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Diverse Habitat Types Support High Bird Diversity in Jali River Estuary, Purworejo, Central Java, Indonesia

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Abstract

The Jali River estuary a compact 5.45-hectare mosaic of nine habitat types on Java's south coast, was surveyed from March to May 2023 to assess its avian diversity and community structure. Using point counts (n=12 points, 3 replicates) conducted during low tide periods, we recorded 229 individual encounters representing 41 species from 19 families. The estuary exhibited high overall bird diversity (Shannon-Wiener H' = 3.212 ± 0.102) with moderate evenness (E' = 0.605). Standardized encounter rates varied across habitats, with the River and Pandanus stand showing the highest values. Analysis of community similarity (Bray-Curtis index) revealed five distinct ecological clusters, demonstrating that bird assemblage composition was driven more by habitat structure and resource availability than by spatial proximity. This was further supported by NMDS ordination (stress = 0.14) and SIMPER analysis, which identified key indicator species such as the Zitting Cisticola for open terrestrial clusters and the Cerulean Kingfisher for mangroves. The estuary's significant conservation value is highlighted by the presence of eight species protected under Indonesian law (PERMENLHK P.106/2018), including the globally Endangered Great Knot (*Calidris tenuirostris*) and the Vulnerable Christmas Frigatebird (*Fregata andrewsi*). These findings underscore that even small, heterogeneous estuaries can support high avian diversity and serve as vital refuges for threatened species, necessitating targeted conservation strategies focused on preserving critical habitats like mudflats, river corridors, and Casuarina stands.

Keywords: Avian community, bray-curtis similarity, conservation significance, habitat mosaic, indicator species

1. Introduction

Estuaries are semi-enclosed coastal bodies of water where freshwater from rivers meets and mixes with oceanic seawater [1,2]. These transitional zones are among the most productive ecosystems on Earth, providing essential habitats for a wide array of bird species, including water, seabirds, and terrestrial birds [3]. The complex interplay between aquatic and terrestrial environments in estuaries creates a variety of niches that support feeding, breeding, and resting activities in avian communities.

Despite their ecological importance, estuaries face significant threats from anthropogenic activities. Coastal development, aquaculture expansion, pollution, and unregulated tourism contribute to the degradation and fragmentation of these critical habitats [4,5]. Therefore, understanding the ecological value and functioning of estuarine ecosystems is crucial for their effective conservation and management.

The southern coast of Java Island hosts several estuarine areas that are recognized for their significant bird diversity [6]. Habitat heterogeneity has been identified as a key driver of this diversity, with structurally complex environments supporting richer avian communities than homogeneous landscapes [7]. Additionally, many Javan estuaries serve as vital stopover sites for migratory shorebirds along the East Asian-Australasian Flyway, further emphasizing their conservation importance [8,9].

The Jali River estuary in Purworejo, Central Java, represents a typical small estuarine system along Java's southern coast, characterized by a mosaic of distinct habitat types, including

river channels, mangrove patches, sand dunes, and mudflats. Despite the recognized ecological value of similar ecosystems in the region, no comprehensive study has documented the avian community in this estuary. This research gap limits our understanding of the conservation significance of the area and hinders the development of evidence-based management strategies.

This study aims to provide the first comprehensive assessment of bird diversity in the Jali River estuary, specifically addressing the following research question: "Do micro-habitat structures drive compositional turnover in bird communities independent of spatial proximity?" We hypothesized that bird community composition is influenced more by habitat structural complexity and resource availability than by the simple geographic distance between sampling points.

To test this hypothesis, we employed standardized point-count methods to quantify avian diversity across nine distinct habitat types. We calculated standard ecological indices (Shannon-Wiener diversity, evenness, and Bray-Curtis similarity) to characterize community patterns and identify the environmental drivers of avian distribution. While advanced analytical approaches, such as hierarchical occupancy modeling, can account for imperfect detection in avian surveys, our study utilized repeated point counts following established methodologies [10,11] to provide robust baseline data on the avian community structure of the estuary.

Recent research on small-area estuarine mosaics has demonstrated that even compact landscapes can sustain substantial biodiversity when habitat heterogeneity is high [12,13]. By documenting the bird community composition and distribution patterns in this understudied estuary, our study not only addresses a significant knowledge gap but also contributes to understanding how small-scale habitat diversity maintains regional biodiversity. These findings provide a scientific basis for developing targeted conservation strategies for the Jali River Estuary and similar small-scale coastal ecosystems facing increasing anthropogenic pressure.

2. Study area and Methods

2.1. Study area

The research was conducted from March to May 2023 in the Jali River Estuary, Purworejo, Central Java (7°51'02.79"S 109°54'55.62"E, 7°51'16.68"S 109°54'53.08"E). The Jali River is bordered by an estuary to the north, the Indian Ocean to the south, the Grabag Subdistrict to the east, and the Ngombol Subdistrict to the west (Figure 1). This location has a coverage of 5.45 ha and consists of nine habitat types: shrimp ponds (0.5 ha), rice fields (1.76 ha), Pandanus stands (0.1 ha), mangroves (0.2 ha), Casuarina stands (0.44 ha), shrubs (1.51 ha), rivers (0.05 ha), mudflats (0.17 ha), and sand dunes (0.72 ha) (Figure 2).

The study area is part of Ngombol, which is managed by local people and the local government. The activities of local people are mostly fishing, aquaculture, and farming (Figure 3). There has been no bird hunting activity in the area.

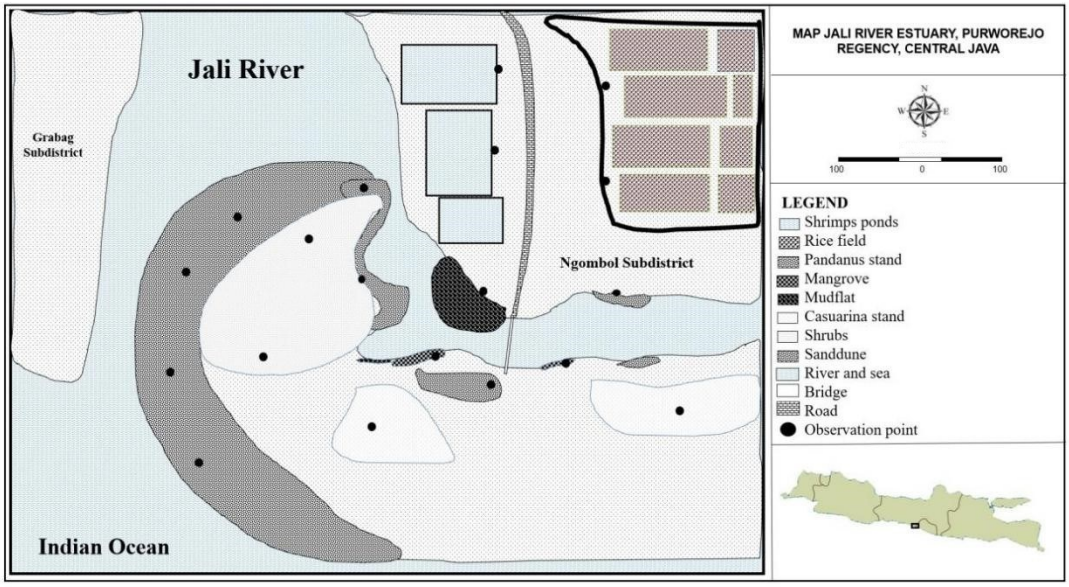

Figure 1. Map of the Jali River Estuary in Purworejo Regency, Central Java. This map delineates primary land cover types—such as mangrove forests and rice fields—within the estuarine zone. It serves to identify observation points within the site and defines the administrative boundary of the study area, which is directly adjacent to the Indian Ocean.

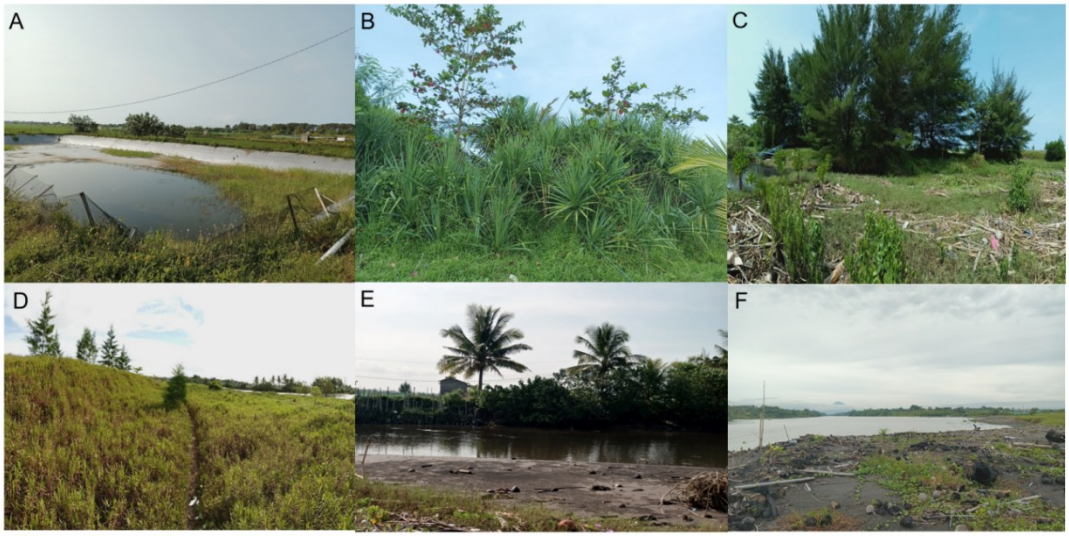

Figure 2. Representative habitats within the coastal study area. The panels (A-F) depict six of the nine identified habitat types: anthropogenic aquaculture (shrimp pond), coastal vegetation (Pandanus and Casuarina stands), shrubland, and intertidal zones (mudflat and sand dune). This visual catalog is essential for analyzing biodiversity distribution and ecological transitions across the landscape.

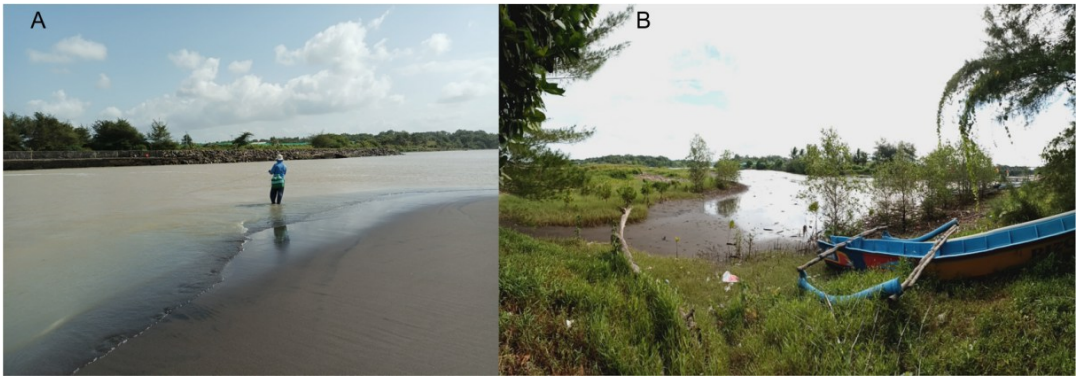

Figure 3. Documentation of primary livelihood activities in the Jali River estuary study area, Purworejo, Central Java. These images capture two primary economic practices: (A) near-shore or riverbank fishing, and (B) offshore fishing activities conducted by fishermen, with the presence of a boat as evidence. These activities represent the direct dependence of the local community on aquatic resources.

2.2. Methods

Bird surveys were conducted from March to May 2023 across nine distinct habitat types in the Jali River Estuary. Data collection employed a combination of exploratory observation ('look and see') and point-count methods [10,11]. A total of 12 fixed-point count locations, spaced 70 m apart with a 30-meter radius, were established to systematically cover the study area (Figure 1). Each point was visited thrice, resulting in a total survey effort of 144 h. To account for environmental variability, the date, start time, weather conditions, and tidal state were recorded for each survey. For population estimation, the mean count across the three replicates for each species at each point was used as a measure of relative frequency to avoid count inflation, acknowledging that these data represent habitat use patterns rather than absolute population densities owing to the lack of detectability modeling.

Data analysis encompassed community diversity and structural composition of the microbiome. Species diversity was calculated using the Shannon-Wiener index (H’), with its standard error (SE) estimated via bootstrapping (1000 iterations) to assess robustness, while Pielou’s evenness index (E’) quantified species distribution uniformity [14,15]. A Bray-Curtis dissimilarity matrix was constructed to examine community similarity. This matrix was used to generate a UPGMA dendrogram with bootstrap support and to perform Non-Metric Multidimensional Scaling (NMDS), providing a visual representation of habitat groupings based on avian assemblage composition. Furthermore, Similarity Percentage (SIMPER) analysis was applied to identify the bird species that contributed most to the dissimilarities between the major habitat clusters identified in the dendrogram.

The conservation status of recorded species was assessed against Indonesian law (P.106/MENLHK/SETJEN/KUM.1/12/2018) [16], the IUCN Red List, and CITES appendices, while taxonomy and nomenclature consistently followed Eaton et al. [17]. This study was conducted as a preliminary non-invasive field observation. All data were collected through visual and auditory means without capturing, handling, or disturbing the birds or their habitats. Therefore, this study adhered to the ethical guidelines for wildlife observation outlined by the Indonesian Institute of Sciences (LIPI), with all activities carried out respectfully within the local community.

3. Results and Discussion

3.1. Results

3.1.1. Bird diversity

The survey recorded a cumulative total of 229 individual bird encounters across nine distinct habitat types in the Jali River estuary, representing 41 species from 19 families. This

cumulative count represents the sum of all individuals observed across the three separate survey repetitions and reflects the overall avian activity and richness, although it should not be interpreted as the total population size at any single time. To provide a robust measure of diversity, the Shannon-Wiener Index (H') was calculated for each habitat type, along with its standard error (SE). The standard error quantifies the uncertainty surrounding the diversity estimate, providing a more statistically sound interpretation. A higher H' value indicates greater species diversity, whereas a smaller SE relative to H' suggests a more reliable estimate.

The analysis revealed that the river habitat had the highest species diversity (H'= 2.649 ± 0.025), closely followed by the Casuarina stand (H' = 2.603 ± 0.024). The low standard errors associated with these indices indicate that the estimates are precise and reliable. The high diversity in the river is likely due to its role as a critical source of food and water, attracting various waterbirds, such as the Javan Pond Heron (*Ardeola speciosa*). In contrast, the shrub habitat showed the lowest diversity (H' = 2.074 ± 0.038). Although species-rich, the Casuarina stand may exhibit a different community structure, which is further explored by the evenness index.

The evenness indices (E'), ranging from 0.745 to 0.945 (Table 2), reveal the uniformity of individual distribution among the species present. The high evenness in mangroves (0.945) indicates a very balanced community in which no single species dominates. Conversely, the lower evenness in the species-rich Casuarina stand (0.750) suggests a slight dominance of a few species, such as the Javan Munia (*Lonchura leucogastroides*), which accounted for 10 of the 43 individuals recorded. Collectively, these findings demonstrate moderately high and statistically robust avian diversity across the estuary habitat mosaic, with the structural complexity and resource availability of each habitat type shaping its distinct bird community.

Table 1. Species composition and abundance of birds across various habitats in the study area. The table shows the distribution of 41 bird species in nine habitat types, along with total individuals per habitat and overall density per hectare. These data were analyzed to assess habitat preferences and ecological diversity of avian communities. Sequence and nomenclature follow Eaton et al. [17].

No	Common name	Scientific name	Shrimps Pond	Rice field	Pandanus stand	Mangrove	Casuarina stand	Shrubs	River	Sand-dune	Mudflat	Total
Waterbird												
1	Cinnamon Bittern	*Ixobrychus cinnamomeus*	-	-	-	-	-	-	1	-	-	1
2	Javan Pond Heron	*Ardeola speciosa*	1	3	-	2	-	-	4	2	2	14
3	Grey Heron	*Ardea cinerea*	-	-	-	-	-	-	-	2	1	3
4	Little Egret	*Egretta garzetta*	-	-	-	-	-	-	2	1	1	4
5	Cattle Egret	*Bubulcus ibis*	-	-	1	-	-	-	-	2	1	4
6	Intermediate Egret	*Ardea intermedia*	-	-	-	1	-	-	-	-	-	1
7	Great Egret	*Ardea alba*	-	-	-	-	-	-	2	-	-	2
										Shorebird		
8	Javan Plover	*Charadrius javanicus*	-	1	-	-	-	-	-	2	-	3
9	Greater Sand Plover	*Charadrius leschenaultii*	-	-	-	-	-	-	-	2	1	3
10	Common Sandpiper	*Actitis hypoleucos*	-	-	-	-	-	-	1	1	1	3
11	Great Knot	*Calidris tenuirostris*	-	-	-	-	-	-	-	8	-	8
12	Whimbrel	*Numenius phaeopus*	-	-	-	-	-	-	-	-	1	1
										Seabird		
13	Gull-billed Tern	*Gelochelidon nilotica*	-	-	-	-	-	-	-	1	-	1
14	Little Tern	*Sternula albifrons*	-	-	-	-	-	-	-	1	-	1
15	Lesser Frigatebird	*Fregata ariel*	-	-	-	-	-	-	1	-	-	1
16	Christmas Frigatebird	*Fregata andrewsi*	-	-	-	-	-	-	-	-	1	1
								Terestrial bird associated with water				
17	Javan Kingfisher	*Halcyon cyanoventris*	-	-	-	-	-	-	1	-	-	1
18	Collared Kingfisher	*Todiramphus chloris*	-	2	1	1	1	-	1	-	-	6
19	Sacred Kingfisher	*Todiramphus sanctus*	-	1	-	-	-	1	-	-	1	3
20	Cerulean Kingfisher	*Alcedo coerulescens*	1	-	-	2	1	-	1	1	-	6
										Terestrial bird		
21	Cave-Swiftlet	*Collocalia linchi*	5	5	5	2	3	5	1	3	5	34
22	Pacific Swallow	*Hirundo javanica*	2	1	1	1	3	2	1	-	-	11
23	Barn Swallow	*Hirundo rustica*	2	1	1	-	-	-	1	-	-	5
24	Zebra Dove	*Geopelia striata*	1	2	1	2	1	-	-	-	-	7

No	Common name	Scientific name	Shrimps Pond	Rice field	Pandanus stand	Mangrove	Casuarina stand	Shrubs	River	Sand-dune	Mudflat	Total
25	Spotted Dove	*Streptopelia chinensis*	-	-	-	-	-	1	-	-	-	1
26	Javan Coucal	*Centropus nigrorufus*	1	1	1	1	1	-	-	-	-	5
27	Savanna Nightjar	*Caprimulgus affinis*	-	-	1	-	3	5	2	-	-	11
28	Barred Buttonquail	*Turnix suscitator*	-	1	-	-	2	1	-	-	-	4
29	Blue-tailed Bee-eater	*Merops philippinus*	-	1	-	-	5	-	1	1	1	9
30	Sunda Pied Fantail	*Rhipidura javanica*	-	-	2	-	2	-	-	-	-	4
31	Sunda Yellow-vented Bulbul	*Pycnonotus goaivier*	2	-	-	-	-	-	-	-	-	2
32	Sooty-headed Bulbul	*Pycnonotus aurigaster*	-	-	2	-	-	-	-	-	-	2
33	Ashy Tailorbird	*Orthotomus ruficeps*	-	-	-	1	1	-	-	-	-	2
34	Common Tailorbird	*Orthotomus sutorius*	-	-	-	-	2	-	-	-	-	2
35	Deignan's Prinia	*Prinia polychroa*	-	-	1	-	-	1	1	-	-	3
36	Zitting Cisticola	*Cisticola juncidis*	3	5	2	2	3	4	2	-	-	21
37	Golden-headed Cisticola	*Cisticola exilis*	-	-	-	-	1	1	-	-	-	2
38	Ornate Sunbird	*Cinnyris ornatus*	1	-	1	-	2	-	-	-	-	4
39	Brown-throated Sunbird	*Anthreptes malacensis*	-	-	-	-	1	-	-	-	-	1
40	Javan Munia	*Lonchura leucogastroides*	2	2	2	-	10	2	5	-	-	23
41	Eurasian Tree Sparrow	*Passer montanus*	2	3	3	-	1	-	-	-	-	9
Total of individual species			12	14	15	10	18	10	17	13	11	120
Total of individuals			23	29	25	15	43	23	28	27	16	229
Density/ha			46.0	16.5	250.0	75.0	97.7	15.2	560.0	37.5	94.1	42.0

Table 2. Ecological indices across different habitat types in the study area. The table presents species richness, Shannon–Wiener diversity index (H' ± SE), and evenness index (E') for nine distinct habitats, reflecting differences in avian community structure and ecological balance. These indices were calculated to quantitatively compare habitat quality and biodiversity.

No.	Habitat type	Species richness	Diversity index (H' ± SE)	Evenness index (E')
1	Shrimp pond	12	2.341 ± 0.154	0.866
2	Rice field	14	2.442 ± 0.138	0.821
3	Pandanus stand	15	2.543 ± 0.134	0.848
4	Mangrove	10	2.246 ± 0.158	0.945
5	Casuarina stand	18	2.603 ± 0.116	0.750
6	Shrubs	10	2.074 ± 0.158	0.796
7	River	17	2.649 ± 0.121	0.832
8	Sand dune	13	2.301 ± 0.142	0.768
9	Mudflat	11	2.183 ± 0.159	0.807
	Total	41	3.212 ± 0.102	0.605

3.1.2. Bird community similarity

Analysis of bird community structure using the Bray-Curtis similarity index revealed clear ecological groupings among the nine habitat types, forming five distinct clusters that reflected functional habitat characteristics, rather than simple spatial proximity. The dendrogram (Figure 4) showed strong clustering between structurally similar habitats: shrubs paired with rice fields in an open-landscape cluster; Pandanus stands, rivers, shrimp ponds, and sand dunes formed a second cluster characterized by semi-aquatic conditions; and mudflats and mangroves comprised a third group despite their adjacency, highlighting the importance of microhabitat differences. The Casuarina stand emerged as a unique cluster, underscoring its distinctive vegetation structure.

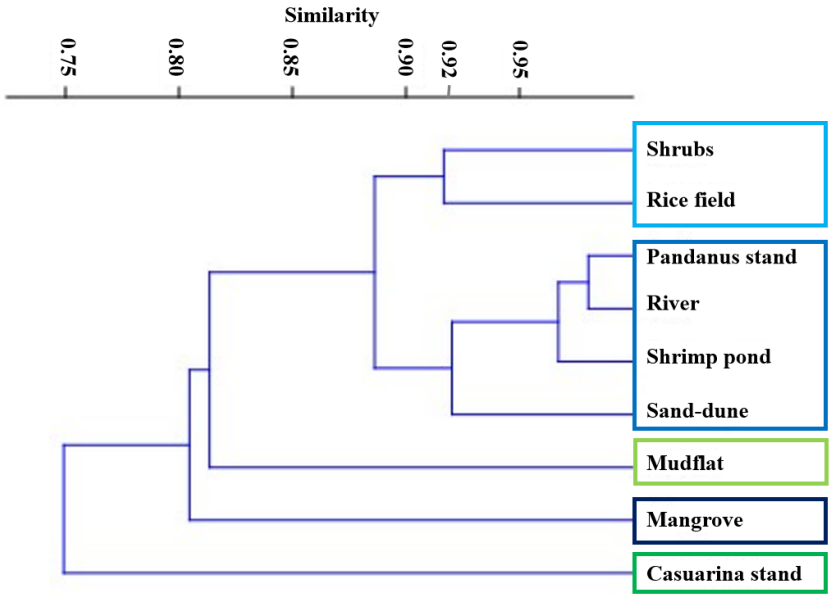

Figure 4. Dendrogram illustrating habitat similarity for bird communities in the Kali Jali estuary, based on the Bray-Curtis index. The hierarchical clustering analysis groups nine habitat types, including mangrove, rice field, mudflat, and shrimp pond, according to the compositional similarity of their avian assemblages. The resulting clusters reveal distinct ecological associations, identifying which habitat types support the most similar or dissimilar bird communities within this coastal landscape.

These patterns were further elucidated through Non-Metric Multidimensional Scaling (NMDS, stress=0.14), which visualized the ecological gradients structuring avian assemblages (Figure 5). The ordination clearly separated habitats along two primary axes: Axis 1 represented a terrestrial-to-aquatic gradient, and Axis 2 reflected vegetation complexity, with structurally simple mudflats and sand dunes positioned opposite dense Casuarina stands and mangroves.

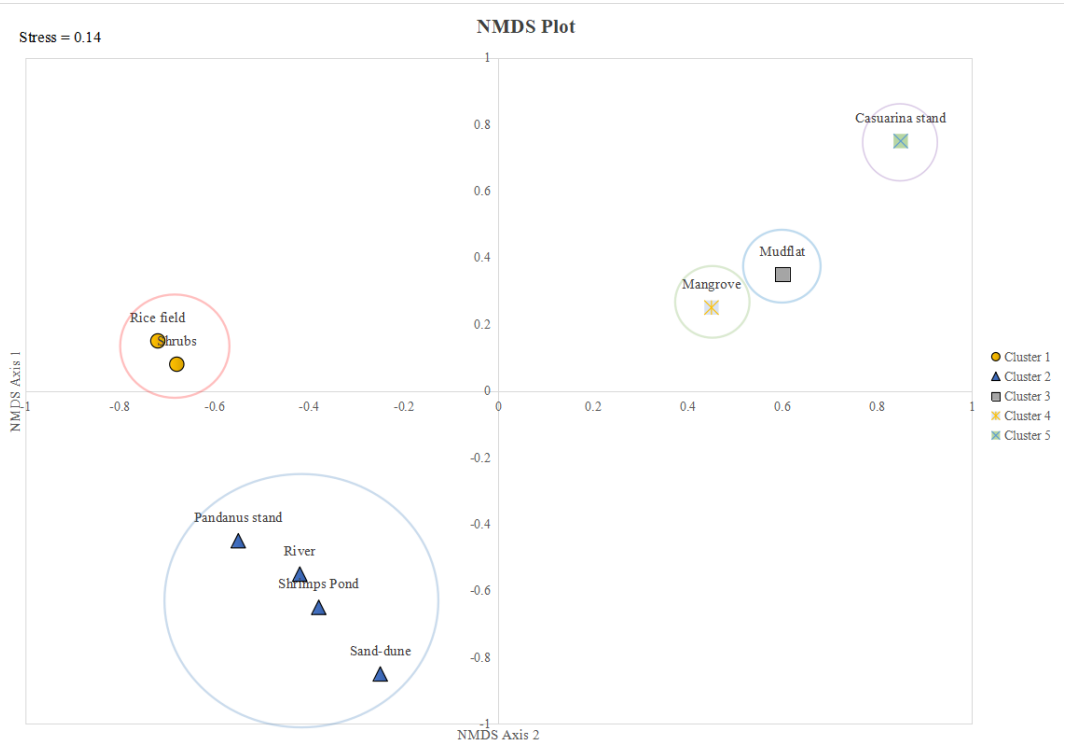

Figure 5. Non-metric Multidimensional Scaling (NMDS) ordination of bird community composition across nine habitat types in the Kali Jali estuary (stress = 0.14). The plot visualizes the dissimilarity in avian assemblages, where spatially closer points represent habitats with more similar bird communities. The ellipses, corresponding to the five major clusters from the dendrogram analysis, statistically group habitats, such as mangrove with mudflat, or rice field with shrub that share significant ecological affinities for bird species.

SIMPER analysis clearly delineated the distinct avian assemblages characterizing the five ecological clusters, underscoring the profound influence of habitat structure on bird community composition. Cluster 1 (Open Terrestrial), comprising ponds, rice fields, and shrubs, is predominantly defined by grassland and open-country species such as the Zitting Cisticola and Savanna Nightjar. In contrast, Cluster 5 (Casuarina Stand) was strongly associated with tree-dominated avifauna, notably the Javan Munia and Blue-tailed Bee-eater. The uniqueness of aquatic and coastal habitats is highlighted by their specialized species: Cluster 3 (mangrove) is distinguished by its association with the Cerulean Kingfisher, whereas Cluster 4 (mudflat) is unequivocally characterized by shorebirds, particularly the Javan Plover. Cluster 2 (Riparian), acting as an intermediate group, lacks a single dominant species but is defined by a mix of generalists. This clear segregation of key species across clusters demonstrates that bird distribution in the Jali River Estuary is not random but a direct reflection of specific habitat resources and structural niches.

Table 3. SIMPER analysis identifying key species driving dissimilarity between major habitat clusters. The table presents pairwise comparisons of avian community composition, highlighting the top three species that contribute most to ecological dissimilarity between clusters, along with their percentage contributions. This analysis aids in identifying indicator species that best characterize differences in habitat types and bird community structures.

No	Cluster Comparison	Key Distinguishing Species	Contribution to Dissimilarity
1.	Cluster 1 (Rice Fields, Shrubs) vs. Cluster 2 (Pandanus, River, Sand Dune)	Zitting Cisticola (*Cisticola juncidis*) Javan Munia (*Lonchura leucogastroides*) Cave Swiftlet (*Collocalia linchi*)	71.7%

No	Cluster Comparison	Key Distinguishing Species	Contribution to Dissimilarity
2.	Cluster 1 vs. Cluster 3 (Mangrove)	Zitting Cisticola (*Cisticola juncidis*) Javan Pond Heron (*Ardeola speciosa*) Cerulean Kingfisher (*Alcedo coerulescens*)	66.0%
3.	Cluster 1 vs. Cluster 4 (Mudflat)	Zitting Cisticola (*Cisticola juncidis*) Savanna Nightjar (*Caprimulgus affinis*) Javan Plover (*Anarhynchus javanicus*)	69.2%
4.	Cluster 1 vs. Cluster 5 (Casuarina Stand)	Zitting Cisticola *(Cisticola juncidis)* Javan Munia *(Lonchura leucogastroides)* Blue-tailed Bee-eater *(Merops philippinu*s)	71.0%
5.	Cluster 2 vs. Cluster 3 (Mangrove)	Javan Munia (*Lonchura leucogastroides*) Cerulean Kingfisher (*Alcedo coerulescens*) Javan Pond Heron (*Ardeola speciosa*)	64.7%
6.	Cluster 2 vs. Cluster 4 (Mudflat)	Javan Munia (*Lonchura leucogastroides*) Javan Plover (*Anarhynchus javanicus*) Javan Pond Heron (*Ardeola speciosa*)	66.8%
7.	Cluster 2 vs. Cluster 5 (Casuarina Stand)	Javan Munia (*Lonchura leucogastroides*) Blue-tailed Bee-eater (*Merops philippinu*s) Zitting Cisticola (*Cisticola juncidis*)	58.1%
8.	Cluster 3 (Mangrove) vs. Cluster 4 (Mudflat)	Javan Pond Heron (*Ardeola speciosa*) Cerulean Kingfisher (*Alcedo coerulescen*s) Javan Plover (*Anarhynchus javanicus*)	67.4%
9.	Cluster 3 (Mangrove) vs. Cluster 5 (Casuarina Stand)	Javan Munia (*Lonchura leucogastroides*) Cerulean Kingfisher (*Alcedo coerulescens*) Javan Pond Heron (*Ardeola speciosa*)	72.3%
10.	Cluster 4 (Mudflat) vs. Cluster 5 (Casuarina Stand)	Javan Munia (*Lonchura leucogastroides*) Javan Plover (*Anarhynchus javanicus*) Blue-tailed Bee-eater (*Merops philippinus*)	73.9%

3.1.3. Conservation status of bird

Beyond its ecological richness, the Jali River Estuary is a site of significant conservation value. We identified seven bird species protected under Indonesian law (PERMENLHK No P.106/2018), highlighting their national importance and the legal need for their preservation. Among these, two species are classified as global threats by the International Union for Conservation of Nature (IUCN). The Great Knot (*Calidris tenuirostris*) is classified as Endangered (EN), and the Christmas Frigatebird (*Fregata andrewsi*) is listed as Vulnerable (VU), marking the estuary as a potential refuge for populations facing severe global decline. The presence of the Christmas Frigatebird is of particular note, as it is also listed under CITES Appendix I, which prohibits all international commercial trade and emphasizes its critical conservation status worldwide.

The regular occurrence of these threatened and protected species, such as the Javan Plover and elegant Great Egret, transforms the estuary from a mere avian habitat into a vital sanctuary. Their reliance on this landscape for foraging and resting underscores the urgent need to recognize and integrate the Jali River Estuary into broader regional conservation strategies. Protecting this area is not just about preserving local biodiversity but also about contributing to the international effort to safeguard migratory and threatened species, ensuring that these remarkable birds continue to grace this ecosystem for generations to come.

Table 4. Conservation, threat, and international trade status of selected bird species in the Jali River Estuary, Purworejo. The table lists the protection status according to Indonesian regulation (PermenLHK No. 106 of 2018), the global extinction risk category (IUCN Red List), and the international trade regulation (CITES) for eight bird species recorded in the study area. This information is essential for assessing conservation priorities and legal protection frameworks for avian biodiversity in the estuary.

No.	Name of bird	Scientific name	PermenLHK No.106 of 2018	IUCN	CITES
1	Javan Plover	*Charadrius javanicus*	P	LC[18]	Non-App
2	Great Knot	*Calidris tenuirostris*	-	EN[19]	Non-App
3	Whimbrel	*Numenius phaeopus*	P	LC[20]	Non-App
4	Gull-billed Tern	*Gelochelidon nilotica*	P	LC[21]	Non-App
5	Little Tern	*Sternula albifrons*	P	LC[22]	Non-App
6	Christmas Frigatebird	*Fregata andrewsi*	P	VU[23]	APP I
7	Great Egret	*Ardea alba*	P	LC[24]	Non-App
8	Sunda Pied Fantail	*Rhipidura javanica*	P	LC[25]	Non-App

Notes: P = Protected, LC = Least Concern, VU = Vulnerable, EN = Endangered, App I = Appendix I, Non-App= Non-Appendix, - = Unprotected

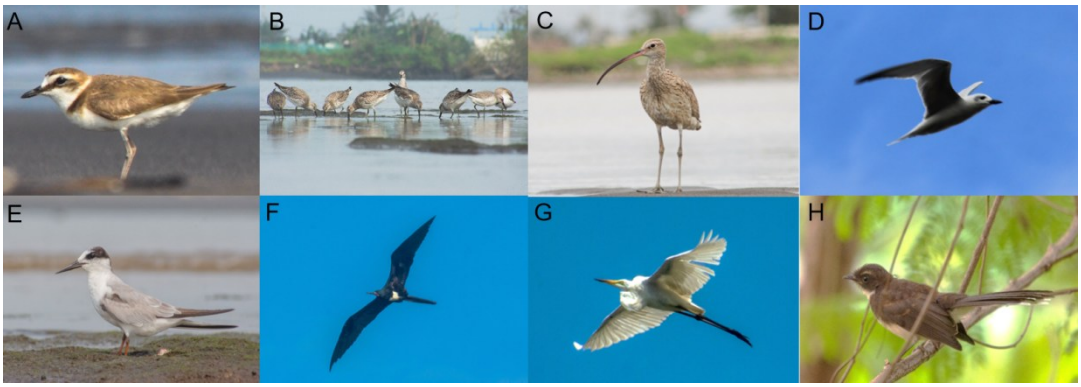

Figure 6. Conservation status of select species in the Jali River Estuary. The panel (A-H) documents eight bird species from diverse families, including migratory shorebirds (e.g., Great Knot), resident waterbirds (e.g., Great Egret), and endemic species (e.g., Javan Plover). The representation highlights species of conservation concern, such as the Critically Endangered Christmas Frigatebird, underscoring the estuary's role as critical habitat for both local and threatened avian populations.

3.2. Discussion

The Jali River Estuary serves as a crucial stronghold for a unique and diverse bird community. This richness stems from the area's pronounced habitat heterogeneity, which creates a mosaic of different ecological niches within a single ecosystem. Cluster and NMDS analyses clearly delineated the nine sampled habitats into five distinct avian assemblages. Notably, the Casuarina stand emerged as a unique cluster, separate even from physically adjacent habitats. This finding strongly suggests that the primary drivers of avian community assembly are not spatial proximity, but rather vegetation structure and the terrestrial-aquatic gradient. This evidence reinforces the established ecological principle that habitat variation is a fundamental foundation for bird species diversity [26–29].

Ecologically, the Jali River Estuary shares functional patterns with other small mangrove estuaries in Southeast Asia, while retaining its own distinct characteristics. Similar to sites like the Setiu Wetlands in Malaysia, the fine-scale habitat mosaic in Jali River estuary ranging from mudflats to dense terrestrial thickets—fosters a high diversity of ecological niches for birds. However, the composition of species and functional groups (guilds) here reveals its unique signature. In terms of standardized diversity metrics, the Jali River estuary presents a

different profile compared to other estuaries along Java's south coast and Indonesia broadly. This study recorded 41 species with a notably high overall Shannon-Wiener Index (H') of 3.212. This richness and diversity exceed figures reported from more specialized estuarine ecosystems, such as the Progo Estuary (26 species) and Segara Anakan (32 species) [6–9,30]. This comparison highlights a crucial ecological contrast: small, structurally complex estuaries like Jali tend to support a more balanced assemblage of terrestrial and aquatic bird groups. In contrast, larger but more homogeneous estuarine systems, such as expansive open lagoons, are typically dominated by waterbirds and migrants, offering fewer niches for forest-associated or terrestrial species.

The guild composition in Jali further elucidates this pattern. Unlike the waterbird-dominated communities reported from open wetland areas like Progo and Segara Anakan, the complex habitat mosaic of the Jali Estuary supports a more balanced spectrum of functional groups. The significant presence of diverse terrestrial species, such as the Javan Munia and Zitting Cisticola, alongside waterbirds, creates a community structure more akin to integrated mangrove-forest systems. This pattern underscores the site's ecological distinctiveness [31,32].

A critical insight from our data is that habitat quality and structural complexity exert a greater influence on bird diversity than does area size alone [33,34]. This is powerfully illustrated by bird density per hectare. Despite its limited spatial extent, the Riverine habitat registered the highest density (560 individuals/ha) alongside high diversity (H'=2.649). Similarly, the Pandanus stand recorded substantial values (250 individuals/ha, H'=2.543). Conversely, more extensive but structurally simple habitats, like shrubland and rice fields, supported lower densities and diversity per unit area. This pattern indicates that structurally complex microhabitats function as biodiversity "hotspots." These small areas disproportionately support avian abundance and richness by providing a variety of niches and resources [35–38].

The conservation significance of the Jali estuary is further elevated by the presence of protected and threatened species [39]. This study documented eight species protected under Indonesian law (PERMENLHK No P.106/2018). Two of these carry global threat classifications: the Great Knot (*Calidris tenuirostris*), listed as Endangered (EN), and the Christmas Frigatebird (*Fregata andrewsi*), listed as Vulnerable (VU) and on CITES Appendix I. The regular occurrence of these high-conservation-value species elevates the estuary's status from a locally important habitat to a vital refuge for populations of global concern.

These findings necessitate targeted management strategies focused on preserving the habitat heterogeneity that defines this estuary. Specific management implications include: (1) safeguarding the hydrological integrity of the mudflats, which are critical for shorebirds like the Javan Plover; (2) ensuring the structural preservation of the unique Casuarina stands that harbor specialized terrestrial birds; (3) promoting best practices in shrimp pond aquaculture to minimize ecological damage while maintaining their function as semi-aquatic habitats [40,41]; and (4) exploring opportunities for limited, well-managed bird ecotourism focused on high-value habitats such as the river corridor and Pandanus stands. An integrated management approach targeting these key habitats is essential to ensure the long-term resilience of the Jali River Estuary as a bastion for unique and valuable avifauna [33].

4. Conclusions

This study establishes the Jali River estuary as a significant avian conservation site, hosting 41 species from 19 families, with high overall diversity (Shannon-Wiener H' = 3.212± 0.102). The avian community structure is predominantly shaped by habitat heterogeneity, forming five distinct ecological clusters that reflect functional habitat characteristics rather than spatial proximity of the habitat. The conservation value of the estuary is underscored by the presence of eight nationally protected species, including the globally Endangered Great Knot (*Calidris tenuirostris*) and the Vulnerable Christmas Frigatebird *(Fregata andrewsi*). To safeguard this unique avifauna, we recommend prioritizing the following habitat-specific management actions: (1) protecting the hydrological integrity of the mudflats and river corridor, which are critical for threatened shorebirds and support the highest bird density;

(2) preserving the structural complexity of the unique Casuarina stands that harbor distinctive terrestrial birds; and (3) implementing sustainable practices in adjacent aquaculture to mitigate the ecological impacts. An integrated management approach focusing on these key habitats is crucial for the long-term conservation of estuaries.

Author Contributions

NHF: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing; **YAM** : Conceptualization, Writing - Review & Editing, Supervision; **AM** : Conceptualization, Writing - Review & Editing, Supervision.

AI Writing Statement

During the preparation of this work, the author(s) used Deepseek and Grammarly for language editing, specifically to refine word choice and rephrase potentially ambiguous sentences to enhance clarity for the reader. Following the use of this tool, the author(s) reviewed and edited the content as necessary and accept full responsibility for the published work.

Conflicts of interest

There are no conflicts to declare.

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