

CLIMATE-INDUCED SHIFT IN POLLINATOR DIVERSITY AND ITS IMPACT ON CROP YIELD STABILITY IN AGRO-ECOLOGICAL ZONES OF PAKISTAN

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DOI: <https://doi.org/10.5281/zenodo.22723658>

Keywords

Climate variability; Pollinator diversity; Crop yield stability; Agro-ecological zones; Ecological resilience; Pakistan

Article History

Received: 07 January 2026

Accepted: 17 March 2026

Published: 31 March 2026

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Abstract

Climate variability poses an increasing threat to agricultural productivity by altering pollinator communities and disrupting ecosystem services essential for crop production. This study examined the effects of climate-induced changes in pollinator diversity on crop yield stability across contrasting agro-ecological zones of Pakistan. A quantitative, multi-zone research design was proposed using farm-level observations, climatic indicators, pollinator diversity measures, and crop-yield data. The analysis incorporated descriptive statistics, correlation analysis, multiple regression, mediation analysis, and agro-ecological zone comparisons. The findings indicated that temperature variability, precipitation variability, and extreme climatic events were negatively associated with pollinator diversity, whereas pollinator diversity and abundance were positively associated with crop yield stability. Pollinator diversity further demonstrated a significant mediating role in the relationship between climatic variability and yield stability, suggesting that climatic stress may influence agricultural performance through ecological changes in pollinator communities. The effects varied across agro-ecological zones, with stronger climate-pollinator relationships observed in comparatively vulnerable environments. The study theoretically extends ecological resilience theory by positioning pollinator diversity as an ecological mechanism supporting agricultural stability under climatic disturbance. The findings highlight the importance of integrating pollinator conservation, landscape diversification, and agro-ecological adaptation into Pakistan's climate-smart agriculture and food-security strategies.

1. INTRODUCTION

Pollination is a fundamental ecological process that links biodiversity with agricultural production, food security, and ecosystem functioning. A substantial proportion of globally important crops benefit from animal-mediated pollination, particularly by bees, flies, butterflies, moths, and other insects. Consequently, changes

in pollinator abundance, species composition, and functional diversity can have direct implications for crop reproductive success and agricultural productivity. Recent global evidence demonstrates that insufficient pollinator visitation is not merely an ecological concern but can constitute a measurable constraint on crop production. Turo et al. (2024), using 198,360

plant-pollinator interactions and 2,083 yield measurements across 32 crops and 120 study systems, found evidence of pollinator limitation in approximately 28%–61% of crop systems. Similarly, Vezzani et al. (2025) reported positive relationships between pollinator abundance and yield for 21 of 24 crop species examined, demonstrating that variation in pollinator populations can have meaningful consequences for agricultural production.

The ecological importance of pollinator diversity extends beyond pollinator abundance alone. Different pollinator species may differ in body size, foraging behavior, floral preferences, activity periods, thermal tolerance, and responses to environmental stress. Consequently, a diverse pollinator community can provide complementary and partially redundant pollination services, potentially enhancing the resilience of crop reproduction to environmental disturbances. A recent global meta-analysis by Artamendi et al. (2025) demonstrated that reductions in pollinator species diversity consistently decrease plant reproductive success, including seed set, fruit set, and fruit weight. These findings indicate that biodiversity loss may compromise ecosystem functioning even when total pollinator abundance is not completely eliminated.

Climate change represents an increasingly important driver of such ecological disruption. Rising temperatures, altered precipitation patterns, droughts, heat extremes, and shifts in seasonal climatic conditions can modify pollinator survival, abundance, distribution, phenology, and foraging behavior. Climate-induced changes may also alter the temporal synchronization between crop flowering and pollinator activity, potentially reducing effective pollination during critical reproductive periods. The vulnerability of pollinators to climatic changes is particularly relevant for species with narrow environmental tolerances or restricted geographical distributions. Recent modelling research on *Apis dorsata* in Pakistan indicates that climate change could substantially reduce suitable habitat for this important pollinator, with particularly pronounced losses projected in

northern high-altitude areas under severe future climate scenarios (Khan et al., 2025).

The climate-pollinator relationship is especially significant in developing agricultural economies where crop production is strongly dependent on ecological conditions and where farmers may have limited capacity to compensate for environmental disruptions through technological inputs. Pakistan represents an important case because its agricultural landscapes encompass substantial climatic, topographic, and ecological heterogeneity. The country's agricultural systems range from irrigated plains and rainfed areas to mountainous, semi-arid, and arid environments. Such heterogeneity creates considerable spatial variation in temperature, precipitation, water availability, vegetation, land-use intensity, and pollinator habitats. Consequently, the effects of climate change on pollinator communities and agricultural productivity are unlikely to be uniform across the country.

Evidence from Pakistan already demonstrates the agricultural consequences associated with declining pollinator populations. Khan et al. (2022), in a 13-year study of loquat orchards in the Pothwar region, documented an 89.9% decline in overall flower-visiting insect abundance between 2006 and 2018. During the same period, average yield per loquat tree declined by approximately 61%, while pollinator abundance emerged as a strong predictor of crop yield and fruit quality. This evidence provides an important empirical basis for investigating whether changes in pollinator communities can contribute to agricultural instability in Pakistan.

More recent evidence from southern Punjab further demonstrates that pollinator communities are strongly influenced by agricultural management and landscape structure. Ahmad et al. (2025), examining 42 commercial mango orchards, found greater pollinator species richness and abundance in landscapes containing semi-natural habitats and in orchards characterized by less pollinator-unfriendly management practices. These conditions were also associated with higher fruit set. Such findings suggest that pollinator diversity is shaped by interacting environmental and

anthropogenic pressures rather than by climate alone.

The potential interaction between climate change and pollinator diversity is therefore critical for understanding agricultural resilience. Climate variability can affect pollinator populations directly through thermal and hydrological stress and indirectly through changes in floral resources, habitat quality, and agricultural management. At the same time, reduced pollinator diversity may increase the vulnerability of pollinator-dependent crops to climatic disturbances by weakening ecological redundancy and reducing the reliability of pollination services. Thus, crop yield instability may arise not only from the direct physiological effects of climate change on crops but also from climate-mediated deterioration of ecological services.

Despite increasing international research on climate change, biodiversity loss, and pollination, important gaps remain in the Pakistani context. Existing Pakistani research has largely focused either on the direct effects of climate variability on agricultural production or on pollinator abundance and management within particular crops or locations. There is comparatively limited integrated evidence examining how climate-induced changes in pollinator diversity translate into crop-yield stability across contrasting agro-ecological zones. This is an important distinction because yield stability concerns the consistency and resilience of agricultural production over time rather than simply the level of production in a particular season.

The present study therefore proposes an integrated climate-biodiversity-agriculture framework in which climatic variability influences pollinator diversity, while changes in pollinator diversity subsequently affect crop yield stability. The study further recognizes agro-ecological zones as an important contextual dimension because the magnitude of these relationships may differ according to climatic exposure, habitat availability, agricultural intensification, irrigation conditions, and crop composition. By examining these relationships simultaneously, the study seeks to extend existing research beyond a simple climate-crop productivity relationship and

provide a more comprehensive explanation of the ecological mechanisms underlying agricultural resilience in Pakistan.

2. Problem Statement

Climate change is increasingly challenging the stability and sustainability of agricultural production in Pakistan through rising temperatures, irregular precipitation, drought, heat extremes, and other forms of climatic variability. Much of the existing agricultural research has concentrated on the direct effects of these climatic changes on crop productivity, water availability, soil conditions, and farm-level adaptation. Although these dimensions are important, they provide an incomplete explanation of agricultural vulnerability because crop production is embedded within ecological systems that provide essential ecosystem services. Pollination represents one of the most important of these services. Changes in climatic conditions can alter pollinator abundance, species richness, distribution, phenology, and foraging activity, potentially reducing the reliability of pollination during crop flowering periods. The consequences may be particularly important for pollinator-dependent crops because reduced pollination can affect fruit set, seed production, fruit quality, and ultimately agricultural yields. Global evidence increasingly confirms that pollinator limitation can constrain crop production, while reductions in pollinator diversity can negatively affect plant reproductive success (Artamendi et al., 2025; Turo et al., 2024).

Pakistan presents a particularly important research context because its agricultural systems occur across highly diverse agro-ecological conditions. Climatic exposure, irrigation availability, land-use intensity, vegetation cover, habitat fragmentation, and farming practices vary substantially across regions. These differences may influence both the vulnerability of pollinators to climate change and the extent to which crops depend upon pollination services. Accordingly, the consequences of climate-induced pollinator changes are unlikely to be spatially homogeneous.

Existing empirical evidence from Pakistan provides clear indications that pollinator decline can be associated with agricultural consequences. The long-term Pothwar study by Khan et al. (2022) documented substantial reductions in flower-visiting insects alongside declining loquat yields. Similarly, Ahmad et al. (2025) demonstrated that landscape structure and agricultural management influence pollinator diversity and fruit set in mango orchards in southern Punjab. Research on *Apis dorsata* further indicates that projected climate change could substantially reduce suitable habitat for an important pollinator species in Pakistan (Khan et al., 2025).

However, these studies do not fully resolve the broader climate-pollinator-agriculture relationship. In particular, there remains insufficient cross-zone evidence regarding whether climatic variability systematically alters pollinator diversity and whether such changes subsequently influence the **stability**, rather than merely the level, of crop yields. The distinction is important because a farming system may maintain relatively high average productivity while simultaneously experiencing increasing year-to-year fluctuations. Such instability can create substantial economic and food-security risks for farmers and consumers.

Another important gap concerns the limited integration of ecological and agricultural indicators. Climate variables are frequently examined independently of biodiversity indicators, while pollinator research often focuses on species abundance, richness, or conservation without directly connecting these measures to long-term agricultural stability. Consequently, the potential mediating role of pollinator diversity between climatic variability and crop-yield stability remains insufficiently investigated, particularly across Pakistan's heterogeneous agro-ecological zones.

This gap has both scientific and policy implications. Without understanding the ecological pathway connecting climate variability with agricultural outcomes, climate-adaptation policies may overemphasize irrigation, improved crop varieties, fertilizers, and other technological

interventions while underestimating the contribution of biodiversity and ecosystem services. A comprehensive assessment of the climate-pollinator-yield relationship can therefore provide a more integrated basis for designing climate-resilient agricultural strategies. Accordingly, the present study addresses this research gap by investigating whether climate-induced variability affects pollinator diversity and whether changes in pollinator diversity subsequently influence crop yield stability across selected agro-ecological zones of Pakistan. It further examines whether these relationships differ according to agro-ecological context, thereby providing a geographically differentiated understanding of ecological resilience within Pakistan's agricultural sector.

3. Research Questions

RQ1: How does climatic variability affect pollinator diversity across different agro-ecological zones of Pakistan?

RQ2: What is the relationship between pollinator diversity and crop yield stability in Pakistan?

RQ3: To what extent do temperature variability, precipitation variability, and extreme climatic events influence pollinator diversity?

RQ4: Does pollinator diversity mediate the relationship between climatic variability and crop yield stability?

RQ5: Do the relationships among climatic variability, pollinator diversity, and crop yield stability differ across Pakistan's agro-ecological zones?

RQ6: Which dimensions of pollinator diversity most strongly explain variations in crop yield stability?

4. Research Objectives

The study aims to:

1. Examine the effect of climatic variability on pollinator diversity across selected agro-ecological zones of Pakistan.
2. Assess the effects of temperature variability, precipitation variability, and extreme climatic events on pollinator diversity.

3. Determine the relationship between pollinator diversity and crop yield stability.
4. Evaluate the mediating role of pollinator diversity in the relationship between climatic variability and crop yield stability.
5. Compare the climate–pollinator–yield relationships across contrasting agro-ecological zones of Pakistan.
6. Identify the dimensions of pollinator diversity that most strongly contribute to crop yield stability.
7. Develop evidence-based recommendations for integrating pollinator conservation into climate-resilient agricultural policies and practices in Pakistan.

5. Significance of the Study

5.1 Theoretical Significance

The study contributes to ecological and agricultural theory by integrating climate variability, biodiversity, ecosystem services, and agricultural resilience within a single analytical framework. Existing climate–agriculture models frequently emphasize the direct effects of temperature and precipitation on crop production. By introducing pollinator diversity as a potential ecological mediator, the study expands this perspective and proposes that climate change may influence agricultural stability through both direct and indirect pathways.

The study also contributes to ecological resilience theory by examining whether greater pollinator diversity can enhance the stability of crop production under climatic stress. Recent evidence that declining pollinator diversity reduces reproductive success supports the theoretical proposition that biodiversity contributes to ecosystem functioning and resilience (Artamendi et al., 2025).

5.2 Empirical Significance

Empirically, the study addresses an important geographical gap by focusing on Pakistan, where long-term evidence concerning pollinator populations and crop production remains comparatively limited. Existing evidence from Pothwar and southern Punjab demonstrates the

relevance of pollinators to crop production, but a broader agro-ecological comparison remains necessary (Ahmad et al., 2025; Khan et al., 2022). By integrating climatic indicators, pollinator diversity measures, and crop-yield stability indicators, the study can provide a more comprehensive assessment of how ecological changes translate into agricultural outcomes.

5.3 Practical Significance

The findings can assist farmers, agricultural extension services, and land managers in identifying practices that protect pollination services under changing climatic conditions. Potential applications include conservation of semi-natural habitats, reduction of pollinator-unfriendly pesticide practices, maintenance of flowering resources, diversification of agricultural landscapes, and protection of nesting and foraging habitats.

Such measures are particularly relevant because recent Pakistani evidence indicates that landscape composition and farm-management practices significantly influence pollinator richness, abundance, diversity, and fruit set (Ahmad et al., 2025).

5.4 Policy Significance

The study can support policymakers in integrating pollinator conservation into climate-smart and climate-resilient agriculture policies. Rather than treating biodiversity conservation and agricultural productivity as separate policy objectives, the study provides a basis for considering pollination services as an integral component of agricultural resilience.

The findings may be particularly useful for provincial agriculture departments, environmental agencies, biodiversity authorities, agricultural universities, and climate-policy institutions in designing agro-ecological-zone-specific conservation strategies.

5.5 Food-Security Significance

Crop yield stability is fundamental to long-term food security. Global evidence demonstrates that inadequate pollination can contribute to yield limitations, while greater pollinator abundance is

positively associated with yields across numerous crops (Turo et al., 2024; Vezzani et al., 2025). Therefore, protecting pollinator diversity may represent an additional pathway for reducing agricultural vulnerability under climate change. For Pakistan, where agricultural production is exposed to substantial climatic variability, strengthening pollination services could complement conventional adaptation measures and contribute to more stable agricultural production.

5.6 Institutional and Research Significance

The study can provide a foundation for establishing long-term pollinator monitoring and climate-agriculture databases in Pakistan. It can also encourage interdisciplinary collaboration among entomologists, ecologists, climatologists, agricultural economists, agronomists, and environmental scientists.

Literature Review

The relationship between climate change, pollinator diversity, and agricultural productivity has emerged as an increasingly important area of interdisciplinary research. Recent literature indicates that climate change should not be understood only as a direct threat to crop physiology; it can also affect agricultural production indirectly through changes in pollinator communities and the ecosystem services they provide. This distinction is particularly important for Pakistan, where agricultural production occurs across substantially different climatic and agro-ecological environments.

1. Climate Change and Pollinator Diversity

Climate change can influence pollinators through multiple ecological mechanisms, including temperature stress, altered precipitation, drought, changes in floral-resource availability, habitat modification, and disruption of seasonal activity. A recent systematic global synthesis by Cheng et al. (2025) found that climate change substantially affects plant and pollinator traits, with pollinator fecundity, body size, life-history characteristics, developmental

processes, and physiological performance generally declining under warming conditions. However, responses in abundance and resource-acquisition behavior were more heterogeneous, indicating that climate effects are species- and ecosystem-specific.

An important implication of this literature is that climate change does not necessarily produce a uniform decline in all pollinators. Instead, species with different thermal tolerances and ecological niches may respond differently. Such differential responses can modify community composition and functional diversity even where total pollinator abundance remains relatively stable. This distinction is highly relevant to the present study because pollinator diversity, rather than abundance alone, is proposed as the principal ecological mechanism linking climate variability with crop yield stability.

Recent research on Pakistan provides particularly relevant evidence. Khan et al. (2025) modelled the current and future distribution of *Apis dorsata* in Pakistan and reported substantial potential losses of suitable habitat under future climate scenarios, particularly in northern high-altitude areas. The study demonstrates that climate change can alter the geographical distribution of important pollinator species and potentially reduce the availability of pollination services in climatically vulnerable regions.

However, the evidence also indicates that climate effects must be interpreted alongside other environmental pressures. Agricultural intensification, habitat fragmentation, pesticide exposure, monoculture, and landscape simplification may interact with climatic stress and amplify pollinator vulnerability. Thus, examining climate variables in isolation may underestimate the actual ecological pressures affecting pollinator communities.

2. Pollinator Diversity and Crop Productivity

A substantial body of recent research establishes a positive relationship between pollinator communities and agricultural production. Reilly et al. (2024) conducted a global analysis based on 93 crop-pollination studies across six continents and found that both wild insects and honey bees

contribute substantially to crop yields. Importantly, pollinator species diversity remained positively associated with crop yields even after accounting for total visitation rates. This finding provides strong support for considering diversity as an independent ecological dimension rather than merely a proxy for abundance.

Similarly, **Turo et al. (2024)** analyzed 198,360 plant-pollinator interactions and 2,083 yield measurements covering 32 crops and 120 agricultural systems. Their findings showed that approximately 28%–61% of crop systems exhibited some degree of pollinator limitation. Particularly important was the finding that increasing pollinator visitation to levels already observed in relatively high-performing farms could substantially reduce yield gaps in pollinator-limited systems.

More recent evidence reinforces this relationship. **Vezzani et al. (2025)** examined 24 crops using global yield and pollinator-abundance data and found positive relationships between pollinator abundance and crop yield for 21 crops. However, the magnitude of these relationships varied according to management systems and climate zones. This finding is highly relevant to the present research because it demonstrates that pollination benefits are **context dependent** and cannot be assumed to be identical across geographical environments.

The literature therefore suggests three important conclusions. First, pollinators contribute directly to crop production. Second, species diversity can contribute beyond simple visitation frequency. Third, climatic and agricultural contexts modify the strength of pollinator-yield relationships. These conclusions provide a strong basis for examining such relationships across Pakistan's contrasting agro-ecological zones.

3. Pollinator Diversity and Yield Stability

While much of the literature examines crop yield levels, a comparatively more recent research direction focuses on yield stability. Yield stability is conceptually different from average productivity because a system may produce high average yields while remaining highly vulnerable to environmental shocks.

Pollinator diversity may enhance yield stability through functional complementarity, response diversity, and ecological redundancy. Different pollinator species may respond differently to temperature, rainfall, drought, and other environmental disturbances. If one species declines under particular conditions, another species with different ecological characteristics may partially maintain pollination services.

This mechanism is consistent with recent research by **Genung and Winfree (2025)**, which demonstrated that dominant pollinator species can stabilize pollination services through response diversity. Their findings reinforce the proposition that stability depends not merely on the number of species present but also on how different species respond to environmental variation.

The literature therefore suggests a potential biodiversity insurance mechanism: greater diversity may reduce fluctuations in ecosystem functioning because species do not respond identically to environmental stress. Applied to agriculture, this implies that diverse pollinator communities could help maintain relatively consistent pollination services when climatic conditions fluctuate.

A particularly relevant recent study by **Vezzani et al. (2026)** examined crop yield development under climate change and found that relationships between climate, pollinator dependency, and yield varied substantially by crop and region. The authors emphasized that crop yields may become less stable as climatic conditions move beyond historical optima and argued that pollinator dependency should be incorporated into climate-adaptation and yield-prediction frameworks. This supports the present study's emphasis on yield stability rather than yield magnitude alone.

4. Landscape Structure, Agricultural Intensification, and Pollinator Communities

Pollinator diversity is also strongly influenced by landscape characteristics. Agricultural intensification can reduce floral resources, nesting sites, and semi-natural habitats while

increasing exposure to pesticides and other disturbances.

A recent review by Fijen et al. (2025) concluded that crop diversification can enhance pollinator biodiversity by increasing the temporal and spatial availability of floral resources. The authors emphasize that diversification may simultaneously support ecosystem services and agricultural production.

More extensive global evidence is provided by Sritongchuay et al. (2026), who synthesized 101 studies involving 920 site replicates. Their meta-analysis found that pollinator species richness increased with crop diversity in surrounding landscapes, while pollinator abundance increased with the number of different crops and declined as agricultural area expanded. Crop production and fruit set also tended to benefit from greater landscape heterogeneity. These findings demonstrate that landscape structure represents an important contextual factor that should be controlled for when examining climate-pollinator relationships.

This literature has an important implication for the proposed Pakistani study. If landscape heterogeneity, crop diversity, pesticide use, and habitat availability influence pollinator communities, then attributing changes in pollinator diversity exclusively to climate change could generate biased conclusions. Accordingly, these factors should be incorporated as control variables or contextual variables within the analytical framework.

5. Evidence from Pakistan

Research directly examining the climate-pollinator-crop relationship in Pakistan remains relatively limited compared with the rapidly expanding global literature. Nevertheless, available evidence indicates that pollination is already an important agricultural concern.

Khan et al. (2022) documented a major decline in flower-visiting insects in loquat orchards in the Pothwar region over a 13-year period. The decline in pollinator abundance coincided with substantial reductions in loquat yield and fruit quality. This longitudinal evidence is particularly important because it demonstrates that changes

in pollinator populations can be associated with measurable agricultural consequences within Pakistan.

Research in southern Punjab has similarly emphasized the importance of landscape and management conditions. Ahmad et al. (2025) found that landscape composition and farm-management practices affected pollinator abundance and species richness in mango orchards. Their findings indicate that maintaining suitable habitats and reducing pollinator-unfriendly management practices can contribute to improved pollination outcomes.

The Pakistani literature therefore provides evidence for the pollinator → crop productivity relationship but remains comparatively underdeveloped in relation to the full climate → pollinator diversity → crop yield stability pathway.

6. Agro-Ecological Differences and Contextual Variation

A major limitation in existing literature is the tendency to generalize ecological relationships across broad geographical areas. However, pollinator communities respond to local temperature regimes, precipitation, vegetation, elevation, agricultural intensity, and habitat availability.

Pakistan provides an appropriate natural setting for investigating such heterogeneity because its agricultural systems span irrigated plains, rainfed regions, mountainous ecosystems, semi-arid environments, and arid agricultural zones. Climate exposure and agricultural practices differ considerably among these environments.

Recent research also indicates that crop responses to climate and pollination are not uniform. Vezzani et al. (2026) found substantial differences in climate-yield relationships according to crop pollination dependency and geographical region. Similarly, Sritongchuay et al. (2026) demonstrated that landscape structure modifies pollinator diversity and crop production.

Consequently, the present study's agro-ecological-zone approach is theoretically and empirically justified. Rather than assuming one national relationship, it investigates whether the strength

of the climate–pollinator–yield relationship varies among ecological contexts.

7. Critical Synthesis of Existing Literature

The recent literature establishes several important relationships:

First, climate change affects pollinator physiology, phenology, distribution, and potentially community composition (Cheng et al., 2025; Khan et al., 2025).

Second, pollinator diversity and abundance are positively associated with crop productivity across many agricultural systems (Reilly et al., 2024; Turo et al., 2024; Vezzani et al., 2025).

Third, biodiversity may enhance ecosystem-service stability because different species can respond differently to environmental disturbances (Genung & Winfree, 2025).

Fourth, landscape heterogeneity and crop diversification can support pollinator diversity and agricultural production (Fijen et al., 2025; Sritongchuay et al., 2026).

Fifth, the strength of pollinator–yield relationships depends on climate, crop characteristics, management, and geographical context (Vezzani et al., 2025, 2026).

Despite these advances, the literature remains fragmented. Climate studies frequently focus on pollinator responses without examining agricultural consequences. Crop studies often examine pollination and yield without incorporating climatic drivers. Similarly, biodiversity studies frequently focus on pollinator richness or abundance without explicitly assessing yield stability.

Ecological Resilience Theory

Ecological Resilience Theory provides the most appropriate theoretical foundation for this study. Ecological resilience refers broadly to the capacity of an ecological system to absorb disturbances, reorganize, and maintain essential functions and processes despite environmental change. In the context of pollination, resilience concerns the capacity of pollinator communities to continue providing adequate pollination services despite disturbances such as climate variability, habitat

degradation, agricultural intensification, and species loss.

The theory is particularly applicable because the dependent variable in the proposed study is crop yield stability, rather than simply crop yield. Stability is fundamentally a resilience-related outcome: a resilient agricultural ecosystem should be capable of maintaining relatively consistent production despite climatic and ecological disturbances.

1. Biodiversity as a Source of Ecological Resilience

A central proposition underlying ecological resilience is that biodiversity can contribute to ecosystem stability through functional redundancy and response diversity. Species within a community may perform similar ecological functions but respond differently to environmental disturbances. Consequently, the decline of one species does not necessarily result in the complete loss of an ecosystem function if other species can compensate.

This mechanism is directly applicable to pollinators. Bees, flies, butterflies, moths, and other pollinating insects differ in their thermal tolerances, activity periods, nesting requirements, floral preferences, and responses to drought and rainfall. Consequently, a diverse pollinator community may provide greater insurance against climate-induced disturbances than a community dominated by only a few species.

Recent empirical evidence supports this theoretical proposition. Genung and Winfree (2025) found that response diversity among pollinators can stabilize pollination services, demonstrating that differences in species' environmental responses can contribute to functional stability.

2. Climate Disturbance and Pollinator Resilience

The theory further suggests that environmental disturbances can alter community composition and functional performance. In the present study, climatic variability constitutes the principal external disturbance.

The proposed causal mechanism is:

Climate variability → ecological stress → changes in pollinator diversity → altered pollination services → changes in crop-yield stability

For example, increased temperature or drought may reduce the abundance or activity of climate-sensitive pollinator species. However, species with greater thermal or environmental tolerance may remain active and partially compensate for those losses. Where pollinator diversity is high, the overall pollination function may therefore be more resilient.

Where diversity is low, the loss of even a small number of key pollinators may produce disproportionately large reductions in pollination services and increase crop-yield variability.

3. Agro-Ecological Zones as Resilience Contexts

Ecological resilience is context dependent. The capacity of a system to absorb disturbance depends on its environmental characteristics, species composition, resource availability, and intensity of anthropogenic pressure.

This makes Pakistan's agro-ecological zones particularly important. Irrigated agricultural systems may possess greater water availability and different habitat characteristics than rainfed or arid systems. Similarly, mountainous environments may experience different thermal and precipitation regimes from lowland agricultural areas.

Accordingly, the same climatic shock may produce different consequences for pollinator diversity and crop yields in different zones. The proposed study therefore treats agro-ecological zone as a contextual/moderating factor, rather than assuming a universal climate-pollinator relationship.

4. Application to the Proposed Model

Ecological Resilience Theory provides a clear theoretical explanation for the proposed relationships:

Theoretical concept	Study construct
Environmental disturbance	Temperature, precipitation and extreme climatic events
Ecological community	Pollinator community
Biodiversity/response diversity	Pollinator species richness, abundance and Shannon diversity
Ecosystem function	Pollination services
System resilience	Crop yield stability
Context	Agro-ecological zone
Anthropogenic pressures	Pesticides, agricultural intensity and landscape structure

Thus, the theory explains why pollinator diversity should matter for agricultural stability under climatic stress.

Theoretical Proposition

Based on Ecological Resilience Theory, the study proposes that:

Greater pollinator diversity enhances the capacity of agricultural ecosystems to maintain stable crop production under climatic variability because ecologically diverse pollinator communities provide greater functional redundancy and response diversity.

This proposition directly supports the study's mediation model in which pollinator diversity serves as the ecological mechanism connecting climatic variability with crop-yield stability.

Justification for Selecting Ecological Resilience Theory

Ecological Resilience Theory is preferable to a purely agricultural production theory because the central research problem concerns an ecological mechanism underlying agricultural stability. The study is not simply asking whether climate affects crop yield; rather, it asks whether climate affects

pollinator biodiversity, and whether changes in biodiversity subsequently influence the stability of agricultural

production.

The theory therefore provides a coherent explanation for all three central constructs—climate disturbance, pollinator diversity, and yield stability—while also explaining why the relationship may differ across agro-ecological environments.

Hypotheses

H1: Temperature variability has a significant negative effect on pollinator diversity.

H2: Precipitation variability has a significant negative effect on pollinator diversity.

H3: Extreme climatic events have a significant negative effect on pollinator diversity.

H4: Pollinator diversity has a significant positive effect on crop yield stability.

H5: Pollinator abundance has a significant positive effect on crop yield stability.

H6: Pollinator diversity significantly mediates the negative relationship between climatic variability and crop yield stability.

H7: The negative effect of climatic variability on pollinator diversity is significantly stronger in climatically vulnerable agro-ecological zones.

H8: The positive effect of pollinator diversity on crop yield stability is significantly stronger in agro-ecological zones with greater climatic variability.

Methodology

Research Design

The study employed a quantitative, cross-sectional, multi-zone research design to examine the relationships among climatic variability, pollinator diversity, and crop yield stability across selected agro-ecological zones of Pakistan. A comparative design was incorporated to identify differences in the magnitude of these relationships across agro-ecological settings. The study further employed an explanatory analytical approach to assess the direct effects of climatic variability on pollinator diversity, the effect of pollinator diversity on crop yield stability, and the

mediating role of pollinator diversity in the climate–yield relationship.

Population

The target population comprised pollinator-dependent crop farms located across selected agro-ecological zones of Pakistan. The population included agricultural farms cultivating crops that were substantially dependent on insect-mediated pollination, together with the pollinator communities associated with those agricultural ecosystems. Four contrasting agro-ecological settings were considered: irrigated plains, rainfed/barani areas, northern mountainous areas, and southern arid/semi-arid agricultural areas.

Farm-level observations constituted the principal unit of analysis, while pollinator observations and climatic measurements were incorporated to construct the study variables.

Sampling Technique

A multistage stratified sampling technique was employed. First, Pakistan's agricultural areas were stratified according to agro-ecological characteristics. Four major agro-ecological zones were subsequently selected to represent contrasting climatic and agricultural conditions. Within each zone, relevant districts and agricultural communities were identified. Farms were then selected through proportionate stratified random sampling.

Within selected farms, pollinator observations were conducted systematically during crop flowering periods. The sampling procedure was designed to ensure adequate representation of farms experiencing different levels of climatic exposure, agricultural intensity, irrigation availability, and landscape characteristics.

Sample Size

A sample of 480 farms was selected, with 120 farms from each of the four agro-ecological zones. This balanced allocation facilitated meaningful comparison among zones and provided sufficient observations for multivariate regression, mediation, and moderation analyses.

At each sampled farm, standardized pollinator observations were conducted at predetermined sampling points during the flowering period. Where feasible, observations were repeated across relevant flowering periods to reduce temporal sampling bias.

Data Collection Procedures

Data were collected through the integration of field observations, structured farm-level information, climatic records, and crop-yield data.

First, selected farms were identified and classified according to agro-ecological zone and crop characteristics. Second, trained field researchers conducted standardized observations of pollinator communities during crop flowering periods. Pollinators were recorded according to abundance, taxonomic identity, visitation frequency, and observable functional characteristics.

Third, climatic information relating to temperature, precipitation, drought conditions, and extreme climatic events was compiled for the relevant geographical locations and observation periods. Climatic observations were matched with farm-level and pollinator data to develop indicators of climatic variability.

Fourth, crop-yield information was obtained from farm records and verified, where possible, through farmer interviews and available agricultural records. Multi-year yield observations were used to calculate yield variability and yield stability.

Finally, information concerning farm size, irrigation availability, pesticide application, fertilizer use, crop diversity, landscape characteristics, and farm-management practices was collected as control variables.

Instruments and Measures

A structured Farm and Agro-Ecological Survey Schedule was used to collect farm-level information. A standardized Pollinator Observation Protocol was employed to record pollinator diversity and activity.

Climatic Variability

Climatic variability was operationalized using:

- Temperature anomalies and variability;
- Precipitation anomalies and variability;
- Frequency of extreme temperature events;
- Drought occurrence and intensity; and
- Other relevant extreme climatic events.

Pollinator Diversity

Pollinator diversity was measured using multiple indicators to capture both taxonomic and ecological dimensions:

1. **Species richness** – the number of distinct pollinator species recorded.
2. **Pollinator abundance** – the number of individual pollinators observed.
3. **Shannon diversity index** – calculated from species abundance distributions.
4. **Pollinator visitation rate** – the frequency of pollinator visits to crop flowers.
5. **Functional diversity** – where sufficient species-level trait information was available.

Using multiple indicators reduced the risk of representing pollinator diversity through a single ecological measure.

Crop Yield Stability

Crop yield stability was assessed using multi-year yield observations. Yield variability was measured through the coefficient of variation (CV), while greater stability was represented by lower interannual variation.

An inverse stability indicator was calculated as:

$$Yield\ Stability = 1 - CV$$

Higher values therefore represented greater crop-yield stability.

Control Variables

The analysis controlled for potentially confounding agricultural and environmental characteristics, including:

- Farm size;
- Irrigation availability;
- Pesticide intensity;
- Fertilizer application;
- Crop diversity;
- Landscape complexity;

- Agricultural intensification; and
- Access to agricultural extension services.

Reliability

Reliability was addressed through standardization, repeated field observations, observer training, and internal consistency assessment.

Before formal data collection, field enumerators received standardized training regarding pollinator identification, counting procedures, sampling intervals, and recording protocols. A pilot assessment was conducted on a subset of farms to identify inconsistencies in the observation procedure.

For survey-based multi-item measures, Cronbach's alpha was used to assess internal consistency. A reliability coefficient of 0.70 or above was considered acceptable for established constructs. Where appropriate, composite reliability was also assessed.

For pollinator observations, inter-observer reliability was examined by having multiple trained observers independently record pollinator abundance and visitation at selected sites. Differences between observers were reviewed and resolved through standardized identification and counting procedures.

Validity

Several procedures were employed to establish validity.

Content Validity

The survey and observation instruments were reviewed by specialists in ecology, entomology, agricultural sciences, climate science, and environmental research. Their feedback was incorporated to ensure that the instruments adequately represented climatic variability, pollinator diversity, agricultural management, and crop-yield stability.

Construct Validity

Construct validity was assessed by ensuring that each theoretical construct was represented through conceptually appropriate indicators. Pollinator diversity, for example, was not

measured solely through abundance but incorporated species richness, Shannon diversity, visitation rate, and, where possible, functional diversity.

Criterion-Related Validity

Crop-yield information obtained from farmers was cross-checked against available farm records and relevant agricultural records wherever available. Climatic observations were matched with established meteorological measurements for the relevant locations.

Ecological Validity

The selection of contrasting agro-ecological zones enhanced ecological validity by allowing the proposed relationships to be examined under different climatic, agricultural, and environmental conditions rather than within a single localized farming system.

Overall, the methodology was designed to provide a reliable, valid, and ecologically meaningful assessment of the climate–pollinator–crop yield relationship while accounting for important farm-level and landscape-level confounding factors.

Data Analysis and Interpretation

The statistical results presented below were hypothetical and were included to demonstrate how the proposed data could be analyzed and interpreted. They should not be reported as actual field findings.

Data Analysis Procedure

The collected data were coded and analyzed using descriptive and inferential statistical techniques. Descriptive statistics, including means, standard deviations, minimum and maximum values, were calculated for all major variables. Pearson's correlation analysis was subsequently employed to examine the bivariate associations among climatic variability, pollinator diversity, pollinator abundance, and crop yield stability.

Multiple regression analysis was used to test the direct effects of climatic variability on pollinator diversity and the effects of pollinator diversity on crop yield stability. Mediation analysis was

conducted to determine whether pollinator diversity transmitted the effect of climatic variability to crop yield stability. Agro-ecological zone differences were examined through interaction effects and comparative regression analysis. Control variables were included to reduce the possibility that farm-management and

environmental characteristics explained the observed relationships.

A significance level of $p < .05$ was adopted. Standardized beta coefficients (β), standard errors, t-values, confidence intervals, coefficients of determination (R^2), and adjusted R^2 were used to evaluate the magnitude and significance of the relationships.

Descriptive Statistics

Table 1 presents the descriptive statistics for the principal study variables.

Variable	Mean	SD	Minimum	Maximum
Temperature variability	0.84	0.31	0.21	1.72
Precipitation variability	0.76	0.28	0.18	1.54
Extreme climate events	2.41	1.17	0.00	6.00
Pollinator species richness	14.68	5.21	4.00	29.00
Pollinator abundance	42.35	15.47	11.00	82.00
Shannon diversity	1.94	0.52	0.81	3.02
Crop yield stability	0.71	0.14	0.32	0.94

The descriptive results indicated substantial variation in climatic exposure and ecological conditions across the sampled farms. The mean temperature and precipitation variability values suggested that farms experienced differing degrees of climatic fluctuation. Similarly, the occurrence of extreme climate events varied considerably across observations.

Pollinator species richness averaged approximately 14.68 species per observation unit, while pollinator abundance averaged 42.35

individuals. The relatively large standard deviations indicated considerable ecological heterogeneity among farms. Crop yield stability had a mean of 0.71, suggesting moderate overall stability in the dataset, although the minimum value indicated that some farms experienced considerably greater yield fluctuations than others. These variations provided an appropriate basis for examining whether climatic conditions and pollinator diversity were associated with differences in crop-yield stability.

Correlation Analysis

Table 2 presents the Pearson correlation coefficients among the major variables.

Variables	1	2	3	4	5	6
1. Temperature variability	1					
2. Precipitation variability	.36**	1				
3. Extreme climate events	.48**	.42**	1			
4. Pollinator diversity	-.41**	-.34**	-.38**	1		
5. Pollinator abundance	-.37**	-.31**	-.35**	.76**	1	
6. Crop yield stability	-.29**	-.25**	-.31**	.48**	.44**	1

Note: ** $p < .01$.

The correlation analysis demonstrated that temperature variability, precipitation variability,

and extreme climate events were negatively associated with pollinator diversity. Temperature

variability showed the strongest bivariate association with pollinator diversity ($r = -.41$, $p < .01$), followed by extreme climate events ($r = -.38$, $p < .01$) and precipitation variability ($r = -.34$, $p < .01$).

Pollinator diversity was positively associated with crop yield stability ($r = .48$, $p < .01$), while pollinator abundance also demonstrated a positive relationship with yield stability ($r = .44$, $p < .01$). These findings provided preliminary support for the proposed ecological pathway in

which greater climatic instability was associated with reduced pollinator resources and diversity, whereas greater pollinator diversity was associated with more stable crop production.

The correlations among the independent climatic variables were moderate, suggesting that multicollinearity was unlikely to represent a serious problem. However, diagnostic tests were still required before conducting multivariate regression.

Regression Analysis: Climatic Variability and Pollinator Diversity

Table 3 presents the multiple regression results for the effect of climatic variability on pollinator diversity.

Predictor	β	SE	t	p
Temperature variability	-0.29	0.05	-5.84	<.001
Precipitation variability	-0.19	0.06	-3.51	<.001
Extreme climate events	-0.23	0.05	-4.42	<.001
Farm size	0.04	0.01	0.92	.358
Irrigation availability	0.12	0.04	2.31	.021
Pesticide intensity	-0.17	0.03	-3.29	.001

Model statistics: $R^2 = .39$; Adjusted $R^2 = .37$; $F = 31.84$; $p < .001$.

The regression model was statistically significant and explained approximately 39% of the variance in pollinator diversity. Temperature variability had a significant negative effect on pollinator diversity ($\beta = -.29$, $p < .001$), indicating that greater temperature fluctuations were associated with lower pollinator diversity. Thus, H1 was supported.

Precipitation variability also demonstrated a significant negative relationship with pollinator diversity ($\beta = -.19$, $p < .001$), supporting H2.

Similarly, the frequency of extreme climate events was negatively associated with pollinator diversity ($\beta = -.23$, $p < .001$), providing support for H3.

Among the control variables, irrigation availability was positively associated with pollinator diversity, whereas pesticide intensity had a significant negative effect. This suggests that climatic conditions alone did not fully explain variation in pollinator communities; agricultural management practices also contributed to ecological outcomes.

Regression Analysis: Pollinator Diversity and Crop Yield Stability

Table 4 presents the regression results for crop yield stability.

Predictor	β	SE	t	p
Pollinator diversity	0.34	0.06	5.91	<.001
Pollinator abundance	0.21	0.05	3.74	<.001
Temperature variability	-0.16	0.05	-3.02	.003
Precipitation variability	-0.09	0.04	-2.01	.045
Extreme climate events	-0.12	0.04	-2.46	.014
Irrigation	0.15	0.05	2.88	.004

Predictor	β	SE	t	p
Pesticide intensity	-0.13	0.04	-2.71	.007

Model statistics: $R^2 = .46$; Adjusted $R^2 = .44$; $F = 28.67$; $p < .001$.

The results showed that pollinator diversity had a significant positive effect on crop yield stability ($\beta = .34$, $p < .001$). Therefore, farms characterized by greater pollinator diversity tended to demonstrate more stable crop production across climatic fluctuations. H4 was consequently supported.

Pollinator abundance also had a significant positive effect on crop yield stability ($\beta = .21$, $p < .001$), supporting H5. Importantly, pollinator diversity produced a stronger standardized coefficient than abundance, suggesting that the composition and diversity of pollinator communities may be more important for yield stability than the total number of pollinating individuals alone.

Temperature variability, precipitation variability, and extreme climatic events retained significant negative effects on crop yield stability. This indicated that climatic variability could affect agricultural stability through both direct effects on crops and indirect effects operating through pollinator communities.

Mediation Analysis

A mediation model was estimated to examine whether pollinator diversity mediated the relationship between climatic variability and crop yield stability.

Table 5. Mediation Effects

Effect	β	SE	95% CI	p
Climate variability → Pollinator diversity	-0.43	0.06	[-0.55, -0.31]	<.001
Pollinator diversity → Yield stability	0.37	0.07	[0.23, 0.51]	<.001
Total effect of climate variability → Yield stability	-0.39	0.06	[-0.51, -0.27]	<.001
Direct effect	-0.25	0.07	[-0.39, -0.12]	<.001
Indirect effect through pollinator diversity	-0.14	0.04	[-0.23, -0.07]	<.001

The mediation analysis indicated that climatic variability had a significant negative effect on pollinator diversity, while pollinator diversity had a significant positive effect on crop yield stability. The indirect effect of climatic variability on yield stability through pollinator diversity was negative and statistically significant, as the bootstrap confidence interval did not include zero.

The results therefore suggested that pollinator diversity constituted an important ecological

pathway through which climatic variability influenced agricultural stability. However, the direct effect remained statistically significant after pollinator diversity was included in the model. This pattern indicated partial mediation, implying that climatic variability affected crop yield stability both through changes in pollinator diversity and through other direct or indirect mechanisms. Accordingly, H6 was supported.

Agro-Ecological Zone Differences

Table 6. Regression Coefficients by Agro-Ecological Zone

Agro-ecological zone	Climate variability → Pollinator diversity (β)	Pollinator diversity → Yield stability (β)	R ²
Irrigated Plains	-0.31**	0.29**	.34
Rainfed/Barani Areas	-0.42**	0.38**	.43
Northern Mountainous Areas	-0.48**	0.45**	.49
Southern Arid/Semi-arid Areas	-0.44**	0.41**	.46

Note: **p < .01.

The zone-specific analysis demonstrated that the relationship between climatic variability and pollinator diversity differed considerably across agro-ecological contexts. The strongest negative association was observed in the northern mountainous areas ($\beta = -.48$), followed by the southern arid/semi-arid areas ($\beta = -.44$). The weakest relationship was observed in the irrigated plains ($\beta = -.31$).

Similarly, the positive relationship between pollinator diversity and crop yield stability was strongest in the northern mountainous areas ($\beta = .45$) and southern arid/semi-arid areas ($\beta = .41$).

These findings suggested that ecological diversity may become particularly important for maintaining agricultural stability where climatic exposure is relatively high.

The interaction analysis therefore provided support for H7, indicating that the negative consequences of climatic variability for pollinator diversity were stronger in more climatically vulnerable agro-ecological zones. H8 was also supported because the contribution of pollinator diversity to yield stability was comparatively stronger in zones experiencing greater climatic stress.

Summary of Hypothesis Testing

Table 7. Summary of Hypothesis Testing

Hypothesis	Relationship	Result
H1	Temperature variability → Pollinator diversity (-)	Supported
H2	Precipitation variability → Pollinator diversity (-)	Supported
H3	Extreme climate events → Pollinator diversity (-)	Supported
H4	Pollinator diversity → Crop yield stability (+)	Supported
H5	Pollinator abundance → Crop yield stability (+)	Supported
H6	Pollinator diversity mediates climate → yield stability	Supported
H7	Climate effect on pollinators stronger in vulnerable zones	Supported
H8	Pollinator diversity effect on stability stronger under greater climatic variability	Supported

Overall Interpretation of Findings

Taken together, the findings suggested a coherent climate-pollinator-crop stability pathway. Climatic variability was associated with reductions in pollinator diversity, while greater pollinator diversity was associated with greater

crop yield stability. The results further indicated that the effect of climatic variability was not uniform across Pakistan's agro-ecological zones. More climatically exposed zones appeared to experience stronger negative effects on pollinator communities and greater dependence on

pollinator diversity for maintaining stable agricultural production.

The mediation results were particularly important because they suggested that the consequences of climate change for agricultural systems extended beyond direct effects on crop physiology and water availability. Changes in pollinator communities represented an additional ecological mechanism through which climatic instability could influence agricultural performance. The positive contribution of pollinator diversity to yield stability further supported the ecological-resilience perspective, suggesting that diverse pollinator communities may provide a form of ecological insurance by maintaining pollination services when environmental conditions fluctuate.

The stronger effect of pollinator diversity compared with pollinator abundance also suggested that biodiversity quality and community composition may be more important than simply increasing the number of pollinating individuals. Diverse pollinator communities may contain species with different climatic tolerances, activity periods, foraging behaviors, and resource requirements. Consequently, when climatic conditions become unfavorable for some species, other species may partially compensate and sustain pollination services.

Finally, the zone-specific findings indicated that a uniform national climate-adaptation strategy may be insufficient. Irrigated plains, rainfed areas, mountainous regions, and arid/semi-arid agricultural systems differ in their climatic exposure, farming practices, ecological resources, and pollinator communities. Climate-smart agricultural policies should therefore incorporate agro-ecological specificity and pollinator conservation rather than focusing exclusively on irrigation, crop varieties, or other conventional adaptation measures.

Discussion

The findings demonstrated a consistent relationship between climatic variability, pollinator diversity, and crop yield stability across Pakistan's contrasting agro-ecological zones. Temperature variability, precipitation variability,

and extreme climatic events were negatively associated with pollinator diversity, while pollinator diversity and abundance were positively associated with crop yield stability. The mediation analysis further indicated that pollinator diversity constituted an important ecological pathway through which climatic variability could influence agricultural stability.

The negative association between climatic variability and pollinator diversity was consistent with the broader literature indicating that climate change can alter pollinator abundance, phenology, distribution, reproduction, and resource availability. Recent global synthesis has demonstrated that climate change can affect pollinators through multiple physiological and ecological mechanisms, although the magnitude and direction of effects vary among taxa and environments. The present findings extended this perspective by positioning climatic variability within Pakistan's agro-ecological context rather than treating climate change as a geographically uniform pressure.

The finding that temperature variability had the strongest negative association with pollinator diversity was particularly important. Temperature influences pollinator metabolism, development, activity periods, survival, and synchronization with flowering resources. Excessive temperature fluctuations can therefore disrupt both pollinator physiology and plant-pollinator temporal relationships. This interpretation was consistent with recent evidence showing that climate change affects pollinator life-history characteristics and resource acquisition. It also complements Pakistan-specific evidence indicating substantial future habitat losses for *Apis dorsata* under projected climate scenarios.

The negative effect of precipitation variability and extreme climatic events further suggested that pollinator communities were affected not only by gradual climatic change but also by instability and climatic shocks. Irregular rainfall can influence flowering resources, nesting conditions, vegetation availability, and agricultural management practices. Similarly, droughts, floods, heatwaves, and other extreme events may simultaneously affect pollinators and their floral

resources. This finding was particularly relevant to Pakistan because its agro-ecological zones differ substantially in rainfall patterns, irrigation dependence, temperature regimes, and exposure to climatic extremes.

The positive relationship between pollinator diversity and crop yield stability was consistent with recent international evidence. Turo et al. (2024), using a large global dataset, demonstrated that insufficient pollinator visitation frequently limited crop yields. Similarly, Artamendi et al. (2025) found that reductions in pollinator diversity consistently reduced reproductive success in both wild and cultivated plants. Reilly et al. (2024) further demonstrated that wild insects and managed honey bees made important and broadly comparable contributions to crop yields, while pollinator species diversity remained positively associated with production. The present findings therefore support the proposition that agricultural productivity depends not simply on the presence of pollinators but on maintaining sufficiently diverse pollinator communities.

The stronger coefficient for pollinator diversity than for pollinator abundance was theoretically meaningful. A high number of individuals does not necessarily indicate a functionally diverse pollinator community. Different pollinator species may vary in body size, foraging behavior, climatic tolerance, flower preferences, activity periods, and ability to operate under stressful environmental conditions. Consequently, biodiversity can provide greater functional insurance than abundance alone. The finding was compatible with the response-diversity perspective advanced by Genung and Winfree (2025), according to which differences among species in their responses to environmental change can contribute to the stability of ecosystem services.

The mediation analysis provided an important contribution to the study. Rather than conceptualizing climate change as affecting crop production only through direct physiological mechanisms, the findings suggested an indirect ecological pathway: climatic variability reduced pollinator diversity, which subsequently reduced

crop yield stability. This interpretation is consistent with the ecological-services perspective and helps explain why climate adaptation strategies focused exclusively on crop varieties, irrigation, and water management may overlook an important component of agricultural resilience.

The zone-specific results further demonstrated that the climate–pollinator relationship was context dependent. The stronger effects observed in mountainous and arid/semi-arid areas suggested that ecological vulnerability may increase the sensitivity of pollinator communities to climatic stress. Pakistan-specific research has similarly demonstrated substantial spatial differences in climate and vegetation dynamics across agro-ecological zones. Evidence from Southern Punjab also indicates that farm management and landscape composition can substantially influence pollinator communities and crop fruit set. Thus, climatic exposure should be considered together with agricultural management and landscape characteristics.

The findings also supported the Ecological Resilience Theory underpinning the study. From this perspective, climatic variability represented an external disturbance, pollinator diversity represented an important component of ecological response capacity, pollination represented an ecosystem function, and crop yield stability represented an agricultural resilience outcome. Diverse pollinator communities may enhance resilience through response diversity and functional complementarity, allowing pollination services to persist despite unfavorable conditions affecting individual species.

Theoretically, the study therefore extended Ecological Resilience Theory into an agricultural climate-change context by connecting biodiversity, ecosystem functioning, and production stability within a single analytical framework. The results suggested that resilience should not be assessed solely through the ability of crops to tolerate climatic stress; it should also incorporate the ecological networks that support agricultural production.

Conclusion

The study examined the relationship between climatic variability, pollinator diversity, and crop yield stability across contrasting agro-ecological zones of Pakistan. The findings indicated that temperature variability, precipitation variability, and extreme climatic events negatively affected pollinator diversity, whereas pollinator diversity and abundance positively contributed to crop yield stability.

The mediation analysis suggested that pollinator diversity represented an important mechanism linking climatic variability with agricultural stability. The zone-specific findings further indicated that these relationships varied across agro-ecological settings, with stronger effects observed in comparatively climate-vulnerable environments.

Overall, the study highlighted that pollinator conservation should be considered an integral component of climate-resilient agriculture rather than solely a biodiversity-conservation concern. Maintaining diverse and functionally complementary pollinator communities could contribute to the capacity of agricultural systems to sustain relatively stable production under increasing climatic uncertainty. The findings consequently support a transition from narrowly crop-centered climate adaptation toward an integrated climate-biodiversity-agriculture resilience framework.

Implications

Theoretical Implications

The study contributes to Ecological Resilience Theory by demonstrating how biodiversity can function as an ecological mechanism supporting stability under environmental disturbance. It integrates three previously interconnected but often separately examined dimensions: climate variability, pollinator diversity, and agricultural production stability.

The findings also strengthen the theoretical importance of response diversity and functional complementarity. The stronger relationship between pollinator diversity and yield stability compared with pollinator abundance suggests that ecological resilience may depend more on

the diversity of functional responses than on the numerical abundance of a single or limited group of pollinators.

Furthermore, the proposed mediation mechanism extends conventional climate-agriculture models by introducing ecosystem services as an intervening mechanism. This provides a stronger theoretical basis for examining agricultural resilience as an ecological as well as an agronomic phenomenon.

Managerial Implications

Farm managers should treat pollinator conservation as part of routine agricultural risk management. Excessive pesticide use, removal of flowering vegetation, destruction of nesting habitats, and excessive landscape simplification may reduce pollinator diversity and consequently increase vulnerability to climatic fluctuations.

Farm-level decisions should therefore incorporate:

- Pollinator-friendly pesticide management;
- Flowering plants and habitat strips;
- Reduced destruction of natural vegetation;
- Diversification of crops;
- Appropriate irrigation management; and
- Conservation of semi-natural habitats surrounding agricultural land.

The findings also imply that farmers should not rely excessively on a single pollinator group where diversified pollinator communities can be maintained.

Practical Implications

Agricultural extension programs should provide farmers with practical guidance on identifying and conserving native pollinators. Pollinator monitoring could be incorporated into agricultural advisory systems alongside conventional indicators such as soil moisture, pests, rainfall, and crop disease.

Crop diversification and landscape diversification may also provide practical opportunities for improving pollinator resources. Recent global evidence suggests that greater crop diversity in agricultural landscapes can enhance pollinator

richness and abundance while supporting pollinator-dependent crop production.

The development of farm-level pollinator resilience indicators could further help farmers identify areas where ecological vulnerability is increasing.

Policy Implications

At the policy level, pollinator conservation should be incorporated into Pakistan's climate-smart agriculture, biodiversity, food-security, and agricultural extension strategies.

Policy interventions could include:

1. Establishing pollinator conservation zones around major agricultural areas.
2. Promoting integrated pest management and reducing unnecessary pesticide applications.
3. Supporting diversified farming systems.
4. Protecting semi-natural habitats near pollinator-dependent crops.
5. Integrating pollinator indicators into climate adaptation assessments.
6. Developing agro-ecological-zone-specific pollinator management plans.
7. Establishing long-term national pollinator monitoring programs.
8. Supporting research on climate-tolerant native pollinator species.
9. Incorporating pollination services into agricultural risk and food-security assessments.
10. Providing incentives for farmers adopting pollinator-friendly practices.

Recommendations

Based on the findings, the following recommendations are proposed:

1. Establish National Pollinator Monitoring

Pakistan should establish a systematic long-term monitoring program covering pollinator abundance, species richness, diversity, phenology, and geographical distribution across major agro-ecological zones.

2. Promote Pollinator-Friendly Farming

Farmers should be encouraged to maintain flowering vegetation, field margins, hedgerows,

natural habitats, and other resources that provide food and nesting opportunities for pollinators.

3. Strengthen Integrated Pest Management

Unnecessary and indiscriminate pesticide applications should be minimized. Integrated pest management should be promoted, with pesticide timing and application methods designed to reduce exposure during peak pollinator activity.

4. Encourage Crop and Landscape Diversification

Crop diversification should be integrated into climate-smart agricultural programs because diversified landscapes can provide more continuous floral resources and habitat for pollinator communities.

5. Develop Agro-Ecological-Zone-Specific Strategies

A single national pollinator strategy may not adequately address Pakistan's ecological heterogeneity. Mountainous, rainfed, irrigated, and arid/semi-arid agricultural systems should receive differentiated conservation and adaptation interventions.

6. Integrate Pollinators into Climate Adaptation Policies

Climate adaptation policies should explicitly recognize pollination as an ecosystem service that can influence agricultural stability. Climate risk assessments should therefore consider indirect biodiversity-mediated effects on crop production.

7. Strengthen Farmer and Extension Training

Agricultural extension departments should train farmers to identify major pollinator groups, recognize pollinator-friendly habitats, reduce harmful management practices, and incorporate pollinator conservation into farm planning.

8. Protect Native Pollinator Communities

Conservation programs should prioritize native wild pollinators alongside managed honey bees. Maintaining diverse native pollinator

communities may provide greater ecological insurance under variable climatic conditions.

9. Develop Long-Term Climate-Pollinator-Yield Databases

Pakistan would benefit from integrated databases combining meteorological observations, pollinator surveys, crop yields, pesticide use, land-use characteristics, and agricultural management information. Such datasets would improve both scientific understanding and evidence-based policy formulation.

10. Incorporate Pollination into Food-Security Planning

Because yield stability is an important component of food security, pollination services should be recognized within national agricultural resilience and food-security planning rather than being treated exclusively as an environmental issue

Limitations and Future Directions

Despite its proposed contribution, the study had several limitations. First, the research design was based on empirical framework; consequently, the numerical findings were hypothetical and require validation through actual field-based longitudinal research.

Second, the study focused on selected agro-ecological zones and therefore may not fully represent all agricultural environments of Pakistan. Future research should expand geographical coverage to include additional ecological and cropping systems.

Third, pollinator diversity was represented through species richness, abundance, Shannon diversity, and visitation measures. However, species-level identification and functional traits may be difficult to obtain consistently in large-scale field studies. Future research should incorporate functional diversity, phylogenetic diversity, body size, foraging behavior, thermal tolerance, and phenological characteristics.

Fourth, crop yield stability was operationalized through interannual yield variation. Yield, however, can be influenced by numerous factors beyond pollination, including irrigation, soil fertility, pests, fertilizers, seed varieties, farm

management, and market-related decisions. Future studies should use detailed longitudinal farm-level data to isolate the contribution of pollination more precisely.

Fifth, climatic variables were conceptualized primarily through temperature, precipitation, drought, and extreme events. Future research should incorporate additional variables such as humidity, soil moisture, heatwave duration, flood intensity, growing-degree days, and climate extremes at finer spatial and temporal scales.

Sixth, the study treated agro-ecological zone as an important contextual factor but did not fully model landscape connectivity and habitat fragmentation. Future research should employ GIS and remote-sensing techniques to examine habitat availability, land-use change, vegetation cover, fragmentation, and landscape connectivity around agricultural fields.

Seventh, the proposed analysis primarily examined linear relationships. Climate-pollinator relationships may, however, be nonlinear and may include threshold effects. Future studies should therefore employ nonlinear regression, generalized additive models, spatial models, and hierarchical/multilevel approaches.

Finally, future research should adopt longitudinal and experimental designs wherever feasible. Long-term monitoring would allow researchers to distinguish temporary climatic fluctuations from persistent ecological change, while field experiments could directly test whether pollinator-friendly interventions improve crop yield stability under climatic stress.

Future research could consequently develop a more comprehensive Climate-Pollinator-Agricultural Resilience Model integrating climate exposure, pollinator functional diversity, landscape structure, farm management, ecosystem services, and crop productivity. Such research would provide stronger empirical evidence for designing climate-resilient and biodiversity-sensitive agricultural policies in Pakistan.

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