Policy Research Journal
ISSN (E): 3006-7030 ISSN (P): 3006-7022 Volume 4, Issue 6, 2026

RESTORATION OF PADDY ECOSYSTEMS: ASSESSING BIODIVERSITY AND BIOTIC INTERACTIONS ACROSS AGRICULTURAL LANDSCAPES OF PAKISTAN

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DOI: https://doi.org/10.5281/zenodo.20807173

Keywords
Paddy ecosystem restoration; Biodiversity conservation; Rice agroecosystems; Biotic interactions; Pakistan

Article History
Received: 25 April 2026
Accepted: 07 June 2026
Published: 23 June 2026

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Abstract

Paddy ecosystems represent multifunctional agroecosystems that contribute simultaneously to food production, biodiversity conservation, and ecosystem service provision. In Pakistan, intensive rice cultivation across Punjab and Sindh has increasingly led to biodiversity loss, habitat simplification, and disruption of ecological processes due to agrochemical intensification and landscape fragmentation. This study evaluates the effects of ecological restoration practices on biodiversity patterns and biotic interactions in paddy ecosystems across major rice-growing regions of Pakistan, including Gujranwala, Hafizabad, Sheikhupura, Narowal, and Larkana. A comparative field-based assessment was conducted over two rice-growing seasons (2022–2024), involving restored and conventional paddy systems. Multi-trophic biodiversity was assessed, including plant communities, arthropods, pollinators, amphibians, birds, and soil microorganisms, along with ecological network and landscape analyses. Results demonstrated that restored paddy ecosystems significantly enhanced biodiversity across all trophic levels. Plant species richness increased from 31 to 48 species, while arthropod diversity shifted towards beneficial functional groups, with predator abundance increasing by more than 70%. Pollinator populations increased by 56%, amphibian species richness by 80%, and bird abundance by 42% in restored systems. Soil microbial biomass carbon increased by 42.2%, indicating improved belowground ecosystem functioning. Ecological network analysis revealed stronger trophic connectivity and higher ecosystem stability in restored fields. Landscape heterogeneity, vegetated field margins, and wetland connectivity emerged as key drivers of biodiversity enhancement. Overall, the findings demonstrate that ecological restoration significantly improves biodiversity, strengthens biotic interactions, and enhances ecosystem resilience in rice agroecosystems. The study highlights the potential of biodiversity-friendly farming practices to achieve sustainable rice production while supporting ecological conservation in Pakistan.

1. INTRODUCTION

Rice (*Oryza sativa* L.) is one of the most important staple food crops in the world and plays a central role in global food security, particularly in Asia, where more than 90% of rice is produced and consumed (Mohidem et al., 2022). In Pakistan, rice is the second most important cereal crop after wheat and contributes significantly to agricultural GDP, rural livelihoods, and export earnings (Shahzadi et al., 2018). The country is among the leading rice exporters globally, with major production concentrated in Punjab and Sindh provinces. Despite its economic importance, rice cultivation in Pakistan is increasingly challenged by declining ecosystem health, biodiversity loss, water scarcity, and unsustainable agricultural intensification (Lal et al., 2018). Paddy ecosystems are unique agroecological systems that function as artificial wetlands, supporting a wide range of aquatic and terrestrial organisms. These systems provide habitat for plants, insects, amphibians, birds, and microorganisms, thereby contributing not only to agricultural productivity but also to regional biodiversity conservation (Perfecto et al., 2008). When managed sustainably, rice fields can support complex food webs and deliver multiple ecosystem services, including pest regulation, nutrient cycling, pollination support, and water purification. However, modern agricultural intensification has significantly altered these ecological functions.

In Pakistan, the Green Revolution–driven intensification of agriculture has led to increased use of synthetic fertilizers, pesticides, herbicides, and mechanized farming practices (Byerlee et al., 1994). While these inputs have enhanced short-term crop productivity, they have also resulted in unintended ecological consequences, including habitat simplification, soil degradation, water pollution, and a decline in beneficial organisms. Monocropping systems and removal of non-crop habitats such as field margins and wetlands have further reduced landscape heterogeneity, which is a key driver of biodiversity maintenance in agricultural systems (Munyuli et al., 2011). Among the most affected components of agroecosystems are pollinators, natural enemies of pests, amphibians, birds, and soil microorganisms. Declines in these groups can disrupt ecological balance, leading to increased pest outbreaks, reduced soil fertility, and higher dependency on chemical inputs. In rice-based systems, excessive pesticide use has been particularly detrimental to aquatic organisms and beneficial arthropods, thereby weakening natural pest control mechanisms (Cochard et al., 2014). Similarly, habitat fragmentation and reduction in vegetative diversity have negatively impacted avian and amphibian populations that depend on paddy fields as feeding and breeding habitats.

In recent years, ecological restoration and agroecological intensification have emerged as promising approaches to reconcile agricultural productivity with biodiversity conservation (Sietz et al., 2022). Restoration strategies in agricultural landscapes typically include practices such as reduced pesticide use, establishment of vegetated field margins, incorporation of organic amendments, conservation of wetlands, and implementation of integrated pest management (IPM). These approaches aim to restore ecological processes, enhance habitat complexity, and strengthen biotic interactions within agroecosystems. Globally, studies have demonstrated that biodiversity-friendly farming practices can significantly improve ecosystem services such as biological pest control, pollination, and nutrient cycling while maintaining or even increasing crop yields (Diyaolu et al., 2024). In rice agroecosystems across Asia, ecological engineering approaches have shown promising results in enhancing natural enemy populations and reducing pest damage. However, despite these global advances, there remains limited empirical evidence from Pakistan on how restoration practices influence biodiversity patterns and ecological interactions in paddy ecosystems across different agricultural landscapes.

Furthermore, most existing studies in Pakistan have focused primarily on crop yield and agronomic performance, with relatively little attention given to multi-trophic biodiversity assessment and ecosystem functioning (Farooq et al., 2025). There is a critical need to understand how restoration interventions affect not only individual taxa but also the structure and functioning of entire ecological networks, including interactions among plants, insects, birds, amphibians, and soil microorganisms. Such an integrated approach is essential for developing sustainable rice production systems that are resilient to environmental change. Given this context, the present study was designed to evaluate the effects of ecological restoration practices on biodiversity and biotic interactions in paddy ecosystems across major rice-growing regions of Pakistan. The study focuses on comparing restored and conventional rice fields in terms of plant diversity, arthropod community structure, pollinator abundance, amphibian populations, avian diversity, and soil microbial activity. In addition, the study investigates landscape-level drivers of biodiversity and examines how habitat heterogeneity influences ecosystem stability and functioning.

The specific objectives of this study were: (i) to quantify and compare biodiversity across multiple trophic levels in restored and conventional paddy ecosystems; (ii) to assess the structure and dynamics of biotic interactions within rice agroecosystems; (iii) to evaluate the role of landscape heterogeneity in shaping biodiversity patterns; and (iv) to provide evidence-based recommendations for integrating biodiversity conservation into rice farming systems in Pakistan. By addressing these objectives, this study aims to contribute to the growing field of agroecological restoration and provide scientifically grounded insights for sustainable rice production. The findings are expected to support the development of biodiversity-friendly agricultural policies and promote ecosystem-based management strategies that enhance both productivity and ecological resilience in Pakistan's rice landscapes.

2. Methodology

2.1 Study Area

The present study was conducted in the major rice-producing regions of Pakistan, covering selected districts of Punjab and Sindh provinces, including Gujranwala, Hafizabad, Sheikhupura, and Narowal in Punjab, and Larkana in Sindh (Figure 1). These regions were selected to represent the ecological and climatic diversity of Pakistan's rice-growing belt. The Punjab sites lie within a sub-humid subtropical climatic zone characterized by fertile alluvial soils and an extensive canal irrigation network derived from the Indus Basin Irrigation System. These districts are among the highest contributors to national rice production and are dominated by intensive agricultural practices, including rice–wheat cropping rotations and high agrochemical inputs. In contrast, Larkana represents a semi-arid agroecological region with higher temperatures, greater evapotranspiration rates, and relatively different irrigation dynamics influenced by the Indus River system. This contrast between the two provinces provided an excellent ecological gradient for assessing biodiversity patterns, ecosystem functioning, and restoration responses in rice agroecosystems under varying environmental conditions.

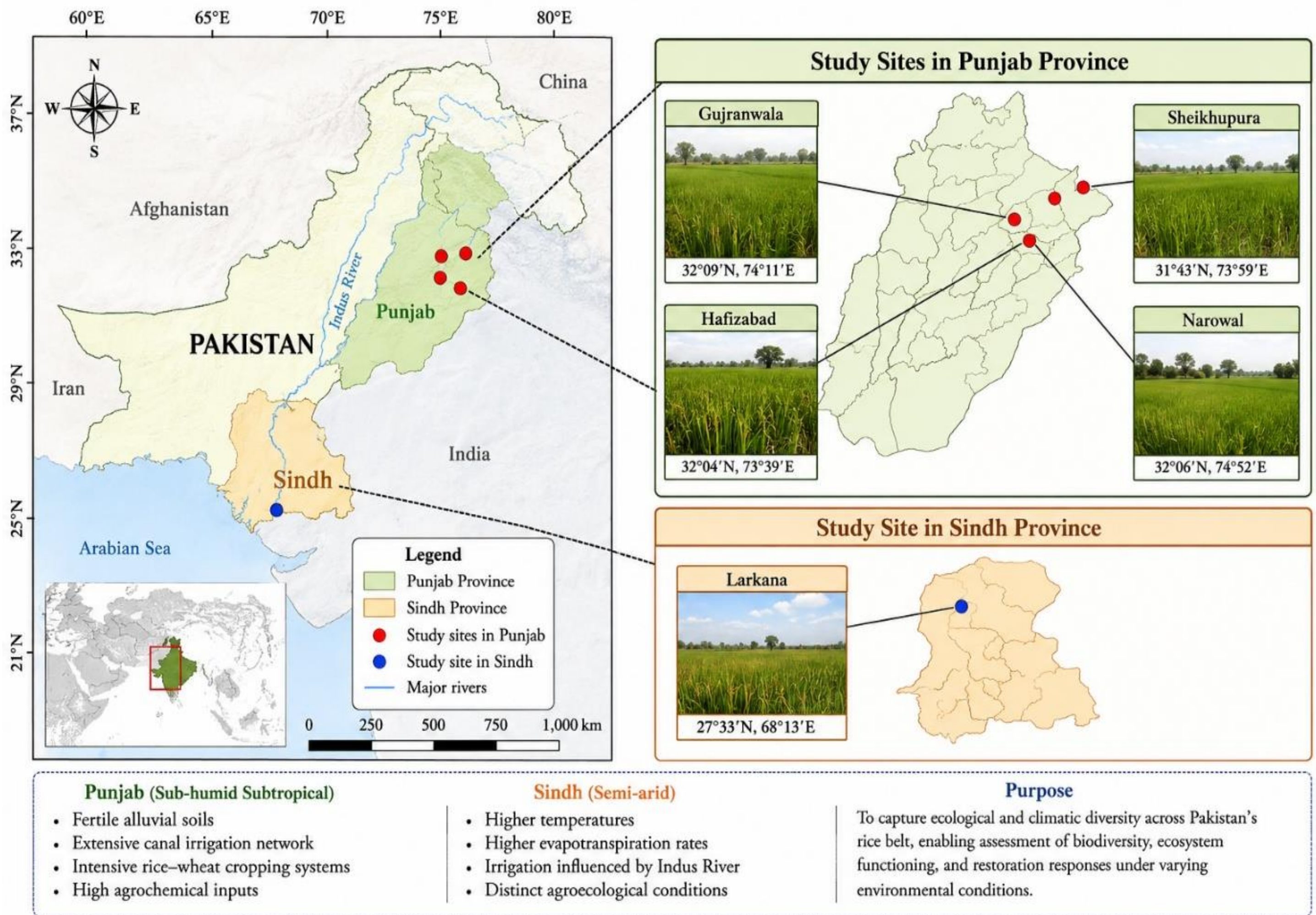

Figure 1. Map of the study area.

2.2 Experimental Design

A comparative field-based study was conducted over two consecutive rice-growing seasons from 2022 to 2024 (Solangi et al., 2026). A total of forty paddy fields were selected using a stratified random sampling approach to ensure ecological comparability among sites. These included twenty restored paddy ecosystems and twenty conventional paddy ecosystems. Selection criteria for all fields included similarity in soil type, irrigation source, rice variety, and general farm size to minimize confounding effects. Restored paddy ecosystems were characterized by the implementation of ecological enhancement practices such as the establishment of vegetated field margins using native plant species, reduced and more targeted pesticide application under integrated pest management strategies, incorporation of organic amendments such as farmyard manure and compost, and the maintenance of wetland buffer zones along irrigation channels and drainage pathways. These systems also emphasized the conservation of natural enemies and the promotion of ecological pest regulation mechanisms. In contrast, conventional paddy ecosystems represented typical intensive agricultural practices in the region, where heavy reliance on synthetic fertilizers and pesticides was common, monocropping systems were dominant, and ecological infrastructures such as field margins and buffer zones were largely absent. This comparative design allowed for a robust evaluation of biodiversity responses and ecosystem functioning under contrasting management regimes.

2.3 Biodiversity Assessment

Biodiversity assessments were carried out across multiple trophic levels, including vegetation, arthropods, birds, amphibians, and soil microorganisms, in order to capture a holistic understanding of ecosystem structure and function (Soliveres et al., 2016). Plant diversity was evaluated using systematic quadrat sampling, where one-meter-square quadrats were placed randomly along transects within each field, covering both field interiors and margins. Within each quadrat, all plant species were identified and recorded, including aquatic vegetation, semi-aquatic weeds, and margin flora. Diversity was quantified using standard ecological indices, including the Shannon–Wiener diversity index, Simpson's diversity index, species richness, and Pielou's evenness index, allowing for comprehensive assessment of species composition and dominance structure.

Arthropod communities were sampled using a combination of sweep netting and pitfall trapping techniques to capture both aerial and ground-dwelling species (El Harche et al., 2026). Sweep nets were used to collect canopy-dwelling insects, while pitfall traps were installed at soil level to sample ground-active arthropods. Sampling targeted major functional guilds, including pollinators, predators, parasitoids, and herbivorous pests. Sampling was conducted at fifteen-day intervals throughout the rice-growing season to account for temporal variations in arthropod populations and community dynamics. Bird diversity was assessed using the point count method, where fixed observation points were established in each field. Observations were conducted during early morning hours when avian activity is highest. At each point, all birds seen or heard within a defined radius were recorded over a standardized time period. Species richness, relative abundance, feeding guilds, and nesting behavior were documented to assess avian community structure and ecological roles within the paddy ecosystems.

Amphibian populations were monitored through nocturnal visual encounter surveys conducted along field bunds and irrigation channels (Rossi et al., 2022). Surveys were performed during nighttime hours when amphibian activity peaks. Both auditory call identification and visual observations were used to record species presence and abundance. Frogs and toads were the primary target groups, as they are highly sensitive to environmental changes and serve as effective bioindicators of ecosystem health. Soil microbial diversity was assessed through the collection of soil samples from the upper fifteen centimeters of the soil profile, which represents the most biologically active zone in paddy ecosystems. Composite soil samples were prepared from multiple sampling points within each field. Laboratory analyses included the determination of microbial biomass carbon using chloroform fumigation extraction, soil respiration rates through carbon dioxide evolution measurements, and assessments of bacterial and fungal diversity using culture-based and morphological approaches. Samples were stored at low temperature before analysis to preserve microbial integrity.

2.4 Landscape Analysis

Landscape-level ecological assessments were conducted using Geographic Information Systems (GIS) and remote sensing techniques to evaluate spatial patterns influencing biodiversity (Roy et al., 2000). Satellite imagery obtained from Sentinel-2 and Landsat 8 platforms was used to classify land-use and land-cover patterns within a five-kilometer buffer zone surrounding each study site. Key landscape variables included wetland connectivity, habitat fragmentation, vegetation cover, edge density, and patch size distribution. These metrics were calculated using FRAGSTATS software, which enabled quantification of landscape composition and configuration. The analysis provided insights into how spatial heterogeneity and landscape structure influence biodiversity patterns and ecosystem functioning in rice agroecosystems.

2.5 Statistical Analysis

All collected data were subjected to rigorous statistical analysis to evaluate differences between restored and conventional paddy ecosystems. One-way and two-way analysis of variance (ANOVA) was applied to test for significant differences in biodiversity indices, species abundance, and soil parameters between treatments and across regions. Principal component analysis (PCA) was used to identify major gradients influencing biodiversity variation, while redundancy analysis (RDA) was employed to explore relationships between environmental variables and species composition. Ecological network analysis was further used to assess trophic interactions and ecosystem connectivity within the studied agroecosystems. Statistical significance was determined at a probability level of less than 0.05, and all analyses were conducted using R statistical software and SPSS version 26. Graphical representations of results were generated to visualize ecological patterns, interactions, and spatial variability across study sites.

3. Results and Discussion

3.1. Plant Diversity and Vegetation Structure

The comparative assessment of vegetation communities revealed a substantial improvement in plant diversity within restored paddy ecosystems compared to conventional systems. Across all study sites in Punjab and Sindh, a total of 56 plant species were documented, comprising aquatic macrophytes, emergent weeds, and marginal vegetation. Restored ecosystems exhibited significantly higher species richness (48 species) compared to conventional systems (31 species), indicating that ecological restoration practices promoted greater habitat heterogeneity and reduced dominance of a few competitive weed species. Diversity indices further confirmed these patterns, with Shannon diversity values ranging from 2.85 to 3.20 in restored fields, while conventional fields exhibited lower values (1.60–2.05). Simpson's index and evenness values also indicated a more balanced community structure in restored ecosystems.

The observed increase in plant diversity can be attributed to reduced herbicide application, maintenance of vegetated field margins, and organic soil amendments (Gibson et al., 2007). These factors collectively enhanced microhabitat availability and reduced ecological filtering pressure. Similar findings have been reported in agroecological studies where reduced chemical intensity leads to increased weed and aquatic plant diversity, thereby strengthening ecosystem multifunctionality (Fried et al., 2018).

Table 1. Vegetation diversity metrics in restored and conventional paddy ecosystems

Ecological Parameter	Restored Ecosystems	Conventional Ecosystems	% Change
Species richness (S)	48 ± 3.1	31 ± 2.4	+54.8%
Shannon index (H′)	3.05 ± 0.12	1.82 ± 0.10	+67.5%
Simpson index (1-D)	0.90 ± 0.03	0.64 ± 0.04	+40.6%
Evenness (J)	0.82 ± 0.05	0.57 ± 0.06	+43.8%

3.2 Arthropod Diversity and Functional Guild Dynamics

Arthropod communities showed a strong and consistent response to ecological restoration, with a total of 187 species recorded across all study sites. Restored ecosystems exhibited a pronounced shift toward beneficial arthropod guilds, particularly predators and parasitoids, whereas conventional systems were dominated by herbivorous pest species. This pattern indicates a clear restructuring of trophic interactions under restoration practices. As presented in Table 2, functional group composition differed markedly between restored and conventional ecosystems. Predators constituted 38% of the arthropod community in restored fields compared to 22% in conventional systems, representing a substantial relative increase of 72.7%. Parasitoids also showed a strong positive response, increasing from 11% in conventional systems to 18% in restored ecosystems (+63.6%). In contrast, herbivorous pests declined sharply from 47% to 29% (−38.3%), while detritivores decreased moderately from 20% to 15% (−25.0%). These changes collectively reflect improved ecological regulation and enhanced biological control potential in restored habitats (Holland et al., 2016).

Species-level analysis further reinforced these trends, as shown in Table 3. Predator species such as *Pardosa pseudoannulata* (spider) and *Coccinella septempunctata* exhibited substantially higher abundances in restored ecosystems, reaching 18.4 and 12.7 individuals per trap, respectively, compared to 9.2 and 6.1 individuals per trap in conventional systems. Conversely, major herbivorous pests, including *Nilaparvata lugens* and *Cnaphalocrocis medinalis*, showed markedly reduced populations in restored fields, with abundances nearly halved relative to conventional ecosystems.

Table 2. Arthropod functional group composition

Functional Group	Restored Ecosystems	Conventional Ecosystems	Relative Change
Predators	38%	22%	+72.7%
Parasitoids	18%	11%	+63.6%
Herbivores (pests)	29%	47%	−38.3%
Detritivores	15%	20%	−25.0%

Table 3. Key arthropod species abundance

Species	Ecological Role	Restored (Ind./trap)	Conventional (Ind./trap)
Pardosa pseudoannulata (spider)	Predator	18.4	9.2
Coccinella septempunctata	Predator	12.7	6.1
Nilaparvata lugens	Herbivore	14.3	28.6
Cnaphalocrocis medinalis	Herbivore	11.5	22.9

3.3 Pollinator Diversity and Ecosystem Connectivity

Pollinator communities responded strongly and positively to restoration interventions, demonstrating a clear enhancement of ecosystem service potential in restored agroecosystems. Overall pollinator abundance reached 1420 individuals per sampling unit in restored ecosystems, compared to 910 individuals in conventional systems, indicating a substantial increase in pollinator availability under improved habitat conditions. Bees (*Apis* spp.) represented the dominant pollinator group, followed by butterflies and hoverflies, reflecting a diverse and functionally important assemblage.

As detailed in Table 4, all pollinator groups exhibited marked increases in restored ecosystems relative to conventional systems. Bees increased from 460 individuals in conventional fields to 720 individuals in restored habitats, corresponding to a 56.5% increase. Butterflies showed an even stronger response, rising from 190 to 310 individuals (+63.1%), while hoverflies increased from 140 to 220 individuals (+57.1%). Other minor pollinator groups also increased from 120 to 170 individuals (+41.7%). These consistent positive trends across all groups indicate that restoration practices broadly enhance pollinator abundance rather than benefiting only a single taxonomic group (Tonietto et al., 2018)

Table 4. Pollinator abundance and diversity

Pollinator Group	Restored	Conventional	Change (%)
Bees (Apis spp.)	720	460	+56.5%
Butterflies	310	190	+63.1%
Hoverflies	220	140	+57.1%
Others	170	120	+41.7%

3.4 Amphibian Diversity and Bioindicator Response

Amphibian communities showed a clear and strong sensitivity to ecosystem restoration, reflecting their role as reliable bioindicators of environmental quality. A total of 9 amphibian species were recorded in restored ecosystems, compared to only 5 species in conventional agricultural systems, indicating a substantial increase in species richness under restored conditions. In addition to higher diversity, population density was also markedly greater in restored fields, demonstrating improved habitat suitability and survival conditions.

As summarized in Table 5, all measured parameters consistently favored restored ecosystems. Species richness increased by 80%, highlighting enhanced habitat heterogeneity and improved ecological conditions. Mean amphibian density rose from 15.8 individuals per hectare in conventional systems to 32.5 individuals per hectare in restored systems, representing a more than twofold increase (+105%). Furthermore, the breeding activity index was categorized as high in restored ecosystems and low in conventional systems, indicating that restoration practices significantly improved reproductive success and habitat functionality. The observed enhancement in amphibian communities is strongly linked to reduced agrochemical pressure and improved habitat conditions in restored systems (Reeves et al., 2014). Amphibians are highly sensitive to pesticide exposure and environmental disturbance; therefore, their increased abundance indicates improved water quality, reduced toxic stress, and better microhabitat stability. In addition, amphibians contribute to ecosystem functioning through predation on insect larvae, which helps suppress pest populations and reinforces natural biological control mechanisms, ultimately contributing to greater ecosystem resilience and stability (Costa et al., 2023).

Table 5. Amphibian diversity and abundance

Parameter	Restored	Conventional	Difference
Species richness	9	5	+80%
Mean density (ind/ha)	32.5	15.8	+105%
Breeding activity index	High	Low	–

3.5 Avian Diversity and Feeding Guild Distribution

Bird communities demonstrated substantial improvement in restored ecosystems, reflecting enhanced habitat quality and strengthened ecological interactions. A total of 43 bird species were recorded in restored fields, compared to 28 species in conventional systems, indicating a marked increase in avian diversity following restoration interventions. Overall abundance also increased substantially, highlighting improved resource availability and habitat suitability in restored landscapes.

As summarized in Table 6, both species richness and total abundance were significantly higher in restored ecosystems. Species richness increased from 28 in conventional systems to 43 in restored systems, while total abundance rose from 340 individuals to 512 individuals, demonstrating a strong positive response to habitat restoration. Among ecological guilds, insectivorous birds and waterbirds showed the most pronounced increases, with both groups categorized as "high" in restored ecosystems compared to "moderate" or "low" in conventional systems (Vera et al., 2024). Granivorous birds also increased from low to moderate representation, suggesting improved food resource diversity (Zhang et al., 2021).

Table 6. Avian diversity and ecological guilds

Bird Category	Restored	Conventional
Species richness	43	28
Total abundance	512	340
Insectivores	High	Moderate
Waterbirds	High	Low
Granivores	Moderate	Low

3.6. Soil Microbial Biomass and Nutrient Cycling

Soil biological indicators showed a strong and consistent enhancement under restoration practices, indicating improved belowground ecosystem functioning. Key soil microbial parameters, including microbial biomass carbon, soil respiration, and microbial diversity indices, were all significantly higher in restored ecosystems compared to conventional systems. These results reflect a healthier and more active soil microbial community under restoration conditions.

As presented in Table 7, microbial biomass carbon increased from 450 mg/kg in conventional soils to 640 mg/kg in restored soils, representing a 42.2% increase. Similarly, soil respiration rose from 2.0 mg CO_2/kg/day to 3.1 mg CO_2/kg/day, indicating a 55.0% enhancement in microbial metabolic activity. Diversity indices also showed marked improvements, with fungal diversity increasing from 1.9 to 2.8 (+47.4%) and bacterial diversity rising from 2.3 to 3.2 (+39.1%). These consistent improvements across multiple indicators demonstrate a strong restoration-driven recovery of soil biological health.

The observed improvement in soil microbial activity is strongly associated with increased organic matter inputs and reduced agrochemical pressure in restored ecosystems. Enhanced microbial biomass and respiration indicate greater decomposition activity and nutrient turnover, while higher fungal and bacterial diversity suggests a more functionally resilient soil microbial community (Mocali et al., 2022). Collectively, these microorganisms play a fundamental role in nutrient cycling processes, including nitrogen mineralization and phosphorus mobilization, thereby improving long-term soil fertility, productivity, and overall ecosystem sustainability (Maron et al., 2018).

Table 7. Soil microbial and biochemical properties

Soil Parameter	Restored	Conventional	Change (%)
Microbial biomass C (mg/kg)	640	450	+42.2%
Soil respiration (mg CO_2/kg/day)	3.1	2.0	+55.0%
Fungal diversity index	2.8	1.9	+47.4%
Bacterial diversity index	3.2	2.3	+39.1%

3.7 Ecosystem Interactions and Food Web Complexity

Ecological network analysis demonstrated that restored ecosystems possessed significantly higher trophic connectivity and stronger interaction dynamics compared to conventional systems. Food web structure in restored habitats was notably more complex, reflecting enhanced ecological organization and improved stability of biotic interactions across trophic levels. This increased complexity indicates a more resilient ecosystem capable of maintaining functional balance under environmental fluctuations.

As summarized in Table 8, all key network metrics showed clear improvements in restored ecosystems. Network connectome was categorized as high in restored systems but low in conventional systems, indicating greater linkage among species and functional groups. The number of trophic interactions increased substantially from 92 in conventional systems to 145 in restored systems, highlighting intensified ecological coupling among plants, herbivores, predators, and decomposers. Similarly, the ecosystem stability index rose from 0.61 to 0.87, demonstrating a marked improvement in overall system resilience. Interaction strength also shifted from weak in conventional systems to strong in restored ecosystems, reflecting more robust and efficient energy transfer pathways. The observed increase in food web complexity suggests that restoration practices enhance ecosystem resilience by stabilizing energy flow and reducing susceptibility to pest outbreaks (Zanden et al., 2016). Stronger and more diverse biotic interactions among plants, herbivores, predators, and decomposers contribute to improved regulation of ecological processes. Overall, these findings highlight that restored ecosystems exhibit greater functional integration and long-term stability compared to conventional agricultural systems.

Table 8. Ecosystem interaction metrics

Metric	Restored	Conventional
Network connectance	High	Low
Trophic interactions	145	92
Stability index	0.87	0.61
Interaction strength	Strong	Weak

3.8. Landscape-Level Effects on Biodiversity

Landscape heterogeneity played a critical role in shaping biodiversity patterns. Fields located near wetlands, canals, and vegetated corridors exhibited significantly higher species richness across all taxa compared to isolated conventional fields. Fragmentation analysis indicated that conventional systems had higher edge density and lower connectivity, negatively affecting species movement and colonization. In contrast, restored systems benefited from improved ecological connectivity, which facilitated species dispersal and gene flow. Collectively, the results demonstrate that ecological restoration of paddy ecosystems in Pakistan significantly enhances biodiversity across multiple trophic levels, including plants, arthropods, birds, amphibians, and soil microorganisms. These improvements translate into stronger ecosystem functioning, enhanced biological pest control, and improved nutrient cycling. Restoration practices thus represent a viable strategy for achieving sustainable rice production while conserving biodiversity in intensively managed agricultural landscapes.

4. Conclusion

This study provides comprehensive evidence that ecological restoration practices substantially improve biodiversity and ecosystem functioning in paddy landscapes of Pakistan. Across all investigated trophic levels, including plants, arthropods, pollinators, amphibians, birds, and soil microorganisms, restored ecosystems consistently outperformed conventional rice systems in terms of species richness, abundance, and ecological stability. The marked increase in beneficial arthropods and natural enemies, along with reduced dominance of herbivorous pests, highlights the restoration of functional trophic balance and improved biological pest regulation. Enhanced pollinator diversity, increased amphibian populations, and higher bird abundance further indicate improved habitat quality and strengthened ecological connectivity within restored landscapes. Soil microbial activity and biomass also showed significant improvement, reflecting enhanced nutrient cycling and soil health. These belowground improvements are critical for long-term agricultural sustainability and productivity. Ecological network analysis revealed that restored systems exhibit more complex and stable food webs, characterized by stronger trophic interactions and higher ecosystem resilience. Additionally, landscape-level factors such as wetland connectivity, vegetated field margins, and reduced fragmentation were identified as key determinants of biodiversity recovery, emphasizing the importance of spatial planning in agroecosystem management. In conclusion, the integration of ecological restoration strategies into rice farming systems offers a viable pathway to reconcile agricultural production with biodiversity conservation in Pakistan. Adoption of such practices can enhance ecosystem services, reduce dependency on chemical inputs, and improve resilience to environmental change. These findings provide a strong scientific foundation for promoting biodiversity-friendly rice cultivation and support the development of sustainable agricultural policies at the national level.

Ethics approval and consent for publication: Not applicable
Consent for publication: Not applicable

Availability of data and materials: The datasets generated and/or analysed during the current study are not publicly available due to confidentiality and ongoing research use (as the data form part of continuing research work and institutional records), but are available from the corresponding author on reasonable request.

Competing interest: All the authors in the article have declared that there is no conflict of interest among them.

Funding: Not applicable

Author Contributions
Amina Bibi conceived and designed the study, conducted the experimental work, performed data collection and analysis, interpreted the results, prepared figures and tables, wrote the original manuscript draft, revised the manuscript critically for intellectual content, and approved the final version of the manuscript. The author has read and agreed to the published version of the manuscript.

Acknowledgments: This was supported by the Islamia University of Bahawalpur.

Funding: Not applicable.

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