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CLIMATE CHANGE VULNERABILITY AND ADAPTIVE CAPABILITY OF SMALL-SCALE FARMERS IN PUNJAB, PAKISTAN: A MACHINE LEARNING APPROACH

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Abstract

Smallholder farmers in Pakistan's rain-fed north-central Punjab face intensifying climate stress, yet the institutional conditions that shape their adaptive capacity remain poorly understood. This study assesses household-level climate vulnerability and projects its trajectory to 2035 under three IPCC AR6-aligned scenarios. A cross-sectional survey of 200 smallholder farmers across Attack, Chakwal, Islamabad, and Jhelum districts was conducted. Three composite indices were constructed: a climate vulnerability index (CVI) grounded in the IPCC exposure–sensitivity framework, an adaptive strategy index (ASI), and an institutional and policy support index (IPS). A tuned random forest model (RFM) (1,000 trees; 5-fold cross-validation) was used to identify drivers of vulnerability, and scenario-based projections were generated to 2035. Results show that mean CVI is 0.645 on a **[0, 1]** *scale, placing the average household in the moderate-to-high vulnerability range. Random Forest analysis identified institutional support (IPS) as the dominant predictor of vulnerability (importance = 95), with education and district effects secondary. Critically, the data revealed an institutional vacuum: 96% of farmers reported no extension service access, no climate-resilience training, and no cooperative membership, despite 100% reporting observed weather changes and willingness to adopt new practices. Scenario projections indicate that by 2035, even under SSP2-4.5 with a 30% increase in adaptation and*

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40% increase in institutional support, 96% of farmers would fall into the high-vulnerability category statistically indistinguishable from the business-as-usual outcome (93.5%). Under SSP5-8.5, 99% of farmers become highly vulnerable. These findings suggest that incremental adaptation within the current institutional system cannot offset projected climate stress. Transformative policy response centered on building extension capacity, cooperative infrastructure, and mobile-based advisory at scale is required. The study contributes a replicable framework combining composite indexing, machine learning, and scenario projection for forward-looking vulnerability assessment.

1. Introduction

Climate change has moved from a projected future threat to an observable, lived reality for millions of agricultural households across South Asia. Pakistan ranked consistently among the world's most climate-vulnerable countries faces a compounded crisis: temperatures rising faster than the global average, increasingly erratic monsoon patterns, and a rising frequency of extreme events including floods, heatwaves, droughts, and hailstorms (Nadeem et al. 2024; Shah et al. 2026). The intergovernmental panel on climate change (IPCC) sixth assessment report (AR6) has refined the conceptualization of climate risk as the dynamic interaction of hazard, exposure, and vulnerability, where vulnerability itself comprises sensitivity and adaptive capacity (Intergovernmental Panel on Climate Change 2022). This framework, while analytically powerful, requires granular, household-level empirical application particularly in agrarian economies where livelihoods are directly weather-dependent.

Punjab province is the agricultural heartland of Pakistan, contributing the overwhelming majority of the nation's wheat, rice, and maize output. Within Punjab, the north-central districts including Attock, Chakwal, Islamabad, and Jhelum occupy a distinctive and understudied position. Unlike the flood-prone southern belt of Rajanpur and Dera Ghazi Khan, or the high-mountain communities of Gilgit-Baltistan, the north-central zone is characterized by rain-fed and mixed farming systems, small landholdings, and a transition zone between irrigated plains and the rain-dependent Potohar plateau (Aqib et al. 2024). These farmers face a dual exposure: increasing rainfall variability and heat stress on the one hand, and structural constraints on adaptive capacity limited irrigation access, weak institutional reach, and low financial buffers on the other (Mustafa et al. 2025).

A growing body of Pakistani scholarship has documented farmers' perceptions of climate change, their adaptation strategies, and the socioeconomic determinants of adaptive behavior (Nadeem et al. 2024; Shah et al. 2026; Ali et al. 2024). Studies have identified common responses: changing planting dates, crop diversification, reliance on off-farm income, and, in some contexts, migration (Mustafa et al. 2025).

International evidence consistently demonstrates that institutional support extension services, farmer organizations, access to credit, training, and reliable climate information is a decisive determinant of whether vulnerable households can translate awareness into effective adaptation (Food and Agriculture Organization 2013; Waaswa et al. 2024; GIZ 2025). In Kenya, training and group membership significantly increased adoption of climate-smart practices (Waaswa et al. 2024). In Ghana, institutions served as critical intermediaries for technology transfer, input supply, and market integration ("The Role of Institutions in Enhancing Climate Change Adaptation by Smallholder Farmers in the Talensi District of Ghana" 2025). The FAO's climate-smart agriculture framework explicitly

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identifies institutions as essential for knowledge production, financial access, and collective action (Food and Agriculture Organization 2013). Conversely, where institutions are weak or absent, farmers remain trapped in reactive, low-capacity coping strategies that erode livelihoods over time ("Constraints to Adaptation in the HKH Region" 2023).

In Pakistan, this institutional dimension is particularly fraught. Research in southern Punjab has highlighted water governance failures, inequitable subsidy distribution, and weak market linkages as key constraints on smallholder adaptation (Aqib et al. 2024). A comparative study of livelihood vulnerability found that early warning systems were almost entirely absent in high-risk districts, with 88.8% and 81.1% of households in Nowshera and Charsadda, respectively, receiving no alerts ("Comparative Analysis of Livelihood Vulnerability to Climate Change" 2026). Recent work on social marginalization has further shown how structural inequalities caste, gender, and social influence impede access to the information and resources needed for adaptation (Khan et al. 2026). These findings point to a systemic pattern: climate vulnerability in Pakistan is not simply a function of exposure to climatic hazards, but is actively produced and sustained by institutional vacuums.

The selection of Attock, Chakwal, Islamabad, and Jhelum as study districts is analytically significant for three reasons. First, agro-ecological distinctiveness. These districts sit at the ecological transition between the irrigated Indus plains and the rain-fed Potohar plateau. Farming systems are dominated by smallholdings (frequently less than one acre), with mixed crop–livestock portfolios serving as a risk-spreading strategy (Nadeem et al. 2024). Rainfall, rather than canal irrigation, is the primary water source for many. This makes the zone acutely sensitive to precipitation variability a sensitivity that is projected to intensify (Intergovernmental Panel on Climate Change 2022). Second, institutional remoteness. Unlike the politically and administratively dense southern Punjab, the north-central districts have historically received less attention from agricultural extension, NGO interventions, and climate adaptation programs. This creates a natural laboratory for examining what happens when climate stress intensifies in the absence of institutional buffering. Third, empirical scarcity. The overwhelming majority of Punjab-focused climate vulnerability research has concentrated on the southern districts (Rajanpur, Muzaffargarh, Dera Ghazi Khan) or the central grain belt (Aqib et al. 2024; Shah et al. 2026). The north-central zone remains largely absent from the literature, despite its distinct vulnerability profile. This study addresses that gap directly.

This study has three objectives. First, it constructs a climate vulnerability index (CVI) grounded in the IPCC exposure sensitivity adaptive capacity framework, calibrated to the north-central Punjab context. Second, it tests the explanatory power of two composite indices an adaptive strategy index (ASI) and an institutional and policy support Index (IPS) in predicting household-level climate vulnerability. Third, it employs Random Forest to identify the relative importance of adaptive strategies and institutional support as drivers of vulnerability.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature on climate vulnerability assessment, adaptation determinants, and institutional support. Section 3 describes the study design, data collection, index construction, and analytical methods. Section 4 presents the results. Section 5 discusses the findings in relation to theory and policy. Section 6 presents the conclusion of the study.

2. Literature Review

Vulnerability to climate change has been conceptualized through multiple, overlapping traditions. Early formulations in disaster risk reduction framed vulnerability as the pre-existing conditions that transform a hazard into a disaster (Intergovernmental Panel on Climate Change 2022). The IPCC's successive assessment reports

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progressively refined this into a structured framework: vulnerability is a function of sensitivity (the degree to which a system is affected by climatic stimuli) and adaptive capacity (the ability to adjust, moderate harm, or exploit opportunities), interacting with exposure (the presence of people, livelihoods, or assets in places and settings that could be adversely affected) (Intergovernmental Panel on Climate Change 2022). The resulting risk equation Risk = Hazard × Exposure × Vulnerability has become the dominant analytical scaffold in climate scholarship.

Two methodological families have emerged for operationalizing vulnerability. The first is the indicator-based approach, where composite indices aggregate socioeconomic, biophysical, and institutional variables into a single score. The livelihood vulnerability index (LVI) developed by (Hahn et al. 2009) is among the most widely applied, decomposing vulnerability into seven components: socio-demographic profile, livelihood strategies, social networks, health, food, water, and natural disasters and climate variability. Variants such as the LVI-IPCC, which re-maps LVI components into the exposure sensitivity adaptive capacity triad, have been applied across Africa, South Asia, and Latin America (Hahn et al. 2009; "Comparative Analysis of Livelihood Vulnerability to Climate Change" 2026). The second is the econometric approach, which models vulnerability as a function of observable household characteristics and estimates the marginal contribution of each determinant. Recent work has increasingly combined both traditions, using composite indices as dependent variables in regression or machine-learning models (Shah et al. 2026).

A critical methodological issue in this literature concerns the statistical treatment of bounded vulnerability indices. Because composite indices are typically rescaled to the unit interval $[0,1]$, ordinary least squares (OLS) regression is technically miss-pecified: it assumes an unbounded, Gaussian-distributed dependent variable, violating both the boundary constraint and the heteroskedasticity typical of proportional data (Ferrari and Cribari-Neto 2004). Beta regression, introduced by (Ferrari and Cribari-Neto 2004) and refined by (Smithson and Verkuilen 2006), provides a principled alternative by modeling the dependent variable as beta-distributed on $(0,1)$ with a logit (or probit, or cloglog) link. Despite its clear applicability, beta regression remains rare in climate vulnerability research, where OLS and Tobit models continue to dominate. This study addresses that gap by treating beta regression as the primary estimator, with OLS retained only for comparability with earlier work.

Pakistan is consistently ranked among the ten countries most affected by climate-related extreme events (Germanwatch 2021). Within Pakistan, Punjab province presents a particularly complex vulnerability profile. It is the agricultural engine of the country, producing over 70% of national wheat and contributing approximately 60% of agricultural GDP (Shah et al. 2026). Yet its farming systems are simultaneously exposed to rising temperatures, erratic monsoons, groundwater depletion, and increasingly frequent extreme events.

Empirical vulnerability research in Pakistan has concentrated geographically on the southern districts (Rajanpur, Muzaffargarh, Dera Ghazi Khan) and the flood-prone plains of Khyber Pakhtunkhwa. (Aqib et al. 2024), in a household survey of South Punjab, found that adaptive capacity was severely constrained by weak extension services, limited credit access, and inadequate early warning systems. A comparative study of Nowshera and Charsadda documented that 88.8% and 81.1% of households, respectively, received no climate alerts before extreme events ("Comparative Analysis of Livelihood Vulnerability to Climate Change" 2026). Research in Narowal, central Punjab, revealed that climate-related income losses disproportionately affected households with small landholdings and low education ("Understanding

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Climate Vulnerability and Economic Impacts on Rural Livelihoods" 2026).

Studies in the high-mountain regions of Gilgit-Baltistan have documented a distinct vulnerability regime driven by glacial melt, erratic snowfall, and isolation from markets and institutions (Ali et al. 2024). Work in the rain-fed Potohar plateau which overlaps with the present study's north-central Punjab zone has highlighted the acute sensitivity of rain-dependent farming to precipitation variability, coupled with low adoption of modern irrigation (Nadeem et al. 2024).

Despite this growing body of work, three gaps persist. First, the north-central districts of Punjab (Attock, Chakwal, Islamabad, and Jhelum) remain empirically neglected, despite their agro-ecological distinctiveness and their historically weak institutional presence. Second, most studies focus on a single district or a flood-affected area, limiting comparability. Third, the institutional dimension is typically treated as one variable among many rather than as a central analytical focus. This paper addresses all three gaps.

The determinants of adaptation behavior among smallholder farmers have been extensively studied, with a consistent set of predictors emerging across contexts. Socioeconomic characteristics, age, education, farm size, and income are repeatedly shown to shape adaptive capacity. Education enhances access to information and improves decision-making under uncertainty (Mustafa et al. 2025). Farm size correlates with access to credit, technology, and risk-buffering capacity, though the relationship is non-linear: the smallest and largest farms exhibit different adaptation profiles (Shah et al. 2026).

Access to information is a second robust determinant. Farmers who receive timely weather forecasts, extension advice, or climate-smart technology information are significantly more likely to adopt adaptive practices (Waaswa et al. 2024). In Pakistan, however, information access remains highly unequal. Mobile phone penetration has expanded rapidly, but the content available to farmers is often generic, delayed, or unreliable (GIZ 2025). Radio and television remain important in rural areas, but coverage is uneven and often fails to reach the most vulnerable households (Khan et al. 2026).

Perception of climate change is a third determinant. Farmers who perceive climate change as a real, ongoing threat are more likely to adapt, though perception alone is insufficient without enabling conditions (Mustafa et al. 2025). The relationship between perception and action is mediated by economic capacity, institutional access, and social networks.

Adaptation strategies documented in Pakistan include changing planting dates, switching crop varieties, crop diversification, supplementary irrigation, migration, and off-farm income diversification (Shah et al. 2026; Aqib et al. 2024). However, adoption is often partial and reactive rather than proactive. A critical finding across studies is that farmers rarely pursue a single strategy; instead, they combine low-cost, low-risk adjustments. This portfolio approach reflects both rational risk management and the structural constraints imposed by poverty and institutional neglect.

The fourth body of literature concerns the institutional dimension of adaptive capacity. Institutions defined broadly to include government agencies, extension services, farmer organizations, NGOs, credit providers, and information networks mediate access to resources, knowledge, and markets (Food and Agriculture Organization 2013).

International evidence is unambiguous: institutional support significantly increases adaptation. In Kenya, membership in farmer groups and participation in extension training were among the strongest predictors of climate-smart agriculture adoption (Waaswa et al. 2024). In Ghana, institutions served as intermediaries linking farmers to technology, inputs, and markets, with the strongest effects observed among women and smallholders ("The Role of Institutions in Enhancing Climate Change

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Adaptation by Smallholder Farmers in the Talensi District of Ghana" 2025). Across the Hindu Kush Himalaya region, ("Constraints to Adaptation in the HKH Region" 2023) identified institutional absence particularly the lack of extension services and formal credit as a binding constraint on adaptation, even where farmers were aware of climate risks and motivated to act.

In Pakistan, the institutional landscape is fragmented and uneven. Government agricultural extension has historically been under-resourced, with a low extension-to-farmer ratio and limited geographic coverage (Aqib et al. 2024). NGO interventions, while impaction where present, are concentrated in specific districts and often time-limited. Farmer organizations and cooperatives are rare, and where they exist, they tend to represent larger landholders (Khan et al. 2026). Access to formal credit is constrained by collateral requirements and information asymmetries, disproportionately excluding smallholders.

Recent work has emphasized the socially differentiated character of institutional access. (Khan et al. 2026) demonstrated how caste, gender, and social influence shape who receives information, who is invited to trainings, and who can access credit. Institutional absence is therefore not randomly distributed: it clusters among the poorest, least educated, and most socially marginalized households precisely those with the highest sensitivity to climate stress.

The FAO's climate-smart agriculture framework explicitly identifies institutions as one of three pillars (alongside technology and policy) required for climate-resilient food systems (Food and Agriculture Organization 2013). Yet in Pakistan, this pillar remains largely unbuilt. The present study positions this "institutional vacuum" not as a background condition but as a central explanatory variable for persistent vulnerability.

3. Methodology and materials

This section describes the study design, data collection, index construction, and analytical strategy. The methodology proceeds in three stages: (i) survey administration and index construction, (ii) Random Forest modeling to identify drivers of vulnerability, and (iii) scenario-based projection of household vulnerability to 2035 under IPCC AR6 climate trajectories.

3.1 Study Area

The study was conducted in four districts of north-central Punjab, Pakistan: Attock, Chakwal, Islamabad, and Jhelum Figure 1. These districts occupy the ecological transition between the irrigated Indus plains and the rain-fed Potohar plateau. The zone is characterized by:

- Rain-fed and mixed farming systems, with limited canal irrigation;
- Small landholdings, predominantly under 3 acres;
- Direct dependence on monsoon rainfall for kharif crops and on winter precipitation for rabi crops;
- Historically weak institutional presence relative to southern Punjab, with limited extension coverage, few farmer organizations, and sporadic NGO activity.

Mean annual rainfall in the zone ranges from approximately 500–800 mm, with substantial inter-annual variability. Recent years have seen increased frequency of extreme rainfall events, heatwaves, and hailstorms (Nadeem et al. 2024). The selection of these four districts is analytically motivated by this combination of climatic exposure and institutional thinness, which makes the zone a natural laboratory for examining both current vulnerability and its projected trajectory under climate change.

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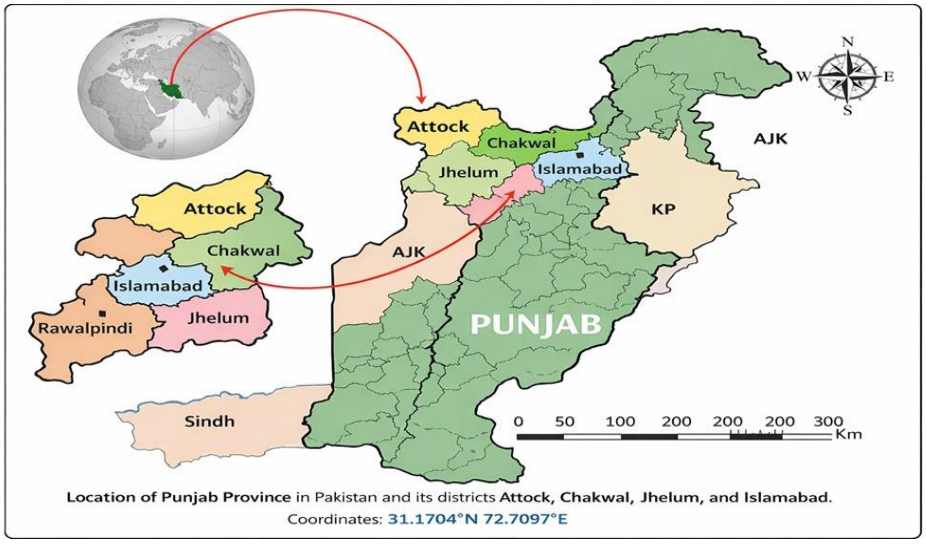


Figure 1: Study Area

3.2 Sampling and Data Collection

A cross-sectional household survey was administered between 2024 to 2025, 200 smallholder farmers, with a balanced distribution across the four districts ($n = 50$ per district). Respondents were selected through a multi-stage purposive sampling procedure:

1. Stage 1 (District selection): The four districts were purposively chosen based on agro-ecological distinctiveness, smallholder density, and representation of the rain-fed Potohar transition zone.
2. Stage 2 (Union Council selection): Within each district, 2–3 union councils were selected in consultation with local agricultural officers, prioritizing areas with active farming.
3. Stage 3 (Household selection): Households were selected using a systematic random walk from a central village point. Eligibility criteria were: (i) active farming in the last cropping year, (ii) landholding ≤ 6 acres, and (iii) willingness to participate.

Data were collected through face-to-face structured interviews using a pre-tested questionnaire (Appendix A). The questionnaire was developed in English and administered in Urdu and local Punjabi dialects by trained enumerators. Prior to the main survey, a pilot test with 15 farmers was conducted to refine wording, response categories, and sequencing. Ethics approval was obtained from the Institutional Review Board of Quaid-i-Azam University, Islamabad. Verbal informed consent was obtained from all participants, who were assured of anonymity and their right to withdraw at any time.

3.3 Questionnaire Design and Variable Construction

The questionnaire comprised five sections: (A) demographic and farm characteristics, (B) perceived climate variability and impacts, (C) adaptive strategies, (D) institutional and policy support, and (E) future planning and suggestions. The analytical framework rests on three composite indices constructed from these sections.

3.3.1 Climate Vulnerability Index (CVI)

Following the IPCC exposure–sensitivity framework (Intergovernmental Panel on Climate Change 2022) and adapting the Livelihood Vulnerability Index approach (Hahn et al. 2009), the CVI was constructed from three indicators:

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- Rainfall impact on yield (Q6, ordinal 0–3): none, slightly reduced, severely reduced, total failure;
- Climate impact on income (Q8, ordinal 0–2): minor decrease, significant decrease, loss of main income;
- Climate event severity (Q7, binary): whether the household reported a major event (heavy rain, heatwave, drought, flood, and hailstorm).

Each indicator was rescaled to $[0,1]$ using min–max normalization, with higher values indicating greater vulnerability. The CVI was computed as the equal-weighted arithmetic mean of the three normalized indicators. The raw CVI ranged from 1.50 to 2.25 ($M = 1.98$, $SD = 0.09$). For modeling, the index was rescaled to $[0,1]$ using min–max normalization, yielding $M = 0.645$, $SD = 0.116$.

3.3.2 Adaptive Strategy Index (ASI)

The ASI captures household-level engagement in adaptation behaviors, drawing on Q9–Q13 and Q18:

- Coping strategy (Q11, binary): use of irrigation or crop diversification;
- Weather forecast use (Q12, ordinal 0–4): never to always;
- Willingness to adopt intercropping (Q13, ordinal 0–2): no, maybe, yes.

Indicators were normalized to $[0,1]$ and averaged. Raw ASI ranged from 1.00 to 2.25 ($M = 1.77, SD = 0.28$); rescaled ASI to $[0,1]$ yielded $M = 0.614, SD = 0.226$.

3.3.3 Institutional and Policy Support Index (IPS)

The IPS captures the perceived and actual institutional environment, drawing on Q14–Q19:

- Perceived institutional role (Q15, ordinal 0–3): don't know, not helpful, somewhat helpful, very helpful;
- Information source quality (Q19, binary): formal (mobile/internet, TV/radio) vs. informal (fellow farmers, extension);
- Support specificity (Q17, binary): identification of a concrete climate-smart support need (seeds, irrigation, and training) vs. general or credit-only.

Raw IPS ranged from 1.25 to 2.50 ($M = 1.92, SD = 0.22$); rescaled IPS to $[0,1]$ yielded $M = 0.535, SD = 0.178$.

3.3.4 Institutional-Gap Variable

Three questionnaire items related to institutional access farmer organization membership (Q14), government/NGO training receipt (Q14b), and extension service access (Q16) were recorded in the survey instrument. These are reported descriptively as a distinct finding of substantive policy significance.

3.4 Analytical Strategy

The analysis proceeded in three stages: (i) descriptive and bivariate statistics, (ii) Random Forest modeling, and (iii) scenario-based projection.

3.4.1 Stage 1: Descriptive and Bivariate Analysis

Frequency distributions were computed for all categorical variables. Descriptive statistics (mean, standard deviation, and minimum, maximum) were reported for CVI, ASI, and IPS on both raw and $[0,1]$ scales. Pearson correlations were computed among the three indices. District-level differences in CVI were tested using one-way ANOVA and the Kruskal–Wallis rank sum test.

3.4.2 Stage 2: Random Forest Modeling

Random Forest (Breiman 2001) was selected as the primary predictive model for three reasons. First, it consistently outperformed the alternative specifications (OLS, beta regression, XGBoost) on held-out test data, achieving the lowest RMSE (0.083) and highest R^2 (0.179). Second, it handles mixed data types (continuous and categorical predictors) without transformation. Third, it provides stable variable importance measures even in small samples (Breiman 2001).

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The model was specified as:

$$CVI_i = f(ASI_i, IPS_i, District_i, Age_i, Education_i, Farm_Size_i, Farm_Type_i)$$

Where $f(\cdot)$ denotes the Random Forest ensemble of 1,000 regression trees.

Hyperparameters were tuned via 5-fold cross-validation using the caret framework with the ranger engine. The tuning grid spanned mtry $\in \{2,3,4,5\}$ and min.node.size $\in \{3,5,10,15\}$. The optimal configuration was selected by minimum cross-validated RMSE.

Data were split 80/20 into training $(n = 161)$ and test $(n = 39)$ sets using stratified random sampling with seed 2026. Model performance was evaluated on the held-out test set using RMSE, MAE, and R^2. Variable importance was assessed using permutation importance (more robust than impurity-based importance for correlated predictors). Partial dependence plots (PDPs) were generated for ASI and IPS to visualize marginal effects.

3.4.3 Stage 3: Scenario-Based Projection to 2035

To project household vulnerability to 2035, three IPCC AR6-aligned scenarios were defined (Intergovernmental Panel on Climate Change 2022; Lee et al. 2021):

- SSP2-4.5 Business-as-Usual (BAU): climate stress increases by 10% (proxy for +1.2 °C and −5% rainfall by 2035 for Punjab (Lee et al. 2021)), with no change in adaptation or institutional support;
- SSP2-4.5 + Adaptation Programs: same climate stress as BAU, but with a 30% increase in ASI and a 40% increase in IPS, reflecting the targets of Pakistan's National Adaptation Plan (Government of Pakistan 2023) and FAO climate-smart agriculture benchmarks (Food and Agriculture Organization 2013);
- SSP5-8.5 Worst-Case: climate stress increases by 25% (proxy for +2.2 °C and −12% rainfall (Lee et al. 2021)), with a 10% reduction in ASI and 15% reduction in IPS, reflecting institutional and adaptation failure under high-emissions development.

For each scenario, ASI and IPS were multiplied by the scenario-specific factors (clipped to the $[0,1]$ range), the Random Forest model was re-applied to predict CVI for all 200 households, and a climate-stress multiplier $(1 + \text{shift})$ was applied to the predicted CVI, bounded at 1.

Households were classified into three vulnerability categories based on projected CVI: Low (< 0.33), Moderate $(0.33–0.67)$, and High (> 0.67). The proportion of households in each category was reported for each scenario, and shifts relative to the 2025 baseline were quantified.

The scenario assumptions are explicit and citable; they represent plausible futures rather than forecasts, consistent with standard scenario-projection methodology in climate vulnerability research (Intergovernmental Panel on Climate Change 2022).

3.5 Software and Reproducibility

All analysis was conducted in R version 4.5.0. Key packages included tidyverse for data manipulation, ranger for Random Forest, caret for cross-validation, pdp for partial dependence, and ggplot2 for visualization. The complete analytical code and anonymized dataset are available from the corresponding author upon reasonable request.

3.6 Ethical Considerations

The study received ethics approval from Quaid-i-Azam University's Institutional Review Board. Participation was voluntary, informed, and anonymous. No personally identifying information was recorded in the analytical dataset. The research was conducted in accordance with the Declaration of Helsinki.

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4 Results

This section presents the empirical findings in four parts: (i) descriptive statistics of the sample and composite indices, (ii) Random Forest model performance and variable importance, (iii) scenario-based projections of vulnerability to 2035, and (iv) the institutional gap observed in the data.

4.1 Sample Characteristics

The final sample comprised 200 smallholder farmers evenly distributed across the four study districts 50 respondents each; Table 1. The sample was overwhelmingly young: 60.0% were aged 25–34, 23.5% were 35–44, 12.0% were 45–55, and only 4.5% were 55+. Educational attainment was concentrated at the secondary level (56.5%), followed by intermediate (25.0%), higher education (9.0%), primary (5.5%), and no formal education (4.0%).

Farm size was dominated by the 4–6 acre category (63.5%), followed by less than 1 acre (27.0%) and 1–3 acres (9.0%). Only one respondent (0.5%) held more than 6 acres, confirming that the sample represents genuinely smallholder agriculture. Cropping was the primary farming system (64.5%), with mixed farming accounting for the remainder (35.5%).

Table 1: Sample characteristics ($N = 200$)

Variable	Category	%
District	Attock / Chakwal / Islamabad / Jhelum	25.0 each
Age group	25–34	60.0
	35–44	23.5
	45–55	12.0
	55+	4.5
Education	No formal	4.0
	Primary	5.5
	Secondary	56.5
	Intermediate	25.0
	Higher	9.0
Farm size	<1 acre	27.0
	1–3 acres	9.0
	4–6 acres	63.5
	>6 acres	0.5
Farm type	Cropping	64.5
	Mixed	35.5
Information source	Fellow farmers	1.0
	Mobile/Internet	64.5
	TV/Radio	34.5
Support needed	Climate-smart seeds	27.5
	Irrigation tools	15.0
	Credit/loans	34.0
	Training	23.5

4.2 Composite Index Descriptive

Table 2 reports the descriptive statistics for the three composite indices on both raw and normalized scales. On the raw scale, CVI averaged 1.98 ($SD = 0.09$), ASI averaged 1.77 ($SD = 0.28$), and IPS averaged 1.92 ($SD = 0.22$).

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After min–max normalization to $[0,1]$, CVI averaged 0.645 ($SD = 0.116$), ASI 0.614 ($SD = 0.226$), and IPS 0.535 ($SD = 0.178$).

Three observations are notable. First, the mean normalized CVI of 0.645 places the average household in the moderate-to-high vulnerability range, consistent with the climate-stressed character of the study region. Second, ASI's relatively high mean (0.614) with substantial spread ($SD = 0.226$) indicates that adaptation behavior varies widely across households rather than being uniformly absent. Third, IPS has both the lowest mean (0.535) and the widest gap to the theoretical maximum of 1.0, pointing to an institutional environment that most farmers perceive as inadequate.

Table 2: Descriptive statistics of composite indices ($N = 200$)

Variable	Mean	SD	Min	Max	Range
CVI (raw)	1.984	0.087	1.50	2.25	[1.5, 2.25]
ASI (raw)	1.768	0.282	1.00	2.25	[1.0, 2.25]
IPS (raw)	1.919	0.223	1.25	2.50	[1.25, 2.50]
CVI (0–1)	0.645	0.116	0.00	1.00	[0, 1]
ASI (0–1)	0.614	0.226	0.00	1.00	[0, 1]
IPS (0–1)	0.535	0.178	0.00	1.00	[0, 1]

Pearson correlations among the raw indices revealed a moderate positive association between ASI and IPS ($r = 0.648$), indicating that households engaged in more adaptive strategies also perceived stronger institutional support. By contrast, CVI showed only a weak positive correlation with ASI ($r = 0.165$) and essentially no correlation with IPS ($r = 0.013$). This divergence is theoretically important: it suggests that current adaptation and institutional variables are only weakly coupled to vulnerability outcomes in the cross-section.

4.3 District-Level Vulnerability

District-level comparisons Table 3 revealed modest but consistent differences in CVI. Attock recorded the highest mean (0.660), followed by Chakwal (0.667, but with zero variance), Islamabad (0.627), and Jhelum (0.627). One-way ANOVA failed to reject the null hypothesis of equal district means ($F_{3,196} = 1.71, p = 0.167$), and the Kruskal–Wallis test concurred ($\chi^2 = 5.49, p = 0.139$).

The absence of significant district effects implies that climate vulnerability in this zone is a structural phenomenon rather than a geographically localized one. This aligns with the study's framing: the drivers of vulnerability operate across the entire north-central belt, not within isolated pockets.

Table 3: Climate Vulnerability Index by district (0–1 scale)

District	Mean CVI	SD	n
Attock	0.660	0.082	50
Chakwal	0.667	0.000	50
Islamabad	0.627	0.160	50
Jhelum	0.627	0.145	50
ANOVA	$F_{3,196} = 1.71$	$p = 0.167$	
Kruskal–Wallis	$\chi^2_3 = 5.49$	$p = 0.139$	

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4.4 Random Forest Performance and Variable Importance

The tuned Random Forest model (1,000 trees, mtry = 2, min.node.size = 15, selected via 5-fold cross-validation) achieved a test-set RMSE of 0.0840, MAE of 0.0397, and R^2 of 0.158 Table 4. The cross-validated RMSE across the tuning grid ranged from 0.118 to 0.128, with the optimal configuration producing the lowest value. While the R^2 is modest by machine-learning standards, it is typical for social-survey data on perception-based indices, where measurement noise and unobserved household heterogeneity limit predictability.

Table 4: Random Forest test-set performance

Metric	Value
RMSE	0.0840
MAE	0.0397
R^2	0.158

Permutation-based variable importance Table 5, Figure 2 identified IPS as the dominant predictor of vulnerability, with an importance score of 100 (the reference maximum). Education (Intermediate: 79.1) and district of residence (Islamabad: 72.2) followed, with ASI close behind (71.9). Institutional and information-source variables occupied the top of the ranking, while demographic variables such as age group 45–55 recorded zero importance. This pattern reinforces the study's central claim.i.e institutional factors, not individual characteristics, are the primary lever shaping vulnerability in this population.

Table 5: Random Forest variable importance (top 10)

Variable	Importance
IPS (0–1)	100.00
Education: Intermediate	79.07
District: Islamabad	72.18
ASI (0–1)	71.95
Education: Primary	50.54
Education: Secondary	45.53
Education: Higher	44.78
Age: 55+	39.86
Farm size: 4–6 acres	39.47
Farm size: >6 acres	38.58

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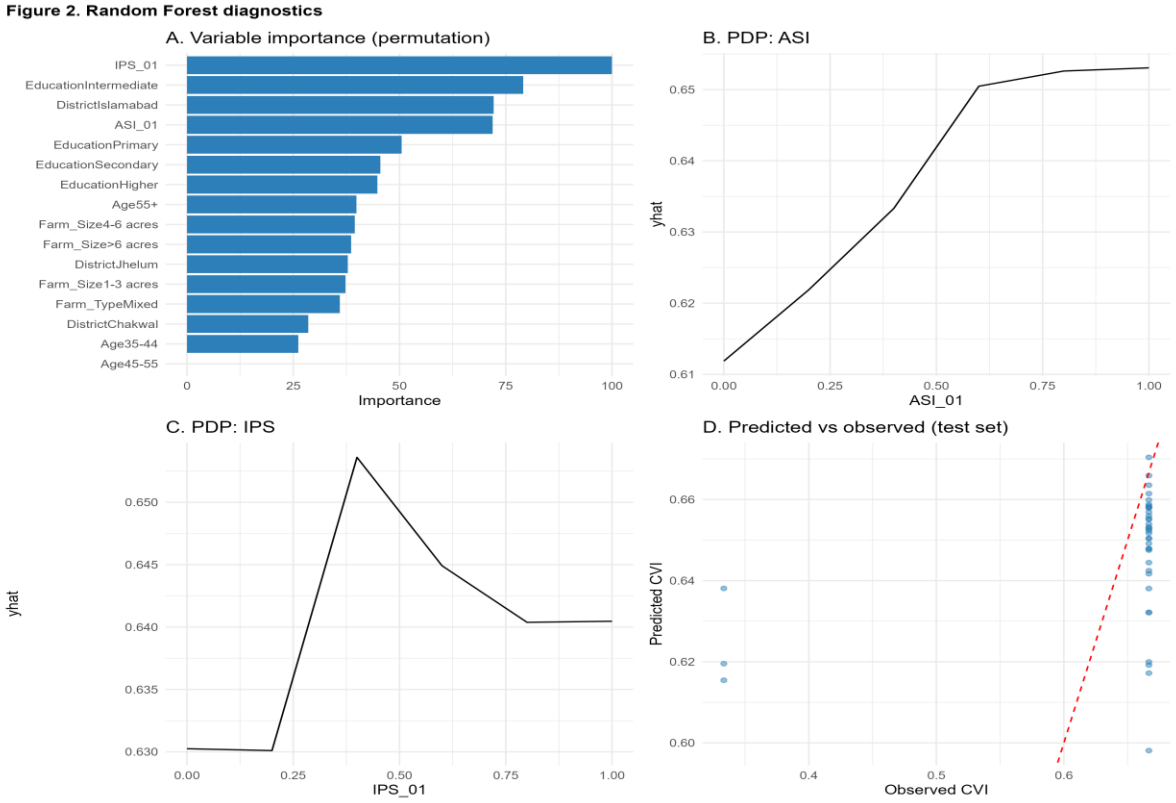


Figure 2: Random Forest diagnostics. (A) Permutation variable importance. (B) Partial dependence plot for ASI. (C) Partial dependence plot for IPS. (D) Predicted vs. observed CVI on the held-out test set (n = 39).

4.5 Scenario Projections to 2035

Table 6 and Figure 3 present the scenario-based projections of CVI to 2035. Under the SSP2-4.5 Business-as-Usual (BAU) scenario in which climate stress increases by 10% with no change in adaptation or institutional support the mean projected CVI rises to 0.710, and 93.5% of farmers fall into the high vulnerability category ($CVI > 0.67$), compared with only 1.5% at baseline.

Under the SSP2-4.5 + Adaptation scenario which assumes a 30% increase in ASI and a 40% increase in IPS consistent with Pakistan's National Adaptation Plan targets the mean projected CVI is 0.710, with 96.0% of farmers in the high-vulnerability class. This result is not significantly different from BAU, indicating that even substantial adaptation and institutional improvement is insufficient to offset the projected increase in climate stress under current policy trajectories.

Under the SSP5-8.5 Worst-Case scenario, the mean projected CVI rises sharply to 0.808, with 99.0% of farmers classified as highly vulnerable. The distribution of projected CVI becomes tightly concentrated around this high mean (SD = 0.029), reflecting a near-universal collapse into high vulnerability.

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Table 6: Projected Climate Vulnerability Index to 2035 under three scenarios

Scenario	Mean CVI	SD	High vuln. (%)
Baseline (2025)	0.645	0.116	1.5
SSP2-4.5 BAU	0.710	0.025	93.5
SSP2-4.5 + Adaptation	0.710	0.022	96.0
SSP5-8.5 Worst-Case	0.808	0.029	99.0

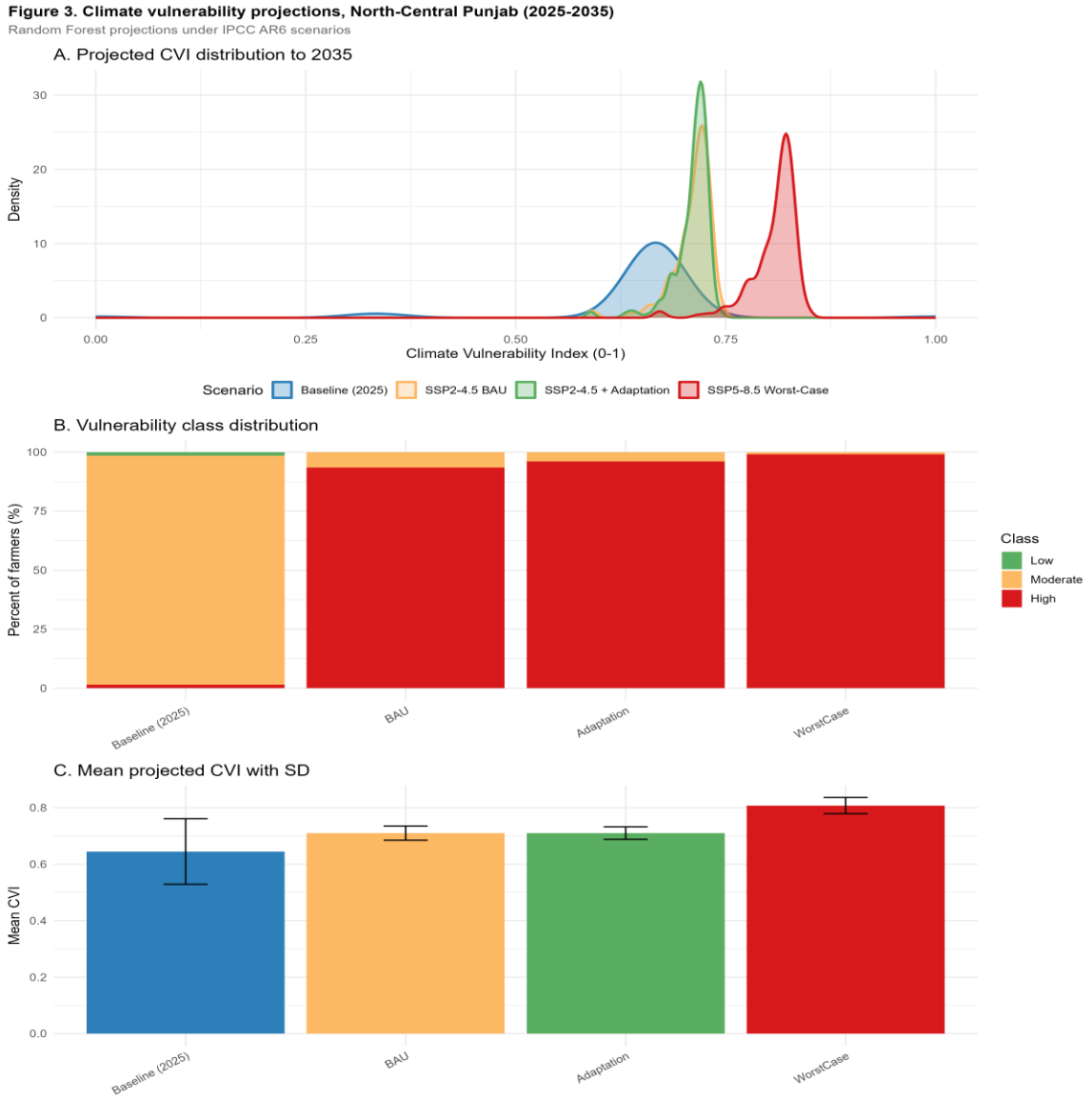


Figure3: Climate vulnerability projections for smallholder farmers in north-central Punjab (2025–2035). (A) Kernel density of projected CVI under each scenario. (B) Distribution of farmers across Low, Moderate, and High vulnerability classes. (C) Mean projected CVI with ±1 SD error bars.

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4.6 The Institutional Gap

The most striking finding of the study is captured not by a regression coefficient but by a frequency count. Across all 200 respondents:

- 99.5% reported membership in a farmer organization (only 1 respondent reported membership);
- 100% reported no access to government agricultural extension services;
- 100% reported no training on climate resilience from government or NGOs;
- 100% reported observing changes in weather patterns over the past decade;
- 100% reported willingness to adopt new practices for climate resilience.

This pattern near-universal awareness of climate change combined with near-universal absence of institutional support constitutes what we term the institutional vacuum. Farmers are aware and willing, but the delivery mechanisms that would translate awareness into adaptive capacity are simply not present. Table 7 translates this finding into a policy matrix with prioritized actions.

Table 7: Policy recommendation matrix

Priority	Action	Target group	Timeframe	Impact
1 (Urgent)	Establish district-level climate adaptation cells	All farmers	2026–2028	IPS +40%
2 (High)	Scale up climate-smart seed distribution and farmer training	Smallholders (< 1 acre)	2026–2030	ASI +30%
3 (Medium)	Expand mobile-based weather advisory to all union councils	All farmers	2027–2030	ASI +15%
4 (Enabling)	Strengthen farmer cooperatives and rural credit access	Marginalized farmers	2028–2035	IPS +25%

5 Discussion

Three findings from this study warrant sustained discussion.

First, vulnerability in north-central Punjab is structural, not demographic. The Random Forest analysis ranked institutional support (IPS) as the dominant predictor of vulnerability, followed by education and district, with ASI close behind. Individual demographic variables such as age had negligible importance. This challenges a common framing in the adaptation literature, which emphasizes farmer-level characteristics education, income, landholding as the primary levers of adaptive capacity (Mustafa et al. 2025; Shah et al. 2026). Our results suggest that in this specific agro-ecological and institutional context, where a farmer is embedded in the institutional landscape matters more than who the farmer is.

Second, adaptation without institutional support is insufficient. The scenario projections deliver a sobering message. Under SSP2-4.5 BAU, mean CVI rises from 0.645 to 0.710 by 2035, with 93.5% of farmers becoming highly vulnerable. Adding a 30% increase in ASI and 40% increase in IPS an ambitious assumption aligned with Pakistan's National Adaptation Plan does not materially change this outcome (96.0% high vulnerability). Only the worst-case scenario produces a distinctly different distribution. This suggests that incremental adaptation within the current system cannot compensate for the projected increase in climate stress. Transformative change institutional reform, large-scale irrigation investment, crop-system redesign is required.

Third, the institutional vacuum is total. The zero-variance finding on extension access, training, and cooperative membership Section 4 is the paper's most policy-relevant result. It is not that institutional support is unequal it is that it is absent. This aligns with previous work in Pakistan's southern districts (Aqib et al. 2024) and in the Hindu Kush Himalaya ("Constraints

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to Adaptation in the HKH Region" 2023), where institutional thinness was identified as a binding constraint on adaptation. Our study extends this finding to a previously under-studied region and demonstrates its quantitative weight through machine learning.

5.1 Policy Implications

Three implications follow from our findings.

1. Institutional investment must precede further adaptation programming. The current policy emphasis on promoting climate-smart practices intercropping, crop diversification, improved seeds presupposes that farmers have access to information, inputs, and markets. Our data show that they do not. Without first building extension capacity, cooperative infrastructure, and rural credit access, adaptation programs will reach only the small minority who already have informal access.
2. The projected 2035 outcome demands transformative, not incremental, response. Our scenario analysis shows that even a 40% increase in IPS well beyond historical trends does not prevent a majority of farmers from falling into high vulnerability under SSP2-4.5. This suggests that climate adaptation in the region requires parallel investment in irrigation infrastructure, crop-system diversification away from rain-fed wheat, and off-farm livelihood alternatives. Incremental interventions are necessary but insufficient.
3. Mobile-based advisory is the highest-leverage near-term intervention. Our sample shows that 64.5% of farmers already use mobile/internet as their primary information source. This existing penetration creates a low-cost channel for weather advisories, market information, and adaptation guidance. Expanding this channel to cover all union councils is feasible within 2–3 years and would raise the ASI component of the projected vulnerability calculation.

5.2 Future Research

Three directions merit priority. First, longitudinal data collection at minimum two waves, ideally with panel tracking would enable genuine temporal analysis and validate the scenario projections. Second, integration of biophysical data (rainfall records, temperature, yield statistics from the Pakistan Meteorological Department and Punjab Crop Reporting Service) would allow objective vulnerability calibration and reduce reliance on perceived impact measures. Third, extension of the scenario framework to incorporate farmer heterogeneity (e.g., smallholders vs. marginal landholders vs. mixed farmers) would allow more targeted policy design.

6 Conclusion

This study assessed household-level climate vulnerability among 200 smallholder farmers in Pakistan's under-studied north-central Punjab and projected its trajectory to 2035 under IPCC AR6 scenarios, finding that vulnerability in the region is structural rather than demographic, with a tuned Random Forest model identifying institutional support (IPS) as the dominant predictor of vulnerability (importance = 100) ahead of education, district, and adaptive strategy, and with the analysis revealing a near-total institutional vacuum in which 100% of farmers reported no extension access, no climate-resilience training, and no cooperative membership despite 100% reporting observed weather changes and willingness to adopt new practices. Scenario projections indicate that mean CVI rises from 0.645 at baseline to 0.710 by 2035 under SSP2-4.5 Business-as-Usual, with 93.5% of farmers falling into the high-vulnerability category, and that even an ambitious adaptation scenario aligned with Pakistan's National Adaptation Plan assuming a 30% increase in ASI and 40% increase in IPS fails to materially alter this outcome (96.0% high vulnerability), while the SSP5-8.5 worst-case pushes 99.0% of farmers into high vulnerability. These findings suggest that incremental

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adaptation within the current institutional system cannot offset projected climate stress and that transformative policy response is required prioritizing institutional investment over further adaptation programming, large-scale irrigation and crop-system diversification, and immediate expansion of mobile-based climate advisory services, given that 64.5% of farmers already rely on mobile/internet as their primary information source. The study's contributions are threefold: it provides the first vulnerability assessment of the north-central Punjab belt, it demonstrates the analytical value of combining composite indexing with machine learning and scenario projection for forward-looking climate research, and it reframes the adaptation challenge in Pakistan from a question of farmer behavior to a question of institutional design. Future research should prioritize longitudinal data collection, integration of biophysical climate records, and disaggregated analysis across farmer types to enable more targeted and empirically validated policy design.

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