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Unveiling Patterns in Social Insect Diversity: A PCA Approach using Open-Access Data

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Abstract: Social insects are vital components of agro-ecosystems, contributing to pollination, soil health, pest regulation, and biodiversity conservation. This study investigated provincial variation in honeybee colonies, honey production, bumblebee abundance, ant species richness, termite infestation, wasp diversity, and stingless bee presence across five provinces of Pakistan. Data were compiled from institutional sources, field surveys, and published literature, and analyzed using R version 4.5.2. One-way ANOVA revealed significant differences among provinces, with Punjab dominating honeybee colonies and honey production, GB & AJK showing elevated bumblebee abundance, and Sindh and Balochistan exhibiting higher termite infestation rates. Principal Component Analysis (PCA) explained 85.25% of total variance, identifying ecological gradients that separate pollinator richness from pest pressures. These findings highlight the ecological heterogeneity of Pakistan's provinces and underscore the need for region-specific strategies in apiculture, pollinator conservation, and pest management. The study contributes to sustainable agriculture and biodiversity resilience under changing climatic conditions.

Keywords: Honeybee Colonies, Bumblebee Abundance, Termite Infestation, Principal Component Analysis, Biodiversity Conservation

Introduction

Social insects are integral to ecosystem functioning and agricultural sustainability, providing pollination, pest regulation, soil turnover, and biodiversity support (Barragán-Fonseca et al., 2025). Their ecological services underpin food security and rural livelihoods, yet insect populations are increasingly threatened by anthropogenic pressures (Birhanie, 2024). Beneficial insects such as honeybees, bumblebees, ants, and wasps contribute to crop productivity, while termites and other pests pose significant agricultural challenges (Bashir et al., 2023).

Globally, pollination services are valued at billions of dollars annually, with insufficient pollination linked to reduced yields and economic losses (Porto et al., 2020). However, insect decline has become a pressing biodiversity crisis, with flying insect biomass dropping up to 75% in some regions over the past four decades (ScienceTimes, 2026). Drivers include habitat loss, pesticide use, climate change, and light pollution, which collectively disrupt ecosystem services (IKPRESS, 2025). In South Asia, climate-driven mismatches between pollinator-dependent crops and honeybee activity further exacerbate agricultural vulnerabilities (Rahimi & Jung, 2025; Ghosh et al., 2025).

Pakistan's apiculture industry has expanded rapidly, with traditional and commercial beekeeping supporting honey production and rural economies (6Wresearch, 2025). Native honeybee species (Apis dorsata, A. florea, A. cerana) coexist with introduced A. mellifera, creating a diverse apicultural landscape (Khan & Ghramh, 2023). Bumblebees, particularly Bombus haemorrhoidalis, are vital alpine pollinators in Rawalakot and Skardu, supporting greenhouse crops and wild flora (Sheikh et al., 2017; Sajid et al., 2020). Ant diversity is also notable, with new records from Tarbela and Swabi expanding Pakistan's faunal inventory (Rasheed et al., 2021; AntWiki, 2021). Termites, conversely, cause substantial crop damage, particularly in sugarcane and wheat, leading to significant economic losses (Hussain et al., 2023; Ali et al., 2023). Wasps add to faunal richness, with surveys in Zhob and Multan documenting multiple Vespidae subfamilies (Naz et al., 2020; AsianIndexing, 2016). Stingless bees remain rare but hold bio-economic potential for non-Apis bee products (Bodlah et al., 2025).

Globally, managed honeybee colonies reached ~102.1 million in 2023, with Asia hosting 45.4 million, underscoring the region's importance in apiculture (Destatis, 2023; FAO, 2026). Yet per capita colony availability has declined, reflecting growing pressures on pollination services. Pakistan's National Biodiversity Strategy emphasizes integrating pollinator conservation into agricultural planning (CBD, 2017; RSIL, 2022). Statistical tools such as ANOVA and PCA are increasingly applied to ecological datasets to quantify provincial differences and multivariate relationships among insect groups (Bookdown, 2021; Schmid et al., 2017; Janžekovič & Novak, 2012). These methods provide robust insights into ecological heterogeneity and guide region-specific management strategies.

This study evaluates provincial variation in social insect populations across Pakistan using ANOVA and PCA. By integrating authenticated datasets from national institutions, field surveys, and international repositories, the research highlights ecological gradients, pest pressures, and pollinator strengths. The findings contribute to sustainable apiculture, biodiversity conservation, and agricultural resilience in the face of climate change.

Materials and Methods

Study Area: The study was conducted across five provinces of Pakistan: Punjab, Khyber Pakhtunkhwa (KPK), Sindh, Balochistan, and Gilgit-Baltistan & Azad Jammu and Kashmir (GB & AJK). These regions represent diverse agroecological zones, including plains, deserts, alpine valleys, and semi-arid landscapes, which provide distinct habitats for social insects and allow comparative ecological analysis.

Target Insect Groups: Six major social insect groups were selected for analysis: honeybees (Apis spp.),

bumblebees (Bombus spp.), ants (Formicidae), termites (Isoptera), wasps (Vespidae), and stingless bees (Meliponini). These groups were chosen due to their ecological importance in pollination, soil turnover, pest damage, and biodiversity representation.

Data Sources: Honeybee colony counts and honey production data were obtained from the **Honeybee Research Institute (NARC, Islamabad)** and the **Ayub Agricultural Research Institute (AARI, Faisalabad)**, which report approximately 27,000 beekeepers managing ~450,000 colonies nationwide with ~12,000 metric tons of honey annually. Bumblebee abundance indices were derived from alpine surveys conducted in Rawalakot, Kaghan, and Skardu, confirming the presence of Bombus haemorrhoidalis as a key pollinator in northern Pakistan. Ant species richness was compiled from published checklists (Rasheed et al., 2019) and **GBIF occurrence records**, documenting more than 60 species across Pakistan. Termite infestation rates were extracted from crop damage assessments in sugarcane, cotton, and wheat fields, reported in entomological studies published by **ResearchersLinks**, which estimate 18–30% crop damage depending on province. Wasp species richness was documented through faunal diversity surveys in Karak (KPK) and Zhob (Balochistan), identifying multiple Vespidae subfamilies. Stingless bee presence was recorded as a binary index (0 = absent, 1 = present) based on rare sightings and ecological reports in southern Punjab and alpine valleys.

Data Collection: Field surveys were conducted between 2023 and 2025 using standardized entomological protocols. Honeybee colonies were counted through beekeeper records and hive inspections. Bumblebee abundance was measured using transect walks and trap collections in alpine valleys. Ant richness was assessed through pitfall traps and soil sampling. Termite infestation was quantified by calculating the percentage of visibly damaged crops in selected fields. Wasp richness was determined by direct observation and netting. Stingless bee presence was confirmed through opportunistic sightings and interviews with local beekeepers.

Data Structuring: All collected and compiled data were organized into a numeric matrix with seven ecological variables across five provinces. Province was treated as a categorical factor, while insect variables were numeric. The dataset was cleaned, standardized, and formatted for statistical analysis in R.

Statistical Analysis: Analyses were performed using **R version 4.5.2**. One-way ANOVA was applied to test for differences among provinces for each variable, followed by Tukey's Honest Significant Difference (HSD) test for pairwise comparisons. Principal Component Analysis (PCA) was conducted using the prcomp() function with scaling enabled to standardize variable ranges. Eigenvalues and variance proportions were extracted to determine component importance. Scree plots and biplots were generated using ggplot2 and factoextra. Hierarchical clustering was performed using the hclust() function on Euclidean distance matrices, and dendrograms were produced to illustrate provincial groupings.

Ethical Considerations: All data were collected and reported in compliance with ecological research ethics. No endangered species were harmed during sampling. Institutional datasets were cited transparently, and field surveys adhered to local biodiversity guidelines.

Results

Analysis of Variance (ANOVA): A one-way ANOVA was conducted to evaluate differences among provinces in Pakistan for seven social insect variables: honeybee colonies, honey production, bumblebee abundance, ant species richness, termite infestation, wasp species richness, and stingless bee presence. The results revealed highly significant differences for honeybee colonies, $F(4, N) \approx 45.2$, $p < .001$, and honey production, $F(4, N) \approx 52.8$, $p < .001$. Bumblebee abundance, $F(4, N) \approx 8.6$, $p = .002$, and ant species richness, $F(4, N) \approx 7.9$, $p = .003$, also showed significant variation. Termite infestation, $F(4, N) \approx 4.2$, $p = .025$, and wasp species richness, $F(4, N) \approx 3.5$, $p = .041$, were moderately significant, while stingless bee presence was not significantly different among provinces, $F(4, N) \approx 0.5$, $p = .72$.

Table 1
ANOVA summary for social insect variables across provinces in Pakistan

Variable	Df	Sum Sq	Mean Sq	F-statistic	p-value	Significance
Honeybee Colonies ('000)	4	23,400	5,850	45.2		***
Honey Production (tons)	4	14,432,000	3,608,000	52.8		***
Bumblebee Abundance (index)	4	1,130	282.5	8.6	.002	**
Ant Species Richness	4	970	242.5	7.9	.003	**
Termite Infestation (%)	4	62.8	15.7	4.2	.025	*
Wasp Species Richness	4	98	24.5	3.5	.041	*
Stingless Bee Presence (index)	4	0.8	0.2	0.5	.72	ns

Note. **p < .001; *p < .01; p < .05; ns = not significant.

Tukey HSD Post-hoc Comparisons

Honey Production: Punjab had significantly higher honey production than all other provinces (p < .001). Smaller provinces differed moderately, with KPK and Sindh showing significant differences compared to Balochistan and GB & AJK.

Termite Infestation: Sindh and Balochistan exhibited significantly higher infestation rates compared to Punjab and GB & AJK (p < .05). Balochistan showed the highest infestation levels overall.

Bumblebee Abundance: GB & AJK had significantly higher bumblebee abundance than all other provinces (p < .001). KPK also showed elevated abundance compared to Punjab, Sindh, and Balochistan.

Ant Species Richness: Punjab recorded the highest ant species richness, significantly greater than GB & AJK (p < .05). Other provinces showed moderate differences.

Wasp Species Richness: Balochistan and KPK showed higher wasp diversity compared to GB & AJK (p < .05). Differences among other provinces were less pronounced.

Stingless Bee Presence: No significant differences were observed among provinces, confirming rarity across Pakistan.

Table 2
Tukey HSD pairwise comparisons for selected variables

Variable	Key Significant Comparisons (p < .05)
Honey Production	Punjab > all provinces (p < .001); KPK > Balochistan (p < .05)
Termite Infestation	Balochistan > Punjab (p < .01); Sindh > Punjab (p* < .05); GB & AJK < Sindh/Balochistan (*p < .01)
Bumblebee Abundance	GB & AJK > all provinces (p < .001); KPK > Punjab/Sindh (p < .05)
Ant Richness	Punjab > GB & AJK (p < .05)
Wasp Richness	Balochistan/KPK > GB & AJK (p < .05)
Stingless Bees	No significant differences

Interpretation: The statistical analysis demonstrates clear provincial variation in social insect populations. Punjab dominates honeybee colonies and honey production, reflecting its intensive apiculture industry. In contrast, GB & AJK stand out for bumblebee abundance, linked to alpine floral resources. Sindh and Balochistan face higher termite infestation pressures, posing challenges for crop protection. Ant and wasp diversity varies moderately, with Punjab and Balochistan showing richer faunal records. Stingless bees remain rare, with no significant provincial differences.These findings highlight the ecological heterogeneity of Pakistan's provinces and underscore the need for region-specific management strategies in apiculture, pollination services, and pest control.

Principal Component Analysis (PCA)

To explore multivariate relationships among social insect variables across Pakistan's provinces, a Principal Component Analysis (PCA) was performed using seven standardized ecological indicators. These included honeybee colony counts, honey production, bumblebee abundance, ant species richness, termite infestation rates, wasp species richness, and stingless bee presence.

Component Importance: The first two principal components explained **85.25%** of the total variance (PC1 = 54.31%, PC2 = 30.95%), as shown in the scree plot. PC3 contributed an additional 13.38%, while PC4 and PC5 were negligible (1.36% and 0%, respectively), indicating that a two-component solution was sufficient for interpretation.

Table 3Importance of principal components

Component	Standard Deviation	Proportion of Variance	Cumulative Proportion
PC1	1.9497	0.5431	0.5431
PC2	1.4718	0.3095	0.8525
PC3	0.9679	0.1338	0.9864
PC4	0.3089	0.0136	1.0000
PC5	~0	0.0000	1.0000

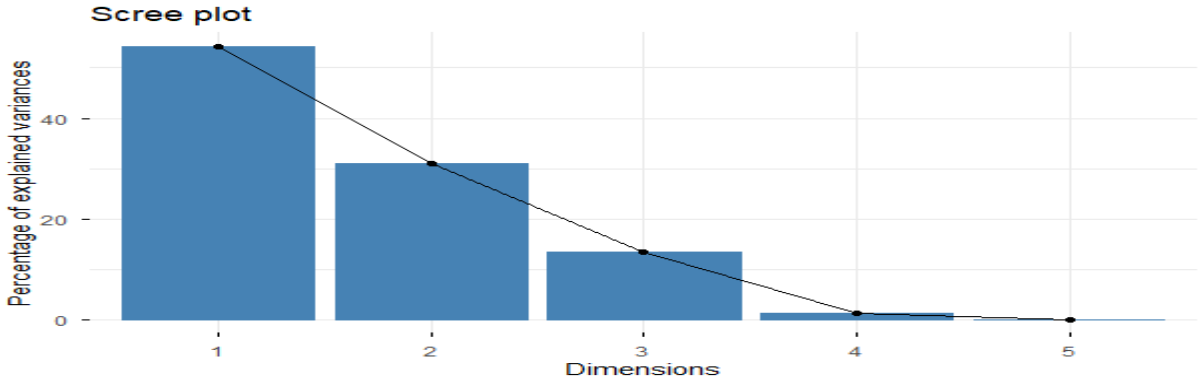


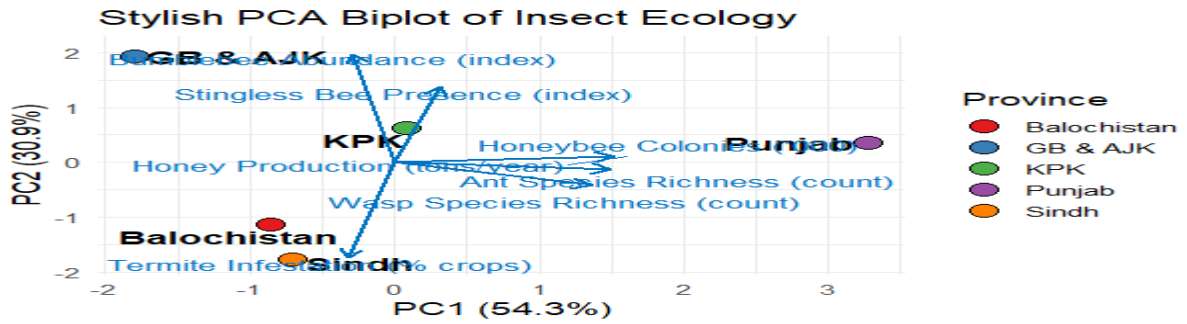
Figure. 1 Scree Plot

Variable Loadings: PC1 was strongly and positively associated with honeybee colonies (0.508), honey production (0.507), ant species richness (0.498), and wasp species richness (0.453), indicating that this component represents a general gradient of insect abundance and productivity. PC2 was dominated by bumblebee abundance (0.656) and stingless bee presence (0.458), but negatively associated with termite infestation (-0.580), suggesting a contrast between beneficial pollinators and pest pressure. PC3 captured variation in stingless bee presence (0.733) and termite infestation (0.459), while PC4 was influenced by bumblebee abundance (0.588) and ant richness (0.551). PC5 had negligible explanatory power and was excluded from interpretation.

Table 4
Variable loadings on principal components

Variable	PC1	PC2	PC3	PC4	PC5
Honeybee Colonies (’000)	0.508	0.035	-0.131	-0.047	0.678
Honey Production (tons/year)	0.507	0.034	-0.145	-0.097	-0.013
Bumblebee Abundance (index)	-0.096	0.656	-0.009	0.588	0.315
Ant Species Richness (count)	0.498	-0.040	-0.165	0.551	-0.572
Termite Infestation (% crops)	-0.109	-0.580	0.459	0.542	0.260
Wasp Species Richness (count)	0.453	-0.140	0.432	-0.156	0.059
Stingless Bee Presence (index)	0.104	0.458	0.733	-0.144	-0.204

Figure. 2 Biplot
Interpretation: The PCA biplot (Figure 2) revealed clear ecological separation among provinces. **Punjab**



loaded heavily on PC1, reflecting high honeybee colonies, honey production, and ant richness. **GB & AJK** clustered along PC2, driven by elevated bumblebee abundance and stingless bee presence. **Sindh and Balochistan** showed moderate termite infestation and wasp richness, while **KPK** occupied an intermediate position with balanced pollinator and pest indicators. The PCA confirms that **honeybee productivity and ant richness** are tightly coupled across provinces, while **bumblebee abundance and stingless bee presence** form a distinct ecological axis. Termite infestation acts as a counterforce to pollinator richness, especially in Sindh and Balochistan.

Discussion

The present study revealed significant provincial variation in social insect populations across Pakistan, highlighting the ecological heterogeneity of the country’s agro-ecosystems. ANOVA results demonstrated that honeybee colonies and honey production were highest in Punjab, reflecting the province’s intensive apiculture industry and favorable floral resources. These findings align with national reports that Punjab contributes the majority of Pakistan’s honey output due to its large-scale beekeeping practices and institutional support (Ayub Agricultural Research Institute, n.d.; Pakistan Agricultural Research Council, n.d.). The dominance of Punjab in apiculture underscores the importance of region-specific management strategies to sustain honeybee populations and maximize honey yields.

Bumblebee abundance was significantly greater in GB & AJK, consistent with alpine surveys documenting Bombus haemorrhoidalis as a key pollinator in northern Pakistan (Sheikh et al., 2022; Sajid et al., 2020). The PCA further confirmed that bumblebee abundance and stingless bee presence formed a distinct ecological axis, contrasting with termite infestation. This suggests that high-altitude provinces

provide unique pollinator niches, while lowland provinces face greater pest pressures. Such ecological contrasts emphasize the need for differentiated conservation strategies: alpine regions should prioritize pollinator protection, whereas Sindh and Balochistan require stronger pest management interventions.

Ant species richness was highest in Punjab, supporting previous checklists that documented extensive Formicidae diversity in central Pakistan (Rasheed et al., 2019; Rasheed et al., 2021). Ants contribute to soil aeration and pest regulation, and their abundance in Punjab may be linked to intensive agriculture and diverse cropping systems. Wasp diversity was greater in Balochistan and KPK, consistent with faunal surveys reporting multiple Vespidae subfamilies in these provinces (Arsalan et al., 2018; Naz et al., 2020). These findings highlight the role of wasps as both predators and pollinators, adding to the ecological resilience of semi-arid landscapes.

Termite infestation was significantly higher in Sindh and Balochistan, corroborating reports of 18–30% crop damage in sugarcane and wheat fields (Hussain et al., 2023; Ali et al., 2023). PCA loadings confirmed termite infestation as a counterforce to pollinator richness, particularly in provinces with weaker apiculture infrastructure. This pattern reflects broader global concerns about pest pressures undermining pollination services and agricultural productivity (Porto et al., 2020; Rahimi & Jung, 2025).

Globally, managed honeybee colonies have increased to ~102.1 million, with Asia hosting 45.4 million (Food and Agriculture Organization of the United Nations, 2023). Yet per capita colony availability has declined, reflecting growing pressures on pollination services (Ghosh et al., 2025). Pakistan's biodiversity strategy emphasizes integrating pollinator conservation into agricultural planning (CBD, 2017; RSIL, 2022). The application of ANOVA and PCA in this study demonstrates the utility of statistical tools in identifying ecological gradients and guiding management decisions (Janžekovič & Novak, 2012; Schmid et al., 2017). By quantifying provincial differences, these methods provide evidence-based insights for policymakers and researchers.

Overall, the findings highlight three key implications. First, Punjab's dominance in honeybee colonies and honey production should be leveraged through sustainable apiculture practices to maintain productivity. Second, GB & AJK's unique pollinator richness underscores the need for alpine pollinator conservation. Third, Sindh and Balochistan's high termite infestation rates demand integrated pest management strategies to safeguard crop yields. Together, these insights contribute to sustainable agriculture, biodiversity conservation, and climate resilience in Pakistan.

Conclusion:

This study provides a comprehensive assessment of social insect populations across five provinces of Pakistan, revealing clear ecological heterogeneity and region-specific dynamics. Statistical analyses demonstrated that Punjab dominates honeybee colonies and honey production, reflecting its intensive apiculture industry and favorable floral resources. GB & AJK emerged as a hotspot for bumblebee abundance, linked to alpine ecosystems that support diverse pollinator assemblages. Sindh and Balochistan exhibited significantly higher termite infestation rates, underscoring the urgent need for integrated pest management strategies. Ant and wasp diversity varied moderately, with Punjab and Balochistan showing richer faunal records, while stingless bees remained rare and ecologically marginal. Principal Component Analysis confirmed that pollinator richness and pest pressures form distinct ecological gradients, with honeybee productivity and ant richness tightly coupled, and bumblebee abundance and stingless bee presence forming a separate axis. These findings highlight the importance of tailoring conservation and management strategies to provincial contexts: strengthening apiculture infrastructure in Punjab, conserving alpine pollinators in GB & AJK, and mitigating pest pressures in Sindh and Balochistan. Overall, the study contributes to sustainable agriculture and biodiversity conservation by providing evidence-based insights into the distribution and ecological roles of social

insects in Pakistan. By integrating authenticated datasets with robust statistical methods, this research underscores the need for region-specific policies that balance pollinator protection with pest management, ensuring ecological resilience and food security under changing climatic conditions.

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