within agroforestry landscapes. Likewise, evaluating beta-diversity provides a measure of species turnover among sites, highlighting the degree to which individual villages contribute uniquely to overall biodiversity patterns in the region (Magurran 2004; Baselga 2010).

Given these knowledge gaps and the ecological importance of agroforestry, this study investigates bird diversity in the upland agroforestry landscapes of Kalibawang, Central Java, Indonesia. Specifically, the research aims to: (i) document the composition and richness of bird species; (ii) analyze spatial variation across four villages representing different habitat conditions; (iii) identify rare, sensitive, or conservation-priority species occurring within the landscape; and (iv) describe functional feeding guilds and beta-diversity to evaluate the ecological complementarity among sites.

MATERIALS AND METHODS

Study area

The study was conducted in four villages—Dempel, Karangsambung, Kalialang, and Margolangu—within Kalibawang, Wonosobo, Central Java, Indonesia (Figure 1). Field surveys were carried out throughout October 2024. The landscape occupies the northern flank of the Southern Serayu Mountains, a mid-elevation physiographic region shaped by volcanic and tectonic processes (van Bemmelen 1949). Elevations range from approximately 550 to 950 m above sea level, with settlements concentrated around 600–750 m and higher agroforestry slopes occurring in Karangsambung and Margolangu. These altitudinal gradients influence vegetation structure, microclimate, and the occurrence of bird species typically associated with upland agroecosystems and forest margins (Whitten et al. 1996; MacKinnon and Phillipps 1993).

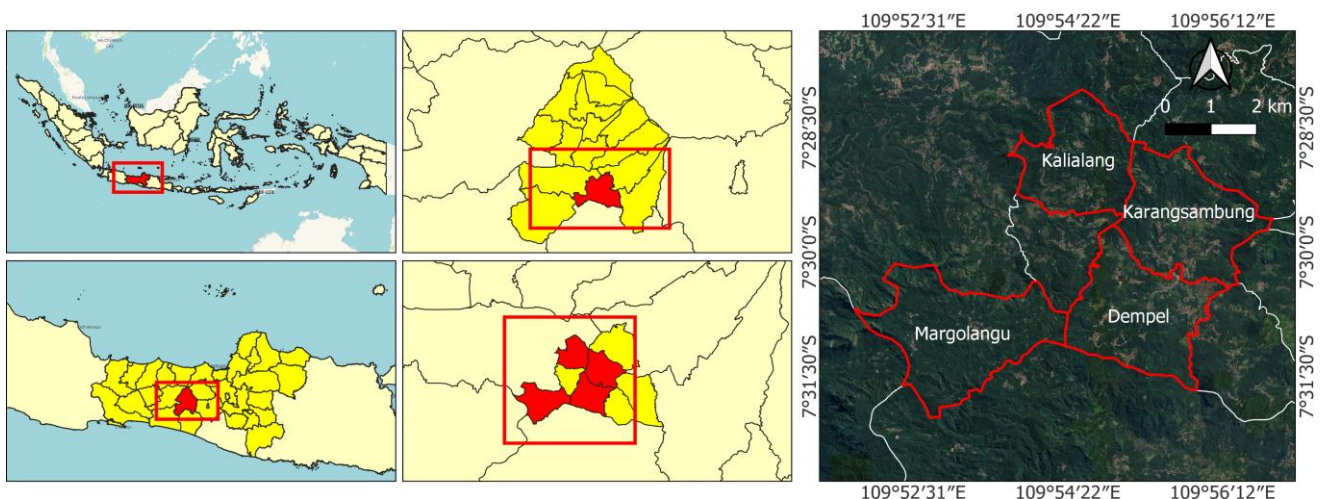


Figure 1. Study area and distribution of bird sampling locations in Kalibawang Sub-district, Wonosobo District, Central Java, Indonesia

Land use in the four villages forms a heterogeneous mosaic dominated by mixed agroforestry gardens, irrigated and non-irrigated rice fields, homegardens, and state-managed pine and damar plantations. Agroforestry plots contain multi-strata vegetation composed of fruit trees such as *Durio zibethinus*, *Artocarpus heterophyllus*, *Persea americana*, bamboo groves, shade trees, and smallholder coffee gardens. These complex vegetational structures resemble upland agroforestry systems widely documented in Java and provide food resources, nesting substrates, and habitat connectivity for diverse bird communities (Michon and de Foresta 1995; Roshetko et al. 2007). In contrast, lower-elevation areas in Dempel and Kalialang contain more open agricultural configurations with rice fields and dryland crops, supporting generalist and wetland-associated species. The climate follows a tropical monsoon regime, with annual rainfall of 2,500-3,500 mm, temperatures of 20-28°C, and relative humidity commonly exceeding 75% (BMKG 2023; BPS Wonosobo 2024).

Survey design and habitat stratification

To incorporate habitat heterogeneity into the sampling framework, the study area was stratified into five dominant habitat types: (i) mixed agroforestry gardens with multi-strata vegetation; (ii) production forest areas dominated by *Pinus merkusii*, *Agathis dammara* or mixed stands of various forestry species; (iii) irrigated and non-irrigated rice fields; (iv) riverbanks and wetlands containing riparian vegetation, small streams, and moist depressions; and (v) settlements and homegardens with ornamental plants, shade vegetation, and small livestock. This stratification reflects the ecological diversity of upland Central Java and ensures that species detection is evaluated across the full range of available habitat conditions.

Across the four villages, 52 fixed observation points were distributed proportionally across habitat types. Points were spaced at least 200-300 m apart to minimize double detections and ensure spatial independence. All points were georeferenced using a handheld GPS unit to support spatial mapping and habitat-level comparisons of bird assemblages. This design provided a consistent representation of ecological gradients within the Kalibawang landscape.

Point counts, transect walks, and sampling effort

Bird surveys followed standard tropical bird monitoring procedures using a combination of 10-minute fixed-radius point counts and slow transect walks (Ralph et al. 1995; Sutherland 2006; Bibby et al. 2000). At each point, all birds seen or heard within a 50-m radius were recorded, a radius widely used in tropical point-count protocols to optimize detectability in heterogeneous habitats (Blake and Loiselle 2001). Transect walks were conducted along footpaths, village roads, and forest edges, with observations taken within 50 m on either side of the transect. Fly-over individuals were excluded unless unambiguously identifiable and ecologically relevant. Each point and its associated transect section were visited two to three times on different days to incorporate temporal variation in detectability, following recommendations for repeated-visit sampling in avian monitoring (Hutto et al. 1986). Surveys were conducted

during peak morning (05:30-09:00) and late afternoon (15:30-17:30) activity periods and postponed under adverse weather conditions. Across all visits, the total sampling effort amounted to approximately 65 hours. No mist-netting, playback, or spotlighting was used; thus, nocturnal species were recorded only opportunistically. The combined point count-transect protocol has been shown to provide robust presence-absence and community-structure data in complex tropical agroforestry landscapes (Marsden 1998).

Species identification and taxonomic standards

Species identification was conducted using 8×42 binoculars and DSLR cameras equipped with telephoto lenses to document morphological and behavioral features (Bibby et al. 2000). Identification was based on plumage coloration, body proportions, flight patterns, vocalizations, elevational range, and microhabitat associations, following the field guides of MacKinnon and Phillipps (1993) and Eaton et al. (2021). Acoustic detections were verified using smartphone or portable audio recordings, particularly for cryptic species or those frequently detected by call (Kroodsma and Miller 1996). Uncertain or ambiguous records were excluded to maintain dataset reliability. Taxonomic nomenclature, English names, and family classifications adhered to the IOC World Bird List version 14.2 (Gill et al. 2024). Conservation status was determined according to three authoritative systems: the IUCN Red List (IUCN 2024), CITES Appendices I-III (CITES 2023), and the Indonesian national protection list under Permen LHK No. 106/2018.

Domestic pigeons (*Columba livia domestica*) and free-flying ornamental birds (e.g., *Streptopelia risoria*, *Serinus canaria domestica*, and *Agapornis* spp.) are listed because they occur as volant individuals detectable during surveys, although they were excluded from ecological index calculations. In contrast, household fowl such as chickens (*Gallus gallus domesticus*), domestic ducks (*Anas platyrhynchos domesticus*), and muscovy ducks (*Cairina moschata domestica*) were not included, as Javanese people culturally regard them as *unggas* (domestic fowl) rather than *manuk* (bird), and they neither form part of the wild avifauna (free-ranging individuals).

Data processing: species richness, functional guilds, and conservation categories

All bird detections from point counts, transect walks, and verified opportunistic observations were compiled into a presence-absence dataset for each village. A species was considered present if detected at least once during systematic surveys or through verifiable opportunistic encounters, consistent with standard detection-nondetection approaches in ecological monitoring (MacKenzie et al. 2002; Kéry and Royle 2016). Species richness per village was computed directly from these presence-absence matrices, following established procedures for estimating and comparing richness using incidence data (Gotelli and Colwell 2001; Magurran 2004). This approach allowed meaningful comparisons across habitat types and landscapes with differing degrees of vegetation complexity.

Functional guilds were assigned to each species based on primary feeding strategy using information from the EltonTraits database (Wilman et al. 2014) supplemented by regional ecological knowledge. Guild categories included insectivores, frugivores, nectarivores, granivores, carnivores, omnivores, and aquatic feeders, following widely used classifications of avian foraging and trophic roles (Sekercioglu 2006; Wilman et al. 2014). Guild assignments were restricted to wild bird species to avoid bias introduced by domestic or human-dependent taxa, ensuring that the ecological interpretation of feeding strategies reflected natural foraging behavior and habitat use. Conservation categories were applied to each species following the IUCN Red List (IUCN 2024), CITES Appendices (CITES 2023), and the national protection regulation (Permen LHK 106/2018), enabling identification of threatened, rare, or high-priority species in the agroforestry mosaic.

Beta diversity, community similarity, and statistical validation

Beta diversity among villages was assessed to quantify species turnover and evaluate community differentiation across the agroforestry landscape. Presence-absence data were used to compute Whittaker's beta diversity (β_w), defined as $\beta_w = (\gamma / \bar{\alpha}) - 1$, where γ represents total species richness in the landscape and $\bar{\alpha}$ is the mean species richness across villages (Whittaker 1960; Magurran 2004). This metric reflects the degree of species replacement and is appropriate for datasets lacking abundance estimates.

To decompose overall beta diversity into turnover and nestedness components, we further calculated Sørensen-based multiple-site dissimilarity and partitioned it into the turnover (β_{sim}) and nestedness (β_{sne}) fractions following Baselga (2010). This approach clarifies whether differences among sites result primarily from species replacement or from richness-driven subset patterns.

Pairwise community similarity was evaluated using Sørensen (Cs) and Jaccard (J) indices, with formulas $C_s = 2c / (a + b + 2c)$ and $J = c / (a + b - c)$, where a and b represent species richness in two villages and c the number of shared species (Sørensen 1948; Koleff et al. 2003; Baselga 2010). Both indices range from 0 to 1, with higher values indicating greater similarity.

To statistically test whether bird communities differed between villages grouped by forest connectivity (high connectivity: Karangsambung, Margolangu; low connectivity: Dempel, Kalialang), we performed permutational multivariate analysis of variance (PERMANOVA; Anderson 2001) and analysis of similarities (ANOSIM; Clarke 1993) based on Sørensen dissimilarity matrices. Both tests were run with 9999 permutations to obtain robust p-values.

We also estimated sampling completeness using the Chao2 incidence-based richness estimator (Chao 1987):

$$S_{Chao2} = S_{obs} + \frac{Q_1^2}{2Q_2}$$

Where S_{obs} is the number of observed species, Q_1 is the number of species recorded in exactly one village (uniques), and Q_2 is the number of species recorded in exactly two villages (duplicates). This estimator provides a conservative

assessment of how well the regional species pool was captured.

Because abundance data were not collected, diversity indices requiring quantitative counts (e.g., Shannon-Wiener, Simpson) were not calculated. Presence-absence approaches reduce uncertainty arising from differing detectability across habitats and allow reliable characterization of spatial community patterns in heterogeneous tropical environments.

RESULTS AND DISCUSSION

Overall bird species richness

A total of 71 bird species representing 32 families were recorded across the agroforestry landscapes of Kalibawang (Table 1). These species span multiple ecological groups, including forest-edge insectivores, canopy frugivores, nectarivores, granivores, and several generalist taxa adapted to mixed agricultural habitats. All richness calculations were based on presence-absence data, ensuring consistency across villages and analyses. The richness documented in this study highlights the ecological importance of traditional agroforestry mosaics, which retain structurally complex vegetation capable of supporting a wide range of avian functional groups. Overall species richness in Kalibawang is comparable to, or higher than, that reported from other mixed-agroecosystem landscapes in Java, indicating that multi-strata vegetation maintained by local communities provides continuous food resources and shelter for both resident and transient species. Evidence from West Java shows a similar pattern, with structurally complex vegetation—particularly in the middle canopy—supporting the highest bird richness, whereas simplified plantation habitats consistently support fewer species (Dinanti et al. 2018).

Sampling completeness, estimated via the Chao2 incidence-based richness estimator, indicated that our surveys captured approximately 61% of the expected regional species pool (observed richness $S_{obs}=71$, estimated total $S_{Chao2}\approx 116$). This suggests that while the inventory documents a substantial proportion of the avifauna, a considerable number of rare, cryptic, or low-detectability species may remain undetected across Kalibawang's heterogeneous agroforestry landscape.

Analysis of taxonomic composition indicates that several families contributed disproportionately to total richness. The most species-rich families were Pycnonotidae (bulbuls), Columbidae (pigeons and doves), Zosteropidae (white-eyes), and Muscicapidae (flycatchers)—groups widely known to thrive in disturbed forests, agroforests, and fruit-dominated homegardens. Bulbuls, for example, are particularly successful in agroforestry systems due to their frugivorous-insectivorous diets and tolerance of semi-open habitats. Likewise, Zosteropidae and Muscicapidae include species that exploit canopy foliage and mid-storey vegetation for feeding and nesting. The representation of forest-associated flycatchers and white-eyes further reflects the proximity of agroforestry plots to remnant forest patches along the Kalibawang foothills, reinforcing the role of landscape connectivity in shaping community composition.

Table 1. Bird species recorded in agroforestry landscapes of Kalibawang, Wonosobo, Central Java, Indonesia

Family	Scientific name	Local name	English name	Village presence*
Accipitridae	<i>Elanus caeruleus</i>	<i>Alap-alap sapi</i>	Black-winged kite	DP, KS, KL, ML
Accipitridae	<i>Nisaetus bartelsi</i>	<i>Elang Jawa</i>	Javan hawk-eagle	DP, KS, KL, ML
Aegithinidae	<i>Aegithina tiphia</i>	<i>Sirtu/Cipoh</i>	Common iora	DP, KS, KL, ML
Alaudidae	<i>Mirafra javanica</i>	<i>Branjangan</i>	Horsfield's bush lark	KL, ML
Alcedinidae	<i>Todiramphus chloris</i>	<i>Cekakak sungai</i>	Collared kingfisher	DP, KS, KL, ML
Alcedinidae	<i>Halcyon cyanoventris</i>	<i>Cekakak biru</i>	Javan kingfisher	KS
Apodidae	<i>Collocalia linchi</i>	<i>Sriti</i>	Linchi swiftlet	DP, KS, KL
Apodidae	<i>Collocalia maxima</i>	<i>Walet sarang hitam</i>	Black-nest swiftlet	DP, KS, ML
Ardeidae	<i>Bubulcus ibis</i>	<i>Blekok sawah</i>	Cattle egret	DP, KS, KL
Campephagidae	<i>Pericrocotus speciosus</i>	<i>Sepah merah</i>	Scarlet minivet	DP, KS, KL, ML
Chloropseidae	<i>Chloropsis sonnerati</i>	<i>Cucak ijo</i>	Greater green leafbird	ML
Ciconiidae	<i>Leptoptilos javanicus</i>	<i>Bangau tongtong</i>	Lesser adjutant	KL
Cisticolidae	<i>Orthotomus cucullatus</i>	<i>Ciblek gunung</i>	Mountain tailorbird	ML
Cisticolidae	<i>Orthotomus ruficeps</i>	<i>Prenjak kepala merah</i>	Ashy tailorbird	KS, ML
Cisticolidae	<i>Orthotomus sepium</i>	<i>Prenjak jawa</i>	Javan tailorbird	KS
Cisticolidae	<i>Orthotomus sutorius</i>	<i>Prenjak hijau</i>	Common tailorbird	ML
Cisticolidae	<i>Prinia familiaris</i>	<i>Cinenen jawa</i>	Bar-winged prinia	DP, KL
Cisticolidae	<i>Prinia inornata</i>	<i>Ciblek sawah</i>	Plain prinia	DP, KS, KL, ML
Columbidae	<i>Columba livia</i>	<i>Merpati batu</i>	Rock pigeon	KL
Columbidae	<i>Columba livia domestica</i>	<i>Merpati (peliharaan)</i>	Domestic pigeon	DP, KS, ML
Columbidae	<i>Geopelia striata</i>	<i>Perkutut</i>	Zebra dove	DP, KS, KL, ML
Columbidae	<i>Spilopelia chinensis</i>	<i>Derkuku</i>	Spotted dove	DP, KS, KL, ML
Columbidae	<i>Streptopelia risoria</i>	<i>Puter</i>	Ring-necked dove	DP, KS, KL
Corvidae	<i>Corvus enca</i>	<i>Gagak hutan</i>	Slender-billed crow	ML
Corvidae	<i>Corvus macrorhynchos</i>	<i>Gagak besar</i>	Large-billed crow	KL
Cuculidae	<i>Centropus sinensis</i>	<i>Bubut</i>	Greater coucal	ML
Cuculidae	<i>Surniculus lugubris</i>	<i>Kedasi</i>	Drongo cuckoo	KS, ML
Dicaeidae	<i>Dicaeum trigonostigma</i>	<i>Kemade</i>	Orange-bellied flowerpecker	ML
Dicaeidae	<i>Dicaeum trochileum</i>	<i>Bangsit</i>	Scarlet-backed flowerpecker	DP
Dicruridae	<i>Dicrurus macrocercus</i>	<i>Srigunting</i>	Black drongo	KS, KL, ML
Estrildidae	<i>Lonchura leucogastroides</i>	<i>Bondol jawa</i>	Javan munia	DP, KS, KL, ML
Estrildidae	<i>Lonchura (Padda) oryzivora</i>	<i>Gelatik jawa</i>	Java sparrow	KS, ML
Fringillidae	<i>Serinus canaria domestica</i>	<i>Kenari</i>	Domestic canary	DP, KS, ML
Laniidae	<i>Lanius schach</i>	<i>Cendet</i>	Long-tailed shrike	DP, KS
Motacillidae	<i>Anthus rufulus</i>	<i>Cici padi</i>	Paddyfield pipit	DP, KS, ML
Muscicapidae	<i>Brachypteryx montana crassa</i>	<i>Sulingan jawa</i>	Javan shortwing	ML
Muscicapidae	<i>Copsychus malabaricus</i>	<i>Murai batu</i>	White-rumped shama	KS, KL, ML
Muscicapidae	<i>Copsychus saularis</i>	<i>Kacer</i>	Oriental magpie robin	KS, ML
Muscicapidae	<i>Cyanoptila cyanomelana</i>	<i>Sulingan biru</i>	Blue-and-white flycatcher	KS
Muscicapidae	<i>Cyornis sanfordi</i>	<i>Sikatan matinan</i>	Rufous-tailed jungle flycatcher	DP, ML
Muscicapidae	<i>Monticola solitarius</i>	<i>Ciung batu</i>	Blue rock thrush	KS
Muscicapidae	<i>Myophonus glaucinus</i>	<i>Cincoang</i>	Javan whistling thrush	KS
Nectariniidae	<i>Aethopyga eximia</i>	<i>Kolibri</i>	Javan sunbird	KS, ML
Nectariniidae	<i>Aethopyga siparaja</i>	<i>Sepah raja</i>	Crimson sunbird	KS
Nectariniidae	<i>Anthreptes malacensis</i>	<i>Konin</i>	Plain-throated sunbird	DP
Nectariniidae	<i>Arachnothera longirostra</i>	<i>Madu rimba</i>	Little spiderhunter	DP, KS, ML
Nectariniidae	<i>Cinnyris asiaticus</i>	<i>Kolibri ungu</i>	Purple sunbird	KL
Nectariniidae	<i>Cinnyris jugularis</i>	<i>Sriganti</i>	Olive-backed sunbird	KS
Nectariniidae	<i>Cinnyris solaris</i>	<i>Sriganti dada-api</i>	Flame-breasted sunbird	ML
Nectariniidae	<i>Leptocoma calcostetha</i>	<i>Sogon</i>	Copper-throated sunbird	KS
Oriolidae	<i>Oriolus chinensis</i>	<i>Kepudang kuduk hitam</i>	Black-naped oriole	KL
Passeridae	<i>Passer montanus</i>	<i>Burung gereja</i>	Eurasian tree sparrow	DP, KS, KL, ML
Phasianidae	<i>Gallus gallus bankiva</i>	<i>Ayam hutan merah</i>	Red junglefowl	ML
Phasianidae	<i>Gallus varius</i>	<i>Ayam hutan hijau</i>	Green junglefowl	KS, KL
Picidae	<i>Chrysophlegma flavinucha</i>	<i>Pelatuk jambul kuning</i>	Greater yellownape	ML
Picidae	<i>Dinopium javanense</i>	<i>Pelatuk bawang</i>	Common flameback	KS
Psittaculidae	<i>Agapornis</i> sp.	<i>Lovebird</i>	Lovebird	DP, KS, ML
Psittaculidae	<i>Loriculus galgulus</i>	<i>Serindit</i>	Blue-crowned hanging parrot	ML
Psittaculidae	<i>Psittacula alexandri</i>	<i>Betet</i>	Red-breasted parakeet	KL, ML
Pycnonotidae	<i>Pycnonotus aurigaster</i>	<i>Kutilang</i>	Sooty-headed bulbul	DP, KS, KL, ML
Pycnonotidae	<i>Pycnonotus goiavier</i>	<i>Trucuk</i>	Yellow-vented bulbul	DP, KS, KL
Pycnonotidae	<i>Pycnonotus simplex</i>	<i>Cucak meranti</i>	Cream-vented bulbul	KS
Rallidae	<i>Amaurornis phoenicurus</i>	<i>Kareo padi</i>	White-breasted waterhen	KL

Rallidae	<i>Gallinula chloropus</i>	Mandar	Common moorhen	KL
Rallidae	<i>Porphyrio indicus</i>	Mandar besar	Grey-headed swampphen	DP, KS
Strigidae	<i>Otus angelinae</i>	Celepuk jawa	Javan scops owl	DP, KL, ML
Sturnidae	<i>Acridotheres javanicus</i>	Jalak kerbau	Javan myna	DP, KS, ML
Sturnidae	<i>Gracupica contra</i>	Jalak suren	Asian pied starling	DP
Timaliidae	<i>Timalia pileata</i>	Kaso-kaso	Chestnut-capped babbler	KS
Zosteropidae	<i>Zosterops flavus</i>	Pleci dada kuning	Javan white-eye	KS
Zosteropidae	<i>Zosterops palpebrosus</i>	Pleci	Oriental white-eye	DP, KS, KL, ML

Note: Village Codes: DP: Dempel, KS: Karangsembung, KL: Kalialang, ML: Margolangu. Scientific names follow Table 2 for consistency with field data and local usage. *Collocalia* is retained instead of *Aerodramus* for swiftlets. *Lonchura oryzivora* is used instead of *Padda oryzivora* for the Java sparrow. The Javan shortwing is kept as *Brachypteryx montana crassa*, although recent IOC taxonomy places it under *Myiomela leucura/montana*

Despite the dominance of generalist and adaptable species, several taxa of ecological and conservation significance were also recorded. Four species required particular attention due to their rarity, specialized habitat preferences, or conservation status: *Brachypteryx montana crassa*, *Myophonus glaucinus*, *Zosterops flavus*, and *Leptoptilos javanicus*. *B. m. crassa*, a subspecies associated with montane forest understory, was recorded in areas with dense vegetation and higher elevation, particularly in Karangsembung. Its presence reinforces the role of upland agroforestry-forest ecotones as microrefugia for shade-dependent and disturbance-sensitive taxa. *M. glaucinus*, a riparian forest-edge specialist, was detected in shaded agroforest and streamside habitats, indicating the persistence of relatively intact microhabitats along small watercourses.

Zosterops flavus, classified as Near Threatened, was encountered in fruit-rich agroforestry locations where mixed canopy trees (e.g., *Artocarpus*, *Durio*, *Persea*) provide continuous foraging opportunities. Its occurrence underscores the conservation value of tree-based agroecosystems in supporting species that have declined elsewhere in lowland Java due to habitat loss and trapping pressure. The detection of *L. javanicus*, a large-bodied stork of conservation concern, is also notable. Although likely representing a transient individual rather than a resident population, its presence suggests occasional use of open agricultural patches and wetland-associated habitats adjacent to agroforestry areas.

Species occurrence varied among the four study villages, reflecting differences in vegetation structure, elevation, and forest connectivity. Karangsembung recorded the highest species richness, consistent with its larger extent of multi-layered agroforest and closer proximity to forest remnants. In contrast, Dempel and Kalialang supported fewer species, corresponding to their greater dominance of open agricultural land and settlement areas. These patterns illustrate how fine-scale habitat heterogeneity and landscape configuration shape local avian assemblages, even within a relatively limited geographic area.

Conservation and legal status

Conservation assessment of the 71 recorded bird species revealed that the avifauna of Kalibawang is dominated by taxa categorized as Least Concern (LC) (55 species; 77.5%) under the IUCN Red List, a pattern typical of agroforestry and mixed-agricultural landscapes in Java,

where adaptable generalist species comprise much of the assemblage. Nonetheless, a notable subset of species occurred in elevated threat categories, including four Near Threatened (NT) species (5.6%), one Vulnerable (VU) species (1.4%), and seven species listed as Endangered (EN) (9.9%). These threatened taxa include *Z. flavus* and several others known to be experiencing population declines across parts of their range. In addition, four domestic or non-wild taxa were recorded and categorized as Not Evaluated (NE), as they fall outside the scope of IUCN wild-species assessments. The occurrence of NT, VU, and EN species within a community-managed agroforestry mosaic highlights the role of such multifunctional landscapes in buffering biodiversity loss and providing habitat for conservation-priority birds.

National protection status, based on Permen LHK No. 106/2018, showed that 20 of the recorded species (28.2%) are legally protected in Indonesia. These include key taxa such as *M. glaucinus*, *Z. flavus*, and *N. bartelsi*, which have experienced pressures from habitat degradation, fragmentation, or trapping in other parts of Java. The detection of such species in Kalibawang suggests that tree-rich agroforestry systems and forest-agroforest ecotones may function as important refuges, particularly for species sensitive to habitat simplification. Although *B. m. crassa* is not nationally protected, its narrow ecological tolerance and association with montane forest understory make its presence noteworthy from a conservation perspective, especially in landscapes undergoing continued land-use change.

At the international level, six species recorded in the study area are listed under CITES Appendix II (8.45%), indicating that although they are not currently at immediate risk of extinction, their trade must be regulated to prevent future population declines. This category primarily includes raptors, parrots, and high-value passerines, several of which were documented in Kalibawang's community-managed agroforestry landscape, such as *Gracupica contra*, *Copsychus malabaricus*, *Loriculus galgulus*, *Nisaetus bartelsi*, *Lonchura (Padda) oryzivora*, and *Psittacula alexandri*. The occurrence of CITES-listed species within a multifunctional, human-modified habitat underscores the importance of locally grounded conservation strategies, particularly in regions where wildlife trade has historically shaped population trajectories and continues to influence the management of culturally valued birds.

Table 2. Conservation status and origin of birds recorded in Kalibawang

Conservation/origin category	Number of species	Percentage (%)	Species name
Origin status			
Introduced/ domesticated	5	7.04	<i>Columba livia</i> , <i>Columba livia domestica</i> , <i>Streptopelia risoria</i> , <i>Serinus canaria domestica</i> , <i>Agapornis</i> sp.
Native	66	92.96	All the rest
Total	71	100	
IUCN			
Near Threatened (NT)	4	5.6	<i>Cyornis sanfordi</i> , <i>Otus angelinae</i> , <i>Psittacula alexandri</i> , <i>Halcyon cyanoventris</i>
Vulnerable (VU)	1	1.4	<i>Leptoptilos javanicus</i>
Endangered (EN)	7	9.9	<i>Acridotheres javanicus</i> , <i>Chloropsis sonnerati</i> , <i>Gracupica contra</i> , <i>Myophonus glaucinus</i> , <i>Nisaetus bartelsi</i> , <i>Lonchura (Padda) oryzivora</i> , <i>Zosterops flavus</i>
Domestic (Not Evaluated)	4	5.6	<i>Columba livia domestica</i> , <i>Streptopelia risoria</i> , <i>Serinus canaria domestica</i> , <i>Agapornis</i> sp.
Least Concern (LC)	55	77.5	All the rest
Total	71	100	
CITES			
Appendix II	6	8.45	<i>Copsychus malabaricus</i> , <i>Gracupica contra</i> , <i>Loriculus galgulus</i> , <i>Nisaetus bartelsi</i> , <i>Lonchura (Padda) oryzivora</i> , <i>Psittacula alexandri</i>
Non Appendix II	61	85.92	All the rest
Not Evaluated	4	5.63	<i>Columba livia domestica</i> , <i>Streptopelia risoria</i> , <i>Serinus canaria domestica</i> , <i>Agapornis</i> sp.
Total	71	100	
Indonesian law (Permen LHK 106/2018)			
Protected	20	28.2	<i>Aethopyga siparaja</i> , <i>Brachypteryx montana crassa</i> , <i>Centropus sinensis</i> , <i>Chloropsis sonnerati</i> , <i>Chrysophlegma flavinucha</i> , <i>Copsychus malabaricus</i> , <i>Cyornis sanfordi</i> , <i>Dinopium javanense</i> , <i>Gallus gallus bankiva</i> , <i>Gallus varius</i> , <i>Gracupica contra</i> , <i>Leptoptilos javanicus</i> , <i>Loriculus galgulus</i> , <i>Myophonus glaucinus</i> , <i>Nisaetus bartelsi</i> , <i>Oriolus chinensis</i> , <i>Otus angelinae</i> , <i>Lonchura (Padda) oryzivora</i> , <i>Psittacula alexandri</i> , <i>Zosterops flavus</i>
Not protected	51	71.8	All the rest
Total	71	100	

A number of domestic or non-wild taxa (e.g., *Columba livia domestica*, *Streptopelia risoria*, *Serinus canaria domestica*, *Agapornis* sp.) were also observed during field surveys. However, following ecological assessment guidelines, these taxa were excluded from diversity, guild-structure, and beta-diversity analyses, as they do not represent natural bird communities and may obscure ecological patterns. In contrast, *C. livia* (feral pigeon) was retained in species richness and community-level analyses, as it represents the only introduced but non-domesticated taxon recorded in the study area and occurs as a free-ranging, self-sustaining population within the agroforestry landscape.

Overall, the conservation profile of Kalibawang's avifauna illustrates a landscape dominated by LC species but still harboring several taxa of conservation concern. The coexistence of legally protected, Endangered, and Near Threatened species within agroforestry systems highlights the role of traditional land-use practices in maintaining habitat conditions suitable for biodiversity persistence. These findings reinforce the importance of safeguarding tree-based agroecosystems and maintaining connectivity with nearby forest remnants to ensure the long-term

viability of sensitive species. Summary information on conservation status, national protection, CITES listing, and species origin is provided in Table 2.

Rare and locally declining species

Among the 11 species identified as rare, locally declining, or habitat-sensitive within the study area, four exhibited particularly clear ecological patterns and microhabitat associations, making them key indicators for discussion. These taxa—*B. m. crassa*, *M. glaucinus*, *Z. flavus*, and *L. javanicus*—showed the strongest linkages to specific microhabitats and the clearest signals of restricted occurrence. Other species listed in Table 3 were encountered less frequently and displayed more generalized habitat use. Therefore, we focus on these four species as prime indicators of microhabitat integrity within the Kalibawang agroforestry landscape. Nevertheless, the full set of 11 species collectively underscores the importance of maintaining habitat heterogeneity to support sensitive avifaunal elements.

Brachypteryx montana crassa, a subspecies typically associated with dense, shaded understorey vegetation in upland forest environments, was among the rarest species

recorded. Its detection only in limited, higher-elevation agroforest patches—particularly in Karangsambung—suggests that only areas maintaining closed-canopy conditions and minimal disturbance provide suitable habitat. The species' cryptic behavior and low vocal activity further reduce detection probabilities, making its presence an indicator of structurally intact microhabitats within the village landscape.

Myophonus glaucinus, a forest-edge and riparian specialist, was encountered infrequently and only in habitats with perennial shade, rocky substrates, or proximity to small streams. The species is sensitive to disturbance and relies on riparian integrity, which may be threatened by agricultural expansion or changes in water flow. Its low detectability in other villages indicates that riparian corridors are unevenly distributed and require targeted protection to maintain suitable foraging and nesting environments.

Zosterops flavus, categorized as Near Threatened, was also detected at low frequency. This species is known to depend on fruit-rich canopies and semi-open forest edges, habitats that persist in agroforestry systems but are vulnerable to simplification of vegetation structure. The species' sensitivity to habitat degradation and trapping pressures across Java heightens the importance of retaining diverse fruiting tree assemblages within community-managed agroforests. Finally, *Leptoptilos javanicus* was documented only as a transient visitor, likely utilizing open agricultural fields or wet patches within the landscape. Although not a resident species in Kalibawang, its occasional occurrence emphasizes the need to maintain landscape-level openness and wetlands that may be important for wide-ranging or migratory individuals.

The ecological implications of these rare or declining species are significant. Their presence signals the persistence of key habitat types—dense understorey, shaded riparian zones, canopy fruit resources, and open wetlands—that collectively support a broad gradient of ecological niches. Protecting these microhabitats will be essential for sustaining sensitive taxa, enhancing community complementarity, and preventing further local declines.

Spatial variation across villages

Spatial variation in bird richness across Kalibawang shows a distinct ecological gradient shaped by differences in habitat mosaics, forest connectivity, and land-use intensity. Karangsambung (KS) exhibited the highest species richness (44 species), followed by Margolangu (ML) with 41 species (Table 4). Both villages lie closest to the forested margins of the Kalibawang Hills, where mixed agroforestry gardens blend with pine stands, bamboo groves, and vegetated slopes. This structural complexity supports a broader variety of ecological niches, enabling the persistence of forest-associated species such as *M. glaucinus*, *L. galgulus*, and several insectivorous taxa that rely on shaded understories or riparian zones. The relatively high number of unique species recorded in KS (12 species) and ML (11 species) further indicates a strong influence of forest-edge habitats in promoting beta diversity and local habitat specialization.

Table 3. Rare or locally declining bird species and their habitat associations in Kalibawang

Species name	Local name	Criteria of rarity/decline	Observation records (village/habitat)
<i>Nisaetus bartelsi</i>	Elang Jawa	Very low encounter frequency; nationally protected; IUCN Endangered; forest specialist	Rarely observed in the pine forest edges of Dempel and Kaliaang; 1-2 visual encounters only
<i>Chloropsis sonnerati</i>	Cucak ijo	High trapping pressure for songbird trade; IUCN Endangered	Only recorded in Margolangu homegardens and mixed agroforestry; mostly heard rather than seen
<i>Lonchura (Padda) oryzivora</i>	Gelatik Jawa	Once abundant, now very rare due to habitat loss and heavy trapping; IUCN Endangered	Scattered records in Karangsambung and Margolangu rice fields; <5 individuals detected
<i>Myophonus glaucinus</i>	Cincoang/Sincowang	Restricted to forested streams; sensitive to disturbance; IUCN Endangered	Detected only once along the shaded riverbanks of Kaliaang; interview-confirmed from elders
<i>Leptoptilos javanicus</i>	Bangau tongtong	IUCN Vulnerable; dependent on wetlands that are declining	Observed only in rice fields near Kaliaang; 1-2 individuals in the post-harvest season
<i>Pittacula alexandri</i>	Betet Jawa	Trapped extensively for the pet trade; IUCN Near Threatened; CITES Appendix II.	Single flock observed in Margolangu agroforestry; also reported by hunters but rarely seen
<i>Loriculus galgulus</i>	Serindit	Forest-dependent, uncommon in disturbed agroforestry	Recorded from bamboo groves in Margolangu; also mentioned in interviews but seldom observed
<i>Otus angelinae</i>	Celepuk Jawa	Nocturnal; cryptic; Near Threatened; protected	Only heard at night in pine forests of Dempel and Margolangu; no visual confirmation
<i>Zosterops flavus</i>	Pleci dada kuning	Endemic and fragmented distribution; IUCN Endangered	Mentioned by 3 respondents in Karangsambung; 1 confirmed photograph from Margolangu
<i>Gracupica contra</i>	Jalak suren	Rapid decline due to hunting and trade; IUCN Endangered	Seen only near human settlements in Dempel; usually single individuals or pairs
<i>Acridotheres javanicus</i>	Jalak kerbau	Native populations are declining, replaced by invasive mynas	Rarely seen in Kaliaang and rice fields of Margolangu; <3 reports

Note: Rare or locally declining bird species in Kalibawang, including criteria of rarity (low observation frequency, restricted habitat, cultural exploitation, or protected status) and field detection records based on point counts and interview validation

In contrast, Dempel (DP) and Kalialang (KL) recorded lower species richness, with 31 and 30 species, respectively, reflecting a more homogenized avifaunal assemblage typical of lower-elevation sites dominated by rice fields, open homegardens, and settlement clusters. These landscape types provide fewer vertical strata and reduced canopy cover, favouring open-area generalists such as *Passer montanus*, *Lonchura leucogastroides*, *Spilopelia chinensis*, and *Pycnonotus aurigaster*. The small number of unique species in DP (3 species) and KL (7 species) suggests that these villages share a similar habitat template, with limited opportunities for forest specialists or disturbance-sensitive taxa.

A key pattern emerging from the village comparison is the consistent presence of 12 shared species across all four villages (Figure 2). These birds constitute the ecological “backbone” of the landscape, characterized by high adaptability to human-modified environments and broad dietary or habitat tolerances. Their uniform distribution illustrates how agroforestry landscapes retain a stable core bird community despite variations in forest connectivity and cultivation intensity among villages.

Despite this shared component, the unique species recorded in each village highlight subtle environmental filters operating at the micro-landscape scale. KS and ML harbour a higher proportion of forest-associated and elevation-linked taxa due to their proximity to remnant vegetation, steeper terrain, and more continuous canopy cover, whereas DP and KL include species more closely associated with wetlands, open agricultural edges, and human settlements. These distinctions demonstrate that each village contributes complementary elements to the overall avifauna of Kalibawang, emphasizing the importance of conserving the full mosaic of agroforestry, agricultural, and semi-natural habitats rather than focusing exclusively on forest margins.

Landscape position and elevation further reinforce this spatial pattern. KS and ML occupy mid-slope to upland zones characterized by cooler microclimates, denser vegetation, and more structurally layered agroforests, whereas DP and KL are situated on valley floors where agricultural intensification and human activity are more pronounced. Consequently, species richness and composition follow a gradient from structurally complex, semi-natural agroforestry systems to simplified, crop-dominated landscapes.

Beta diversity, community similarity, and statistical validation

Patterns of beta diversity across the four villages demonstrate a substantial degree of species turnover, reflecting the heterogeneous nature of agroforestry landscapes in Kalibawang (Table 5). Using Whittaker’s formula, the calculated $\beta_w = 0.95$, indicating moderate species turnover among sites. This value implies that although a core group of species is shared across villages, a considerable portion of the avifauna differs spatially, influenced by variations in habitat structure, elevation, and forest connectivity. In ecological terms, β_w values approaching 1 suggest that individual sites contribute distinct species assemblages to regional biodiversity, underscoring the importance of maintaining the full habitat mosaic rather than focusing conservation efforts on a single village or vegetation type.

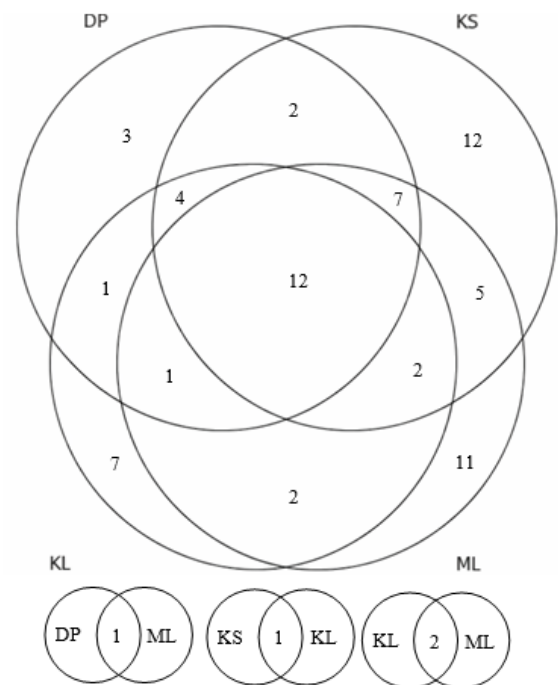


Figure 2. Venn diagram showing the overlap of bird species presence across four villages (Dempel, Karangsambung, Kalialang, and Margolangu) in the agroforestry landscapes of Kalibawang, Central Java, Indonesia

Table 4. Bird species richness and unique species across four villages in Kalibawang, Wonosobo District, Central Java, Indonesia

Village	Species richness (S)	Shared species (all villages)	Unique species	Dominant habitat type	Notes
Dempel (DP)	31	9	3	Agroforestry and rice fields	Moderate-to-low richness; dominated by farmland and homegardens
Karangsambung (KS)	44	9	12	Agroforestry-pine forest edge	Highest richness; strong forest connectivity
Kalialang (KL)	30	9	1	Rice fields, homegardens, wetlands	Lowest richness; dominated by wetland and open-area generalist birds
Margolangu (ML)	41	9	11	Forest-agroforestry ecotone	Higher proportion of forest-associated species due to forest-agroforestry ecotone

Pairwise similarity values based on the Jaccard and Sørensen indices further support this interpretation. Both indices showed intermediate similarity scores among most village pairs, revealing neither strong homogenization nor complete segregation of bird communities. Instead, each pair of villages shared a subset of generalist and adaptable species—such as *P. aurigaster*, *P. montanus*, and *S. chinensis*—but differed in their representation of forest-associated and elevation-sensitive taxa. For example, similarity between Karangsembung and Margolangu was higher than that between Karangsembung and Dempel, reflecting the greater prevalence of shaded agroforest patches, riparian corridors, and forest-edge vegetation in the upland villages. Meanwhile, village pairs located in lower-elevation areas (Dempel and Kalialang) displayed greater similarity due to their reliance on open-field agriculture and settlement-based habitats.

The intermediate similarity detected by Jaccard and Sørensen indicates community complementarity across the study area rather than redundancy. Complementarity is ecologically important because it suggests that conservation value is distributed across multiple habitat types, with each village supporting species not found—or rarely found—elsewhere. This aligns with earlier findings on unique species contributions: Karangsembung and Margolangu host a higher proportion of forest-edge and canopy-associated taxa, whereas Dempel and Kalialang support species linked to wetlands, open farmlands, and simplified agroecosystems.

The combined results of β_w , Jaccard, and Sørensen indices demonstrate that bird communities in Kalibawang form a landscape-level mosaic rather than a uniform assemblage, shaped by gradients in vegetation complexity, riparian habitat availability, and agroforestry management practices. Further partitioning of Sørensen beta diversity ($\beta_{sor} = 0.61$) into turnover and nestedness components revealed that species replacement ($\beta_{sim} = 0.47$) accounted for approximately 77% of total compositional dissimilarity, whereas nestedness ($\beta_{sne} = 0.14$) contributed only 23% (Table 5). This spatial heterogeneity enhances regional richness and strengthens the ecological resilience of bird assemblages by providing multiple niches across villages. From a conservation perspective, maintaining habitat diversity—particularly forest-connected agroforests and intact riparian strips—is essential for sustaining moderate-to-high beta diversity and ensuring that sensitive or specialized species persist alongside more widespread generalists.

To statistically validate the observed community differences, we conducted permutational multivariate analysis of variance (PERMANOVA) and analysis of similarities (ANOSIM), grouping villages by forest connectivity (high: Karangsembung and Margolangu; low: Dempel and Kalialang). PERMANOVA confirmed significant differences in species composition between connectivity groups (pseudo- $F = 4.31$, $p = 0.002$), with forest adjacency explaining approximately 41% of the variation ($R^2 = 0.41$). ANOSIM further supported strong separation between these groups ($R = 0.75$, $p = 0.008$), corroborating that villages adjacent to forest remnants support distinct avian

assemblages compared to those in open agricultural landscapes.

Functional feeding guild structure

Functional guild analysis of the 71 bird species recorded in Kalibawang reveals a community strongly dominated by insectivores (27 species; 38.03%) (Table 6). This proportion places insectivores as the single most important functional group in the assemblage, a pattern characteristic of structurally complex agroforestry systems. Multi-layered canopies, understory shrubs, bamboo patches, and shaded tree gardens create abundant and diverse microhabitats for arthropods, thereby supporting foliage-gleaning, bark-foraging, and ground-associated insectivorous birds. High insectivore representation is widely regarded as an indicator of functional integrity in agroforests, as many species in this guild are sensitive to vegetation simplification and loss of vertical structure. Their dominance suggests that agroforestry mosaics in Kalibawang continue to sustain stable trophic interactions and provide essential foraging niches for both canopy- and understory-associated birds.

Beyond insectivores, omnivores (8 species; 11.27%), granivores (7 species; 9.86%), and nectarivores (7 species; 9.86%) form the next most prominent guilds. Omnivores and granivores were primarily associated with open agricultural fields, settlement edges, and simplified vegetation, reflecting their ecological flexibility and tolerance of human-modified environments. In contrast, nectarivores—including sunbirds (*Aethopyga*, *Cinnyris*, *Leptocoma*) and spiderhunters (*Arachnothera longirostra*)—were closely linked to flowering shrubs, shade trees, and perennial crops, indicating that agroforestry vegetation supports pollination-related guilds essential for both wild and cultivated plant reproduction.

Several mixed-feeding guilds further illustrate the functional complexity of the avifaunal community. Frugivore-insectivores (4 species; 5.63%), represented by bulbuls and leafbirds, were associated with fruit-bearing trees that also harbor abundant arthropods. Nectarivore-insectivores (3 species; 4.23%) and frugivore-nectarivores (2 species; 2.82%) reflect dietary flexibility that allows species to exploit seasonally variable resources within agroforestry matrices. Strict frugivores (3 species; 4.23%) were comparatively fewer, highlighting that fruit resources are abundant but often shared with other feeding strategies rather than supporting exclusively frugivorous assemblages.

Carnivores (5 species; 7.04%), including raptors and piscivorous kingfishers, were present at low but ecologically significant proportions, indicating the persistence of higher trophic levels within the landscape. Single-species guilds such as herbivores (*Porphyrio indicus*) and scavengers (*Leptoptilos javanicus*) further emphasize the breadth of ecological roles represented, despite their limited numerical contribution. Domesticated species (3 species; 4.23%) were recorded as a separate category, acknowledging their presence in the landscape while avoiding distortion of functional ecological patterns.

Table 5. Summary of beta diversity metrics for bird communities in Kalibawang, Wonosobo District, Central Java, Indonesia

Metric	Formula	Value	Interpretation
Total species (γ -diversity)	$\gamma = \text{total unique species}$	71	Total bird richness across Kalibawang
Mean α (average village richness)	$\bar{\alpha} = (31 + 30 + 41 + 44) / 4$	36.5	Average species per village
Whittaker β -diversity	$\beta_w = (\gamma / \bar{\alpha}) - 1$	0.95	Indicates moderate species turnover among villages
Sørensen total (β_{sor})	$\beta_{sor} = \beta_{sim} + \beta_{sne}$	0.61	Total dissimilarity in species composition among villages
Turnover component (β_{sim})	-	0.47	Proportion of beta diversity due to species replacement
Nestedness component (β_{sne})	-	0.14	Proportion of beta diversity due to richness differences (subset patterns)
Turnover proportion	$\beta_{sim} / \beta_{sor} \times 100\%$	$\approx 77\%$	Indicates that species replacement is the dominant driver of community differences
Sørensen similarity range	$2a / (2a + b + c)$	0.48-0.62	Moderate similarity among villages
Jaccard similarity range	$a / (a + b + c)$	0.32-0.45	Communities share some species but remain distinct and complementary

Note: All diversity and similarity values are based on presence-absence data. Individual abundance was not recorded systematically; therefore, abundance-based indices (Shannon-Wiener, Evenness, Simpson Dominance) were not calculated. Species richness, beta-diversity indices (Whittaker's β , Jaccard, Sørensen, and its partition into turnover and nestedness), and functional guild structure were used to describe community composition, following standard rapid ornithological and ethnobiological assessment approaches (Bibby et al. 2000; Sutherland 2006; Baselga 2010). Statistical testing via PERMANOVA/ANOSIM confirmed that differences in community composition between high- and low-connectivity villages were significant ($F = 4.31$, $p = 0.002$, $R^2 = 0.41$)

Guild composition varied moderately among villages, mirroring the habitat gradients described earlier. Karangsembung and Margolangu, which retain more forest-connected agroforestry and denser canopy cover, supported higher proportions of insectivores, mixed frugivore-insectivores, and nectarivores, whereas Dempel and Kalialang—dominated by rice paddies, open fields, and settlement-based vegetation—were characterized by relatively higher representation of granivores and omnivores. This spatial divergence illustrates how landscape configuration and vegetation complexity shape trophic structure and the distribution of ecological roles across villages.

From an ecosystem services perspective, the functional guild composition of Kalibawang's avifauna highlights several key processes. Insectivores contribute to natural pest regulation, potentially reducing populations of herbivorous and crop-damaging arthropods. Frugivores and nectarivores facilitate seed dispersal and pollination, supporting regeneration of agroforestry trees and long-term landscape productivity. Granivores and omnivores contribute to nutrient cycling and resource redistribution, particularly in human-modified habitats. Collectively, these guilds form an integrated ecological network that underpins the resilience and sustainability of agroforestry systems in Kalibawang.

Discussion

Richness and species composition in agroforestry landscapes

The documentation of 71 bird species across the agroforestry landscapes of Kalibawang reflects the ecological resilience of tree-based farming systems in upland Java. The Chao2 estimator suggested that our rapid inventory captured about 61% of the expected regional species pool ($S_{obs}=71$, $S_{Chao2}\approx 116$), which is consistent with typical completeness levels for point-count-based surveys

in heterogeneous tropical landscapes. The documented richness thus provides a reliable baseline for common and easily detected species, while underscoring that further sampling effort would be needed to fully characterize rare and elusive taxa. This level of richness is comparable to that reported from other agroforestry regions in Central Java—including the southern slopes of Merapi, the limestone hills of Gunung Kidul, and adjacent upland areas—where structurally complex agroecosystems are able to sustain diverse avian assemblages despite prolonged anthropogenic modification (MacKinnon and Phillipps 1993; Whitten et al. 1996; Bibby et al. 2000). Studies from the Merapi agroforest belt similarly highlight the role of mixed-fruit gardens, shade coffee, and bamboo stands in maintaining forest-edge and generalist bird communities (Harvey et al. 2006; Perfecto and Vandermeer 2010). Likewise, research in Cikepuh Wildlife Reserve, West Java, demonstrates that agroforestry vegetation provides heterogeneous foraging substrates and microclimatic conditions, enabling the co-occurrence of frugivores, insectivores, and nectarivores even in landscapes with limited natural forest cover (Dinanti et al. 2018).

The dominance of families such as Pycnonotidae, Columbidae, Muscicapidae, and Zosteropidae in Kalibawang also mirrors patterns documented across the central Javan uplands. These families are characterized by high ecological plasticity, including the ability to exploit fruiting and flowering vegetation and to tolerate semi-open habitats typical of agroforestry mosaics (Sekercioglu 2006; Sodhi et al. 2010). Their prevalence indicates that agroforestry systems retain key structural attributes of natural forest edges, such as multi-layered canopies, year-round food resources, and shaded microhabitats that support insectivores and canopy-foraging species (Partasmita et al. 2017; Dinanti et al. 2018; Hakim et al. 2020).

Table 6. Functional feeding guilds of bird species in Kalibawang, Wonosobo District, Central Java, Indonesia

Feeding guild	No. of species	Percentage (%)	Species name
Insectivore	27	38.03%	<i>Aegithina tiphia</i> , <i>Anthus rufulus</i> , <i>Brachypteryx montana crassa</i> , <i>Bubulcus ibis</i> , <i>Centropus sinensis</i> , <i>Chrysophlegma flavinucha</i> , <i>Collocalia linchi</i> , <i>Collocalia maxima</i> , <i>Copsychus malabaricus</i> , <i>Copsychus saularis</i> , <i>Cyanoptila cyanomelana</i> , <i>Cyornis sanfordi</i> , <i>Dicrurus macrocercus</i> , <i>Dinopium javanense</i> , <i>Lanius schach</i> , <i>Mirafra javanica</i> , <i>Monticola solitarius</i> , <i>Myophonus glaucinus</i> , <i>Orthotomus cucullatus</i> , <i>Orthotomus ruficeps</i> , <i>Orthotomus sepium</i> , <i>Orthotomus sutorius</i> , <i>Pericrocotus speciosus</i> , <i>Prinia familiaris</i> , <i>Prinia inornata</i> , <i>Surniculus lugubris</i> , <i>Timalia pileata</i>
Omnivore	8	11.27%	<i>Acridotheres javanicus</i> , <i>Amaurornis phoenicurus</i> , <i>Corvus enca</i> , <i>Corvus macrorhynchos</i> , <i>Gallinula chloropus</i> , <i>Gallus gallus bankiva</i> , <i>Gallus varius</i> , <i>Gracupica contra</i>
Granivore	7	9.86%	<i>Agapornis</i> sp., <i>Columba livia</i> , <i>Geopelia striata</i> , <i>Lonchura leucogastroides</i> , <i>Lonchura oryzivora</i> , <i>Passer montanus</i> , <i>Spilopelia chinensis</i>
Nectarivore	7	9.86%	<i>Aethopyga eximia</i> , <i>Aethopyga siparaja</i> , <i>Anthreptes malacensis</i> , <i>Cinnyris asiaticus</i> , <i>Cinnyris jugularis</i> , <i>Cinnyris solaris</i> , <i>Leptocoma calcostetha</i>
Carnivore	5	7.04%	<i>Elanus caeruleus</i> , <i>Nisaetus bartelsi</i> , <i>Otus angelinae</i> , <i>Todiramphus chloris</i> , <i>Halcyon cyanoventris</i>
Frugivore-Insectivore	4	5.63%	<i>Chloropsis sonnerati</i> , <i>Oriolus chinensis</i> , <i>Pycnonotus aurigaster</i> , <i>Pycnonotus goiavier</i>
Frugivore	3	4.23%	<i>Loriculus galgulus</i> , <i>Psittacula alexandri</i> , <i>Pycnonotus simplex</i>
Nectarivore-Insectivore	3	4.23%	<i>Arachnothera longirostra</i> , <i>Zosterops flavus</i> , <i>Zosterops palpebrosus</i>
Domesticated	3	4.23%	<i>Columba livia domestica</i> , <i>Serinus canaria domestica</i> , <i>Streptopelia risoria</i>
Frugivore-Nectarivore	2	2.82%	<i>Dicaeum trigonostigma</i> , <i>Dicaeum trochileum</i>
Herbivore	1	1.41%	<i>Porphyrio indicus</i>
Scavenger	1	1.41%	<i>Leptoptilos javanicus</i>
Total	71	100%	

Note: Each species was assigned to one primary feeding guild based on dominant dietary traits to avoid double-counting, guild categories represent general feeding tendencies rather than exclusive or quantitative diets

The presence of several rare or habitat-restricted species—including *B. m. crassa*, *M. glaucinus*, and *Z. flavus*—further emphasizes the importance of upland agroforestry as buffer habitat adjoining forest remnants. Comparable studies from the Southern Serayu Mountains show that forest-edge specialists can persist within shaded agroforestry corridors that function as transitional zones between natural forest and cultivated land (Michon and de Foresta 1995; Roshetko et al. 2007). The detection of *Z. flavus*, a Near Threatened species, is particularly notable, as it parallels findings from other Indonesian landscapes where structurally complex, fruit-rich canopies and lightly disturbed forest edges support higher persistence of frugivorous and canopy-gleaning birds (Dinanti et al. 2018; Partasasmita et al. 2017; Pangestu et al. 2023).

The coexistence of forest-associated taxa with widespread generalists in Kalibawang demonstrates how agroforestry systems can mitigate some of the ecological consequences of habitat fragmentation. Island-wide assessments indicate that Java's forest bird diversity has declined markedly due to deforestation, hunting, and conversion to monocultures (Whitten et al. 1996; Sodhi et al. 2010). In contrast, tree-based smallholder agroecosystems maintain habitat continuity through vertical stratification, perennial shade, and alternative foraging patches. These characteristics reduce ecological isolation and facilitate movement of forest-edge species across modified landscapes,

thereby supporting regional-scale species persistence (Erniwati et al. 2016; Dinanti et al. 2018; Hakim et al. 2020; Withaningsih et al. 2025).

The richness recorded in Kalibawang reflects not only the number of species present, but also the capacity of agroforestry landscapes to function as ecologically permeable systems that accommodate both generalist and habitat-associated birds. These findings are consistent with broader evidence that agroforestry systems act as biodiversity reservoirs, particularly in densely populated and fragmented regions (Bhagwat et al. 2008; Clough et al. 2011). By maintaining fruit trees, shade vegetation, bamboo stands, and riparian elements, traditional agroforestry in Kalibawang creates ecological conditions analogous to semi-natural forest edges, underscoring its importance for long-term biodiversity conservation in rural Java.

Conservation implications of rare and protected species

Building on the richness and species composition patterns described above, the presence of several rare, habitat-sensitive, and legally protected bird species in Kalibawang underscores the conservation significance of agroforestry landscapes adjoining the Kalibawang forest corridor. Among the notable taxa, *N. bartelsi*, *M. glaucinus*, *B. m. crassa*, and *Z. flavus* represent species with restricted ecological requirements and declining regional populations. Their occurrence—whether as resident populations or

occasional records—indicates that the structural heterogeneity of agroforestry systems and remaining semi-natural vegetation patches continue to function as critical habitats and movement corridors for sensitive avifauna.

Nisaetus bartelsi, an endemic Javan hawk-eagle and a national symbol protected under Permen LHK No. 106/2018, is one of Indonesia's most threatened raptors, highly dependent on contiguous forest canopies for nesting, hunting, and territorial movement. Even occasional observations of this species in Kalibawang are ecologically meaningful, as they confirm the role of upland forest fragments and forest-adjacent agroforests as functional extensions of its potential habitat. Previous research in West and Central Java has shown that forest raptors decline rapidly when canopy cover drops below critical thresholds or when agroforestry systems are converted into simplified monocultures (Whitten et al. 1996; Nijman 2010). The persistence of tall emergent trees within community-managed agroforests in Kalibawang likely facilitates raptor movement and provides essential vantage structures for foraging.

Similarly, *Myophonus glaucinus*, a riparian forest-edge specialist, was detected only in shaded microhabitats characterized by intact understory vegetation and perennial water flow. Its strong dependence on cool, rocky stream corridors makes it particularly vulnerable to hydrological modification and riparian clearing. Studies from other parts of Java demonstrate marked declines in riparian-dependent forest birds following stream channelization or loss of riparian vegetation, emphasizing the importance of integrated watershed and habitat management (Sodhi et al. 2010). The presence of *M. glaucinus* in Kalibawang therefore highlights the ecological value of maintaining undisturbed riparian buffers within agroforestry matrices.

Brachypteryx montana crassa, a skulking understory insectivore, is largely confined to high-elevation forest interiors and dense shrub layers. Its occurrence in upland agroforestry stands—particularly those directly adjacent to forest margins—suggests that agroforests retaining dense ground vegetation can function as microrefugia for montane forest taxa. Literature from the Javan uplands indicates that many montane species are highly sensitive to fragmentation, with local extirpation occurring when understory cover is reduced or canopy continuity is disrupted (Whitten et al. 1996; MacKinnon and Phillipps 1993). Maintaining shaded, multi-strata agroforests may therefore partially buffer fragmentation effects for such species.

The detection of *Zosterops flavus*, listed as Near Threatened by the IUCN, is particularly significant given its documented decline in human-modified landscapes due to trapping pressure and habitat simplification. This species relies heavily on fruit-rich canopies and semi-natural vegetation, both of which remain available within Kalibawang's traditional agroforestry systems. Previous studies have identified Central Java as an important stronghold for *Z. flavus*, especially in landscapes where mixed-fruit gardens are maintained (BirdLife International 2023). Its occurrence reinforces the conservation importance

of sustaining tree diversity and limiting vegetation homogenization within agroforestry landscapes.

Taken together, these four species exemplify the broader conservation function of forest-agroforestry corridors in Kalibawang. Such corridors facilitate movement, provide buffer habitats, and maintain ecological gradients essential for both forest-dependent and edge-tolerant species. Preserving canopy continuity, protecting riparian strips, and preventing conversion to monoculture agriculture therefore emerge as key strategies for sustaining the long-term viability of sensitive taxa and maintaining Kalibawang as an ecologically important conservation landscape in Central Java.

Spatial variation and landscape heterogeneity

Spatial differences in species richness among the four villages reflect the strong influence of habitat complexity, vegetation continuity, and landscape configuration on avian assemblages. Karangsembung (KS), which recorded the highest species richness (44 species), and Margolangu (ML) with 41 species, are characterized by structurally complex agroforestry systems and close proximity to forest remnants along the Kalibawang foothills. These villages occupy mid-slope to upland positions, where multi-strata vegetation, shaded understory, riparian segments, and fruit-rich canopies create a heterogeneous habitat matrix. Such conditions are well known to support diverse foraging and nesting assemblages, particularly forest-edge and microhabitat-dependent species (Harvey et al. 2006; Michon and de Foresta 1995). The occurrence of forest-associated taxa such as *M. glaucinus* and *B. m. crassa* further emphasizes the role of canopy continuity and low disturbance intensity as key drivers of spatial variation in species richness (Whitten et al. 1996; MacKinnon and Phillipps 1993).

By contrast, Dempel (DP; 31 species) and Kalialang (KL; 30 species) are dominated by open agricultural landscapes, including extensive rice fields, monoculture plots, and settlement-based homegardens with reduced vertical structure. These simplified habitat configurations favor disturbance-tolerant generalists, such as *P. montanus*, *L. leucogastroides*, and *P. aurigaster*, while supporting fewer forest-associated or microhabitat-specialist taxa. Comparable patterns have been widely reported across Indonesia, where simplified agricultural matrices act as ecological filters that exclude sensitive species and promote homogenized bird communities (Waltert et al. 2004; Hakim et al. 2020; Withaningsih et al. 2025).

The contrast between structurally complex agroforestry systems and open wet-rice landscapes illustrates a central principle of landscape ecology: increasing habitat heterogeneity enhances niche availability and supports higher species diversity. Agroforests that combine diverse food resources, multiple vertical layers, and favorable microclimates sustain a broad range of avian ecological strategies, whereas open fields reduce available strata and constrain species composition. Similar spatial patterns have been documented in the Merapi agroforest belt and the Kalibawang uplands (Roshetko et al. 2007; Perfecto and Vandermeer 2010), in West Java where middle-canopy

richness is highest (Dinanti et al. 2018), and in northern Badung, Bali, where structurally complex habitats consistently support greater avian diversity than simplified plantations (Yuni et al. 2022).

Statistical validation using permutational multivariate analysis (PERMANOVA) confirmed that forest connectivity significantly structures bird communities (pseudo-F = 4.31, $p = 0.002$), explaining approximately 41% of the variation in species composition ($R^2 = 0.41$). Analysis of similarities (ANOSIM) further supported strong separation between villages with high versus low forest connectivity ($R = 0.75$, $p = 0.008$). These results reinforce that the observed spatial patterns are not merely descriptive but reflect statistically significant ecological differentiation driven by landscape configuration.

These spatial patterns are also consistent with island biogeography theory, particularly with respect to habitat isolation and effective patch size. Villages with stronger connectivity to forest remnants—such as Karangsembung and Margolangu—function as “larger habitat islands”, facilitating colonization and persistence of forest-edge and mid-elevation species. In contrast, more homogeneous agricultural matrices resemble “smaller, isolated islands”, where immigration is limited and local extinction risks are higher for sensitive taxa (Whitten et al. 1996; MacArthur and Wilson 1967). Agroforestry corridors therefore act as stepping-stone habitats, facilitating dispersal for species such as *Z. flavus*, *M. glaucinus*, and *L. galgulus*. This connectivity effect aligns with habitat-suitability models of *N. bartelsi*, which highlight the importance of continuous canopy cover and well-connected forest patches for forest-dependent birds in human-modified landscapes (Nursami et al. 2018). Similar processes have been observed in Sumatra, Indonesia, where simplified oil-palm matrices disproportionately favor disturbance-tolerant assemblages while excluding forest-dependent species (Erniwati et al. 2016).

The spatial heterogeneity observed in Kalibawang demonstrates that landscape configuration—rather than local habitat quality alone—plays a decisive role in shaping avian assemblages. Maintaining agroforestry complexity, canopy continuity, and connectivity with forest remnants is therefore essential to sustain spatial complementarity among villages and to support long-term biodiversity persistence in the Kalibawang landscape.

Functional guilds and ecosystem services

The functional guild structure of Kalibawang’s avifauna highlights the key ecological services contributed by birds within agroforestry landscapes. Insectivorous species constitute the dominant functional group (27 species; 38.03% of all taxa), underscoring the role of agroforests as reservoirs of natural pest-control agents. Insectivores such as *Copsychus saularis*, *M. glaucinus*, and foliage-gleaning warblers (*Orthotomus*, *Prinia*) rely on shaded, structurally complex vegetation that supports diverse arthropod communities. Numerous studies demonstrate that insectivorous birds can significantly reduce herbivorous insect populations and lower crop damage, particularly in heterogeneous landscapes (Harvey et al. 2006; Sekercioglu

2006). Their high representation in Kalibawang indicates that traditional agroforestry practices—characterized by canopy shade, fruit trees, bamboo stands, and mixed understory—maintain microhabitats essential for stabilizing trophic interactions and ecosystem functioning. This pattern is consistent with evidence that even moderately disturbed or logged forests can continue to deliver key ecological processes when structural complexity is retained (Edwards et al. 2014). Bird-exclusion experiments in Indonesian smallholder systems further support the role of insectivores in suppressing insect herbivory, although the magnitude of effects varies with forest configuration and landscape context (Pradana et al. 2025).

Frugivores, nectarivores, and mixed frugivore-insectivore guilds together form another important functional component of Kalibawang’s bird community, contributing to seed dispersal and pollination services. Frugivorous and frugivore-insectivorous taxa—particularly bulbuls (*Pycnonotus* spp.), leafbirds (*Chloropsis sonnerati*), and orioles (*Oriolus chinensis*)—act as effective seed dispersers, while nectarivores such as *Aethopyga*, *Cinnyris*, *Leptocoma calcostetha*, and spiderhunters (*Arachnothera longirostra*) support pollination of flowering crops and wild shrubs. The persistence of these guilds reflects the availability of fleshy fruits, nectar resources, and flowering phenology typical of diverse agroforestry systems, which are critical for maintaining plant reproductive cycles and long-term landscape resilience in human-modified environments (Whitten et al. 1996; Sodhi et al. 2010). Comparable relationships between plant diversity and frugivore or nectarivore richness have been documented in other Indonesian landscapes, including Bantimurung Bulusaraung National Park, where feed-plant richness strongly predicts bird functional diversity (Putri 2015; Partasasmita et al. 2017).

In contrast, omnivores (8 species; 11.27%) and granivores (7 species; 9.86%) are more closely associated with anthropogenic habitats. Species such as *Acridotheres javanicus*, *L. leucogastroides*, *P. aurigaster*, *P. montanus*, and typically thrive in disturbed or settlement-dominated environments, exploiting a wide range of food resources. Their higher representation in villages with simplified agricultural matrices, such as Dempel and Kalialang, reflects increased human influence and reduced vegetation stratification, a pattern widely reported in tropical agricultural landscapes (MacKinnon and Phillipps 1993; Sodhi et al. 2010). While these guilds contribute to nutrient cycling and resource redistribution, their dominance often coincides with declines in more specialized insectivorous and forest-associated taxa.

Taken together, the functional guild composition of Kalibawang’s avifauna reveals a landscape-level functional mosaic. Insectivores underpin natural pest regulation, frugivores and nectarivores sustain seed dispersal and pollination processes, and omnivores and granivores serve as indicators of anthropogenic pressure. These complementary roles highlight the importance of retaining multi-layered, tree-based agroforestry vegetation to maintain ecosystem services, buffer against biodiversity loss, and enhance the ecological resilience of rural landscapes.

Beta diversity and community complementarity

The moderate to relatively high beta diversity observed among the four villages, reflected in a Whittaker β_w value of 0.95, indicates substantial species turnover and confirms that each village contributes distinct elements to the regional avifauna of Kalibawang. Rather than forming a single homogeneous bird community distributed evenly across the landscape, avian assemblages show clear spatial differentiation shaped by variation in vegetation structure, canopy continuity, riparian availability, and land-use intensity. A β_w value approaching 1 suggests that local communities share a common core of widespread species but differ considerably in additional taxa associated with specific habitat conditions, a pattern widely documented in tree-based agricultural landscapes of Central Java and Southeast Asia (Sekercioglu 2006; Sodhi et al. 2010).

The Sørensen and Jaccard similarity indices further reinforce this pattern by revealing moderate similarity and clear complementarity among villages, with no pair of sites sharing identical species pools. Villages with stronger forest connectivity, such as Karangsembung and Margolangu, share a higher proportion of forest-edge and shade-tolerant species linked to upland agroforestry and riparian vegetation. In contrast, Dempel and Kalialang are characterized by assemblages dominated by generalist and disturbance-tolerant species adapted to open fields, rice paddies, and settlement-based habitats. This differentiation reflects well-established responses of bird communities to land-cover modification, where habitat simplification favors generalists while structurally complex vegetation retains specialists (Waltert et al. 2004; Sodhi et al. 2010). Collectively, these patterns demonstrate that no single village can be considered redundant in terms of biodiversity contribution, as each supports unique species and functional roles.

From a landscape perspective, elevated beta diversity indicates that total species richness in Kalibawang is maintained primarily through habitat heterogeneity rather than uniformly high local richness. The mosaic of agroforestry systems, riparian corridors, mixed-fruit gardens, and open agricultural fields collectively sustains a broader regional species pool. Loss or simplification of any single habitat component would therefore result in a disproportionate decline in regional diversity, particularly through the disappearance of habitat-restricted or microhabitat-dependent species. Evidence from restoration and corridor-based studies shows that structurally complex riparian vegetation and tree-based corridors enhance avian movement, reduce isolation effects, and strengthen community cohesion across fragmented landscapes (Jansen 2005).

Maintaining this landscape mosaic not only supports biodiversity conservation but also enhances ecological resilience by distributing complementary ecosystem services across villages, including pest regulation, seed dispersal, and pollination. This need becomes increasingly urgent under projected land-use change scenarios. Global analyses predict that rapid urban expansion and agricultural intensification will continue to exert strong pressure on biodiversity in densely populated regions such as Java

(Seto et al. 2012). Within this context, Kalibawang's agroforestry landscapes represent a multifunctional system in which beta diversity and community complementarity are central to sustaining both ecological integrity and long-term rural landscape resilience.

In conclusion, this study demonstrates that agroforestry landscapes in Kalibawang Sub-district, Central Java, Indonesia, support a high and ecologically meaningful avian diversity, with a total of 71 bird species representing 32 families recorded across four villages. Species richness varied spatially, with Karangsembung exhibiting the highest richness (44 species), followed by Margolangu (41 species), while Dempel and Kalialang supported 31 and 30 species, respectively. The detection of several conservation-priority species—such as *N. bartelsi*, *M. glaucinus*, *B. m. crassa*, and *Z. flavus*—highlights the ecological importance of maintaining structurally complex, tree-based farming systems adjacent to the Kalibawang foothills. Spatial analyses reveal pronounced differences among villages, with higher richness associated with stronger forest connectivity and more heterogeneous agroforestry strata, while villages dominated by open agricultural land and settlements tend to support more homogenized bird assemblages. The relatively high beta diversity observed across sites indicates that each village contributes uniquely to the regional species pool, confirming that the conservation value of Kalibawang arises from its landscape mosaic rather than from any single habitat type. Taken together, these findings affirm that traditional agroforestry systems function as critical biodiversity reservoirs and ecological connectors within a heavily modified region of Central Java, Indonesia.

ACKNOWLEDGEMENTS

The authors express their sincere appreciation to the communities of Kalibawang (Dempel, Karangsembung, Kalialang, and Margolangu), Central Java, Indonesia, for their support during field surveys and local interviews. We also thank the village leaders and field assistants who facilitated site access and contributed valuable ecological insights. This study benefited from constructive discussions with colleagues working on agroforestry and avian ecology in Central Java, Indonesia.

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Table S1. Bird species recorded in the agroforestry landscapes of Kalibawang, Central Java, Indonesia, with origin and conservation status, as well as habitat, feeding guilds, folk classification, human uses, and method of capture

Family	Scientific name	Local name	Village presence*	Origin	IUCN	CITES	Permen LHK 106/2018	Dominant Habitat	Feeding guild	Body size	Color
Accipitridae	<i>Elanus caeruleus</i>	<i>Alap-alap sapi</i>	DP, KS, KL, ML	Native	LC	-	-	Grassland / open fields	Carnivore	Medium	Grey-white with black shoulder patches
Accipitridae	<i>Nisaetus bartelsi</i>	<i>Elang Jawa</i>	DP, KS, KL, ML	Native	EN	II	✓	Forest	Carnivore	Large	Dark brown with pale underparts
Aegithinidae	<i>Aegithina tiphia</i>	<i>Sirtu/Cipoh</i>	DP, KS, KL, ML	Native	LC	-	-	Agroforestry	Insectivore	Small	Green-yellow
Alaudidae	<i>Mirafra javanica</i>	<i>Branjangan</i>	KL, ML	Native	LC	-	-	Grassland / open fields	Insectivore	Small	Brown streaked
Alcedinidae	<i>Todiramphus chloris</i>	<i>Cekakak sungai</i>	DP, KS, KL, ML	Native	LC	-	-	Riverine	Carnivore	Medium	Blue back, white throat
Alcedinidae	<i>Halcyon cyanoventris</i>	<i>Cekakak biru</i>	KS	Native	NT	-	-	Riverine	Carnivore	Medium	Bright blue body, purple head
Apodidae	<i>Collocalia linchi</i>	<i>Sriti</i>	DP, KS, KL	Native	LC	-	-	Settlements	Insectivore	Small	Grey-brown
Apodidae	<i>Collocalia maxima</i>	<i>Walet sarang hitam</i>	DP, KS, ML	Native	LC	-	-	Cliffs / rocky areas	Insectivore	Small	Dark brown, glossy wing
Ardeidae	<i>Bubulcus ibis</i>	<i>Blekok sawah</i>	DP, KS, KL	Native	LC	-	-	Rice fields	Insectivore	Medium	White, orange plumes in breeding
Campephagidae	<i>Pericrocotus speciosus</i>	<i>Sepah merah</i>	DP, KS, KL, ML	Native	LC	-	-	Forest	Insectivore	Small-medium	Red/orange with grey-black wings
Chloropseidae	<i>Chloropsis sonnerati</i>	<i>Cucak ijo</i>	ML	Native	EN	-	✓	Agroforestry	Frugivore-Insectivore	Medium	Bright green body, yellow throat
Ciconiidae	<i>Leptoptilos javanicus</i>	<i>Bangau tongtong</i>	KL	Native	VU	-	✓	Wetlands	Scavenger	Large	Grey-white body, black wings
Cisticolidae	<i>Orthotomus cucullatus</i>	<i>Ciblek gunung</i>	ML	Native	LC	-	-	Forest	Insectivore	Small	Olive-green, grey belly
Cisticolidae	<i>Orthotomus ruficeps</i>	<i>Prenjak kepala merah</i>	KS, ML	Native	LC	-	-	Agroforestry	Insectivore	Small	Olive-green body, reddish-brown crown, whitish belly
Cisticolidae	<i>Orthotomus sepium</i>	<i>Prenjak jawa</i>	KS	Native	LC	-	-	Agroforestry	Insectivore	Small	Olive-green upperparts, pale grey underparts
Cisticolidae	<i>Orthotomus sutorius</i>	<i>Prenjak hijau</i>	ML	Native	LC	-	-	Agroforestry	Insectivore	Small	Greenish-brown
Cisticolidae	<i>Prinia familiaris</i>	<i>Cinenen jawa</i>	DP, KL	Native	LC	-	-	Agroforestry	Insectivore	Small	Brown back, barred wings
Cisticolidae	<i>Prinia inornata</i>	<i>Ciblek sawah</i>	DP, KS, KL, ML	Native	LC	-	-	Rice fields	Insectivore	Small	Brown-grey, pale underparts
Columbidae	<i>Columba livia</i>	<i>Merpati batu</i>	KL	Introduced	LC	-	-	Settlements	Granivore	Medium	Grey-blue with dark wing bars
Columbidae	<i>Columba livia domestica</i>	<i>Merpati (peliharaan)</i>	DP, KS, ML	Domesticated	NE	NE	-	Settlements	Domesticated	Medium	Grey, white, brown morphs

Columbidae	<i>Geopelia striata</i>	<i>Perkutut</i>	DP, KS, KL, ML	Native	LC	-	-	Agroforestry	Granivore	Small	Brown barred, bluish face
Columbidae	<i>Spilopelia chinensis</i>	<i>Derkuku</i>	DP, KS, KL, ML	Native	LC	-	-	Rice fields	Granivore	Medium	Grey-brown with spotted wings
Columbidae	<i>Streptopelia risoria</i>	<i>Puter</i>	DP, KS, KL	Domesticated	NE	NE	-	Settlements	Domesticated	Medium	Pale grey-white
Corvidae	<i>Corvus enca</i>	<i>Gagak hutan</i>	ML	Native	LC	-	-	Forest	Omnivore	Medium	Glossy black
Corvidae	<i>Corvus macrorhynchos</i>	<i>Gagak besar</i>	KL	Native	LC	-	-	Grassland / open fields	Omnivore	Large	Glossy black
Cuculidae	<i>Centropus sinensis</i>	<i>Bubut</i>	ML	Native	LC	-	✓	Agroforestry	Insectivore	Medium-large	Black head, chestnut wings
Cuculidae	<i>Surniculus lugubris</i>	<i>Kedasih</i>	KS, ML	Native	LC	-	-	Forest	Insectivore	Small-medium	Glossy black, red eyes
Dicaeidae	<i>Dicaeum trigonostigma</i>	<i>Kemade</i>	ML	Native	LC	-	-	Agroforestry	Frugivore-Nectarivore	Small	Orange belly, olive back
Dicaeidae	<i>Dicaeum trochileum</i>	<i>Bangsit</i>	DP	Native	LC	-	-	Agroforestry	Frugivore-Nectarivore	Small	Black head, red back, whitish belly
Dicruridae	<i>Dicrurus macrocercus</i>	<i>Srigunting</i>	KS, KL, ML	Native	LC	-	-	Grassland / open fields	Insectivore	Medium	Glossy black, forked tail
Estrildidae	<i>Lonchura leucogastroides</i>	<i>Bondol jawa</i>	DP, KS, KL, ML	Native	LC	-	-	Rice fields	Granivore	Small	Brown-black with a white belly
Estrildidae	<i>Padda / Lonchura oryzivora</i>	<i>Gelatik jawa</i>	KS, ML	Native	EN	II	✓	Rice fields	Granivore	Small	Grey body, black head, white cheeks
Fringillidae	<i>Serinus canaria domestica</i>	<i>Kenari</i>	DP, KS, ML	Domesticated	NE	NE	-	Settlements	Domesticated	Small	Yellow or orange
Laniidae	<i>Lanius schach</i>	<i>Cendet</i>	DP, KS	Native	LC	-	-	Agroforestry	Insectivore	Medium	Grey back, orange flank, black mask
Motacillidae	<i>Anthus rufulus</i>	<i>Cici padi</i>	DP, KS, ML	Native	LC	-	-	Grassland / open fields	Insectivore	Small	Brown streaked
Muscicapidae	<i>Brachypteryx montana crassa</i>	<i>Sulingan jawa</i>	ML	Native	LC	-	✓	Forest	Insectivore	Small	Dark blue (male), brown (female)
Muscicapidae	<i>Copsychus malabaricus</i>	<i>Murai batu</i>	KS, KL, ML	Native	LC	II	✓	Forest edge	Insectivore	Medium	Black body, white rump
Muscicapidae	<i>Copsychus saularis</i>	<i>Kacer</i>	KS, ML	Native	LC	-	-	Agroforestry	Insectivore	Medium	Black and white
Muscicapidae	<i>Cyanoptila cyanomelana</i>	<i>Sulingan biru</i>	KS	Native	LC	-	-	Forest	Insectivore	Small	Blue upperparts, white belly
Muscicapidae	<i>Cyornis sanfordi</i>	<i>Sikatan matinan</i>	DP, ML	Native	NT	-	✓	Forest	Insectivore	Small	Brown body, rufous tail
Muscicapidae	<i>Monticola solitarius</i>	<i>Ciung batu</i>	KS	Native	LC	-	-	Cliffs / rocky areas	Insectivore	Medium	Blue-grey (male), brown (female)
Muscicapidae	<i>Myophonus glaucinus</i>	<i>Cincoang</i>	KS	Native	EN	-	✓	Riverine	Insectivore	Medium	Dark blue metallic
Nectariniidae	<i>Aethopyga eximia</i>	<i>Kolibri</i>	KS, ML	Native	LC	-	-	Agroforestry	Nectarivore	Small	Metallic green, yellow belly
Nectariniidae	<i>Aethopyga siparaja</i>	<i>Sepah raja</i>	KS	Native	LC	-	✓	Forest edge	Nectarivore	Small	Bright red crown, yellow-green body
Nectariniidae	<i>Anthreptes malacensis</i>	<i>Konin</i>	DP	Native	LC	-	-	Agroforestry	Nectarivore	Small	Olive back, metallic throat (male)

Nectariniidae	<i>Arachnothera longirostra</i>	<i>Madu rimba</i>	DP, KS, ML	Native	LC	-	-	Agroforestry	Nectarivore- Insectivore	Small- medium	Olive-brown body, long curved bill
Nectariniidae	<i>Cinnyris asiaticus</i>	<i>Kolibri ungu</i>	KL	Native	LC	-	-	Agroforestry	Nectarivore	Small	Shiny purple-blue (male), olive-yellow (female)
Nectariniidae	<i>Cinnyris jugularis</i>	<i>Sriganti</i>	KS	Native	LC	-	-	Agroforestry	Nectarivore	Small	Yellow belly, olive back
Nectariniidae	<i>Cinnyris solaris</i>	<i>Sriganti dada-api</i>	ML	Native	LC	-	-	Agroforestry	Nectarivore	Small	Bright orange chest, metallic head
Nectariniidae	<i>Leptocoma calcostetha</i>	<i>Sogon</i>	KS	Native	LC	-	-	Agroforestry	Nectarivore	Small	Metallic green-purple
Oriolidae	<i>Oriolus chinensis</i>	<i>Kepudang kuduk hitam</i>	KL	Native	LC	-	✓	Agroforestry	Frugivore- Insectivore	Medium	Bright yellow body, black eye-stripe, and nape
Passeridae	<i>Passer montanus</i>	<i>Burung gereja</i>	DP, KS, KL, ML	Native	LC	-	-	Settlements	Granivore	Small	Brown head, black throat spot
Phasianidae	<i>Gallus gallus bankiva</i>	<i>Ayam hutan merah</i>	ML	Native	LC	-	✓	Forest edge	Omnivore	Medium	Red/orange plumage, long tail
Phasianidae	<i>Gallus varius</i>	<i>Ayam hutan hijau</i>	KS, KL	Native	LC	-	✓	Forest	Omnivore	Medium	Green, bronze feathers, red-blue head
Picidae	<i>Chrysophlegma flavinucha</i>	<i>Pelatuk jambul kuning</i>	ML	Native	LC	-	✓	Forest	Insectivore	Medium	Green body, yellow crest
Picidae	<i>Dinopium javanense</i>	<i>Pelatuk bawang</i>	KS	Native	LC	-	✓	Agroforestry	Insectivore	Medium	Golden back, red crest, black wings
Psittaculidae	<i>Agapornis</i> sp.	<i>Lovebird</i>	DP, KS, ML	Domesticated	NE	NE	-	Settlements	Granivore	Small	Green-yellow, red, or blue face
Psittaculidae	<i>Loriculus galgulus</i>	<i>Serindit</i>	ML	Native	LC	II	✓	Agroforestry	Frugivore	Small	Bright green body, red beak
Psittaculidae	<i>Psittacula alexandri</i>	<i>Betet</i>	KL, ML	Native	NT	II	✓	Agroforestry	Frugivore	Medium	Green body, red chest, yellow bill
Pycnonotidae	<i>Pycnonotus aurigaster</i>	<i>Kutilang</i>	DP, KS, KL, ML	Native	LC	-	-	Agroforestry	Frugivore- Insectivore	Medium	Brown-grey, dark head, white vent
Pycnonotidae	<i>Pycnonotus goiavier</i>	<i>Trucuk</i>	DP, KS, KL	Native	LC	-	-	Agroforestry	Frugivore- Insectivore	Medium	Brown, yellow under-tail
Pycnonotidae	<i>Pycnonotus simplex</i>	<i>Cucak meranti</i>	KS	Native	LC	-	-	Agroforestry	Frugivore	Medium	Brown-grey, pale vent
Rallidae	<i>Amaurornis phoenicurus</i>	<i>Kareo padi</i>	KL	Native	LC	-	-	Wetlands	Omnivore	Medium	Black, white face, chestnut back
Rallidae	<i>Gallinula chloropus</i>	<i>Mandar</i>	KL	Native	LC	-	-	Wetlands	Omnivore	Medium	Dark brown-black, red bill with yellow tip
Rallidae	<i>Porphyrio indicus</i>	<i>Mandar besar</i>	DP, KS	Native	LC	-	-	Wetlands	Herbivore	Medium- large	Purple-blue body, red bill
Strigidae	<i>Otus angelinae</i>	<i>Celepuk jawa</i>	DP, KL, ML	Native	NT	-	✓	Forest	Carnivore	Small	Grey-brown streaked
Sturnidae	<i>Acridotheres javanicus</i>	<i>Jalak kerbau</i>	DP, KS, ML	Native	EN	-	-	Grassland / open fields	Omnivore	Medium	Black with white wing-patches
Sturnidae	<i>Gracupica contra</i>	<i>Jalak suren</i>	DP	Native	EN	II	✓	Agroforestry	Omnivore	Medium	Black-white body, orange face patch

Timaliidae	<i>Timalia pileata</i>	<i>Kaso-kaso</i>	KS	Native	LC	-	-	Agroforestry	Insectivore	Small	Brown body, chestnut cap
Zosteropidae	<i>Zosterops flavus</i>	<i>Pleci dada kuning</i>	KS	Native	EN	-	✓	Agroforestry	Nectarivore-Insectivore	Small	Yellow-green body
Zosteropidae	<i>Zosterops palpebrosus</i>	<i>Pleci</i>	DP, KS, KL, ML	Native	LC	-	-	Agroforestry	Nectarivore-Insectivore	Small	Green above, yellow throat

Note:

1. Village codes: DP: Dempel (31 sp.); KS: Karangsambung (44 sp.); KL: Kalialang (30 sp.); ML: Margolangu (41 sp).
2. Habitat types (observed land-use categories): Agroforestry gardens (mixed fruit trees, coffee, bamboo), pine forests (*Pinus merkusii*), rice fields (*sawah*), riverbanks (riparian vegetation), and settlements/homegardens (*pekarangan*).
3. Origin of Species: Native = wild, naturally occurring species in Indonesia; Introduced/domesticated = non-native or captive species found around settlements.
4. Feeding guild classification: Insectivore, frugivore, nectarivore, granivore, omnivore, carnivore/raptor.
5. Conservation Status:
 - IUCN Red List: LC: Least Concern; NT: Near Threatened; VU: Vulnerable; EN: Endangered.
 - National status (RI): Based on Indonesian Regulation Permen LHK No. 106/2018 (protected species list).
 - CITES: Appendix I-III (international trade regulation).
6. Taxonomic reference and synonym notes:

Scientific names follow the IOC World Bird List (v.14.2). Some nomenclature differs from Indonesian Permen LHK 106/2018 but refers to the same taxa. Examples:

 - *Lonchura oryzivora* = *Padda oryzivora* (Java sparrow)
 - *Myophonus glaucinus* = *Myophonus caeruleus* (Javan whistling thrush)
 - *Gracupica contra* is sometimes listed as *Sturnus contra*
 - *Dinopium javanense* = *Picus javanensis*
 - *Chrysophlegma flavinucha* = *Picus flavinucha*
7. Exclusion criteria: Only wild bird species were included in richness, guild, and conservation analyses. Domesticated poultry (*Gallus domesticus*, *Anas platyrhynchos domesticus*, *Columba livia domestica*) and fully captive ornamental birds were excluded.