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REVIEWED BY

Ramadas Sendhil,
Pondicherry University, India
Geetilaxmi Mohapatra,
Birla Institute of Technology and Science,
India

*CORRESPONDENCE

Bharath Kumar Mannepalli
✉ bharath.m@bhu.ac.in

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The adaptation triangle: a multivariate analysis of vulnerability, resilience and livelihood strategies in semi-arid regions of India

Bharath Kumar Mannepalli^{1*}, Saket Kushwaha¹,
Virendra Kamalvanshi¹, Pradip Kumar Parida², Evans Kemboi¹,
Ankit Yadav¹, Prakhar Deep¹ and Reshmi Mukherjee¹

¹Department of Agricultural Economics, Banaras Hindu University, Varanasi, UP, India, ²Centre for Comparative Politics & Political Theory, School of International Studies, Jawaharlal Nehru University, New Delhi, India

India's semi-arid regions covering 37% of its geographical area were among the most climate-vulnerable ecosystems globally characterized by erratic rainfall, intense heat and fragile livelihoods. Despite extensive research, few studies have comprehensively investigated household vulnerability, resilience and their interplay in these dry regions. This study formulates the "adaptation triangle" framework to examine the interlinkages among livelihood strategies, vulnerability and resilience. Employing a multistage stratified random sampling methodology, primary data was collected from 375 households in Rajasthan, Telangana and Tamil Nadu, encompassing 69 socioeconomic, environmental and institutional factors. Composite indices for household livelihood vulnerability (HLVI) and resilience (HRI) were constructed in accordance with IPCC and FAO guidelines. Multivariate linear regression was employed to investigate the influence of 13 livelihood strategies on HLVI and HRI, while multinomial logistic regression evaluated their effect on household transitions within the vulnerability-resilience matrix's four quadrants. National-level data indicates moderate vulnerability (HLVI = 0.517) and low resilience (HRI = 0.489) with 37.07% of households categorized in the most at-risk high vulnerability-low resilience (HVLR) quadrant. Key adaptive strategies such as income diversification, rainwater harvesting, adjusting sowing dates and adoption of crop and livestock insurance were found to substantially reduce vulnerability and enhance resilience. Households dependent on casual labor face heightened climate risk was also found to be significant. This study reinforces that livelihood choices are not only survival responses but pivotal levers in shaping climate adaptation outcomes. Policy recommendations include promoting diversified and climate-resilient livelihoods, expanding social safety nets, scaling up insurance access, microfinances and investing in water harvesting and agro-ecological infrastructure. The adaptation triangle framework provides a valuable lens to inform targeted interventions and build long-term resilience among vulnerable populations in India's semi-arid regions.

KEYWORDS

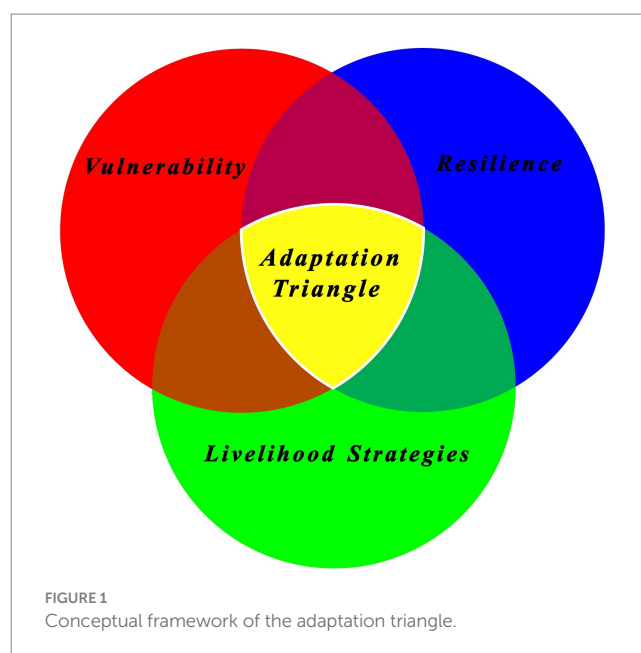
climate change, vulnerability, resilience, adaptation, livelihood strategies, semi-arid agriculture

1 Introduction

At present climate change is an unparalleled challenge for the global countries, manifesting its impacts in diverse forms across the planet. It has ushered in a new era of uncertainty, particularly in regions characterized by environmental fragility and socio-economic vulnerability. In terms of climate extremes, India was the seventh-most vulnerable country (Mohanty and Wadhawan, 2021). The semi-arid zones make up a significant 37% of India's total geographical area (Kalsi, 2007) and they were characterized by irregular rainfall, elevated temperatures and the ecosystems hanging in the balance. These regions had become pools of adversity in the era of climate change marred by a variety of environmental fragility, socio-economic vulnerability and the continuous attack of unpredictable climatic extremes. It was uncharted territory where the effects of climate change hit especially hard (Ramilan et al., 2022; Ye et al., 2022). These regions were even more at risk because of their unique characteristics adding urgency to the need for a closer look at how they are affected and how they are adapting.

Households in semi-arid India reliant primarily on agriculture and allied activities, confront unique vulnerabilities triggered by climate change. Climate-induced disruptions in agriculture, water resources and ecosystems can lead to food insecurity, displacement, loss of income and even social unrest. The burgeoning impacts of climate change marked by soaring temperatures, erratic precipitation and escalation of extreme weather phenomena, further emphasize these vulnerabilities (IPCC, 2014). As the impacts of climate change escalate, these vulnerabilities undermine the resilience of the most affected households jeopardizing their capacity to sustain the livelihoods in face of evolving environmental challenges (Sam et al., 2016). Therefore, it becomes imperative for policymakers to comprehend the intricate dynamics of vulnerability, resilience and livelihood strategies in these regions. Such understanding is pivotal for formulating policies that address the unique challenges faced by households heavily dependent on agriculture and allied activities, ensuring the resilience of livelihoods in the ever-changing climate landscape (Janssen et al., 2006).

In this challenging settings the nexus between vulnerability, resilience and livelihoods assumes critical significance. Traditional approaches that examine these dimensions in isolation are increasingly insufficient. Instead, there is an urgent need for integrative frameworks that recognize their interdependence. The adaptation triangle framework was employed in this study as a conceptual and analytical lens in response. As shown in Figure 1 the adaptation triangle framework articulates livelihood strategies were not merely passive outcomes but rather deliberate choices influenced by the dynamic, interdependent forces of vulnerability and resilience. The framework offers a more comprehensive and practical approach to climate adaptation by emphasizing the simultaneous reduction of vulnerability, improvement of resilience and backing of sustainable livelihoods. This approach reflected the literatures calls for integrated analysis. According to Gallopín (2006) vulnerability and resilience were related concepts that need to be evaluated in tandem in order to comprehend system dynamics. In the same way, Cutter et al. (2008) emphasized on frameworks that connect resilience capacities and social vulnerability in order to offer a comprehensive understanding of community-level responses. More recently, Tanner et al. (2015) showed how livelihood strategies determine adaptive capacity in



climate-affected regions demonstrating that livelihoods serve as the link between vulnerability and resilience. Livelihood resilience frameworks were operationalized in studies like Quandt (2018) and Speranza et al. (2014) that measured how strategies reduce vulnerability and influence adaptation outcomes. The vulnerability and adaptation frameworks were further integrated by Reed et al. (2013) highlighting the importance of integrative approaches for policy relevance. Recognizing this interdependence was crucial for designing holistic, context-sensitive policy responses that move beyond mere technical approaches towards building genuinely adaptive communities. Ultimately this study endeavors to bridge critical knowledge gaps by providing a grounded understanding of the adaptation triangle in the semi-arid contexts of India. In doing so, it contributes not only to academic research but also to the formulation of evidence-based, community-centric adaptation policies that are urgently needed in the era of escalating climate change (Janssen et al., 2006).

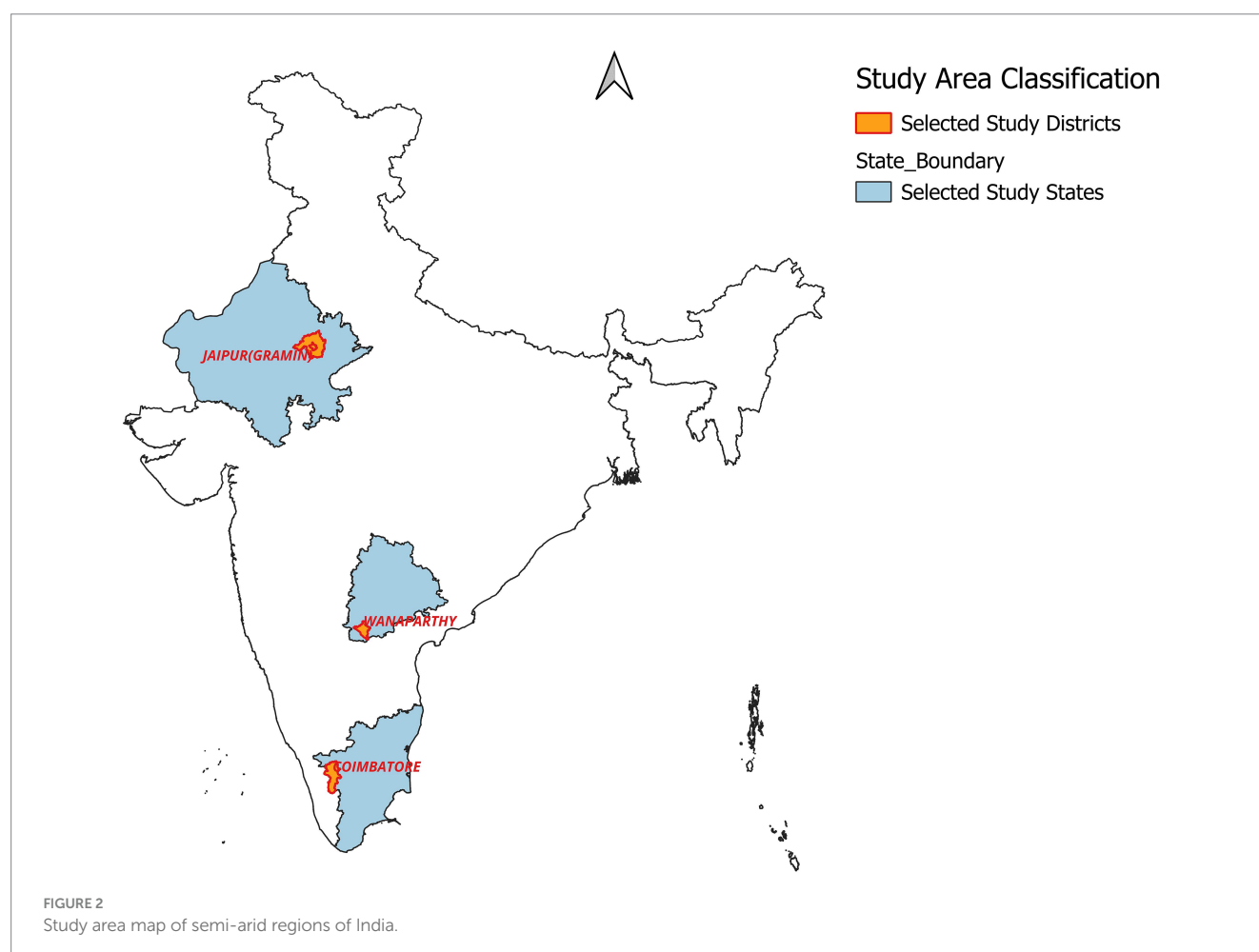
The national research landscape pertaining to vulnerabilities, resilience and livelihoods within India have primarily focused on individual dimensions rather than delving into their intricate relationships. Existing studies have notably addressed isolated aspects of vulnerabilities (Mohanty and Wadhawan, 2021; Sam et al., 2016) and resilience (Mondal et al., 2023; Jayadas and Ambujam, 2021). Compared to vulnerability, a few research efforts have investigated resilience and emphasized on experiential knowledge (Mishra and Suar, 2007), adaptive capacities (Jayadas and Ambujam, 2021) and climate resilience finance (Noels et al., 2024; Dasgupta and Sharma, 2025) within remote regions. Most of these studies have predominantly emphasized community-based and geographic-based vulnerability and resilience, ignoring the individual households valuable insights and contextual factors. A noticeable gap exists in the comprehensive examination of the interconnected dynamics between resilience, vulnerability and livelihoods strategies to the climate change adaptation within semi-arid regions.

Numerous studies have explored the complex relationship between resilience and vulnerability across diverse contexts. Scholars

have conceptualized them both as opposing forces and overlapping dimensions (Gallopín, 2006; Cutter et al., 2008; Maru et al., 2014; Usamah et al., 2014; Joakim et al., 2015; Ha-Min et al., 2020). It was widely acknowledged that vulnerability and resilience were not mutually exclusive and often coexist within communities (Adger, 2006) with some studies suggesting that vulnerabilities themselves can paradoxically foster resilience (Eriksen and Brown, 2011). Factors such as the adoption measures (O'Brien et al., 2007), geographic variability (Cutter et al., 2008) and socio-economic conditions (O'Brien et al., 2007) have been shown to influence the vulnerability-resilience dynamic. While previous research has illuminated the co-existence of vulnerability and resilience (Ha-Min et al., 2020) a critical gap remains in understanding how livelihood strategies shape this interplay. Specifically, limited attention has been given to how household-level livelihood choices influence the adaptive capacity of communities, particularly in semi-arid regions where agriculture and allied activities form the backbone of survival strategies. Building on previous research that sheds light on the multiple linkages between resilience and vulnerability, this study examines how livelihood characteristics influence this relationship. To answer this, the following research questions were framed: “How vulnerability and resilience interact in the context of climate change in semi-arid regions of India? and how do they influence household livelihoods to inform effective adaptation strategies for vulnerable households to the climate change?”

2 Materials and methods

The study focused on semi-arid regions constituting approximately 37% of India's geographic area. A multistage stratified random sampling framework was employed in this study to ensure robust representation of spatial and socio-ecological heterogeneity across three semi-arid states which represent the western, central and southern semi-arid agro-ecological zones of India: Rajasthan, Telangana and Tamil Nadu as shown in Figure 2. These states were selected in particular because of their distinct drought profiles and climate factors such as long-term variations in temperature, precipitation, drought vulnerability etc. (Rao et al., 2013; Dasgupta et al., 2024). District profiles pertaining to these climatic factors were used to select the districts such as Jaipur (Rajasthan) falls under high to very high vulnerability, Wanaparthy (Telangana) as medium vulnerability and Coimbatore (Tamil Nadu) was categorized as low to medium vulnerability. A Modified Menn-Kendall (MMK) test (Mann, 1945; Kendall, 1975; Hamed and Rao, 1998) was also used on long-term rainfall and temperature data of the study area to know the climatic trends. This stratified selection was developed to make sure that the analysis captures the socioeconomic and agroclimatic diversity in resilience outcomes as well as the wide variety of vulnerabilities observed throughout India's semi-arid regions. Two blocks were selected within each district and then five villages were randomly selected within each block, for a total of ten villages per



district. In order to ensure accurate representation of intra-regional diversity in vulnerability and resilience patterns, a minimum of twelve households each village were chosen at random, resulting in an overall sample of approximately 375 households. Determination of total sample size was done by employing Cochran's finite population formulae of Equations 1, 2 as we know the total household population size of the study area is 15,854.

$$n_0 = \frac{Z^2 \cdot p \cdot (1-p)}{e^2} = \frac{1.96^2 \cdot 0.5 \cdot (1-0.5)}{0.05^2} = 384.16 \approx 385 \quad (1)$$

Equation 1 is employed to estimate an ideal sample size for a desired level of precision (Cochran, 1977) where n_0 is the initial sample size for infinite population, Z is the confidence interval, i.e., Z -value, p is the percentage of the population that shares the attribute and e is the desired precision level of the margin of error.

$$n = \frac{n_0}{1 + \frac{n_0 - 1}{N}} = \frac{384.16}{1 + \frac{384.16 - 1}{15854}} = 375.12 \approx 375 \quad (2)$$

We employed the Equation 2 for adjusting the initial sample size with the known population size where n is the adjusted sample size with the population, n_0 is the initial sample size for infinite population and N is the total household population size of the study area.

The MMK test was used to find long-term trends in temperature and rainfall. The Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) is a non-parametric rank-based method extensively utilized in hydrology and climatology due to its independence from the assumption of normality and its ability to adapt to outliers. The classical MK test presumes the independence of observations, a condition frequently contravened in climatic time series owing to serial correlation. Positive autocorrelation increases the MK statistic's variance, which could lead to inaccurate trend detection. To rectify this issue the MMK test introduced by Hamed and Rao (1998) was utilized which adjusts the variance of the MK statistic by accounting for autocorrelation via the effective sample size. This yields more dependable significance levels for trend estimation. This study analyzed annual average rainfall (1901–2024), mean annual maximum temperature (T_{max} ; 1951–2024) and mean annual minimum temperature (T_{min} ; 1951–2024) sourced from IMD gridded datasets (Srivastava et al., 2009; Pai et al., 2014). The test was performed at a 5% significance level with positive and negative standardized Z values signifying ascending and descending trends, respectively.

To assess resilience and vulnerability interplay, household resilience index (HRI) and the household livelihood vulnerability index (HLVI) were developed by using a similar methodology which was also used for calculating the “human development index (HDI),” “climate vulnerability index (CVI),” “household livelihood vulnerability index” and “livelihood vulnerability index” (IPCC, 2014; Sam et al., 2016; FAO, 2016a, 2016b; Ha-Min et al., 2020). Major components (for vulnerability and resilience as given in Tables 1, 2 respectively) and sub-components were identified and assigned weights based on equal distribution. Normalization Equations 3, 4 was applied for standardization based on the assumption that particular subcomponents positive or negative relationship with the vulnerability and resilience (Sam et al., 2016). Once the data have been normalized,

indicators then averaged using Equation 5 to get the value of the major components for each household. Equations 6, 7 were used to generate HLVI and HRI, respectively.

$$Index X_s = \frac{X_s - X_{min}}{X_{max} - X_{min}} \quad (3)$$

$$Index X_s = \frac{X_{max} - X_s}{X_{max} - X_{min}} \quad (4)$$

where X_s is the normalized index value and X_s is the original value of the indicator for household S , X_{max} and X_{min} are the maximum and minimum values of the indicator at the household level.

$$M_s = \frac{\sum_{i=1}^n Index X_s}{n} \quad (5)$$

where M_s is the major component index affecting household S and X_s index, the number of indicators for each major component is denoted by n and i is the normalized value of the i^{th} indicator for household S .

$$HLVI = (SDP \times W_i) + (LS \times W_{ii}) + (SN \times W_{iii}) + (H \times W_{iv}) + (W \times W_v) + (F \times W_{vi}) + (D \times W_{vii}) \quad (6)$$

$$HRI = (IFA \times W_i) + (APS \times W_{ii}) + (SSN \times W_{iii}) + (AC \times W_{iv}) + (A \times W_v) \quad (7)$$

where, for Equations 4, 5 HLVI = household livelihood vulnerability index and HRI = household resilience index and the explanatory variables are the probable major components of HLVI & HRI given in the Tables 1, 2. The weight assigned to each major component is denoted by the W , which is based on the idea that each indicator should be given equal weight. This maintains structural balance for interactive analysis between HLVI and HRI by ensuring that no one dimension drives the index disproportionately. In order to maintain comparability and transparency, equal weighting had also been used in similar vulnerability and resilience interactive studies (Ha-Min et al., 2020; Nunes, 2021).

HLVI and HRI were graphically represented for each household categorizing them into patterns based on vulnerability and resilience scores. Four possible co-existence patterns were identified: high vulnerability & high resilience; high vulnerability & low resilience; low vulnerability & high resilience and low vulnerability & low resilience. This graphical representation aids in identifying and understanding the diversity of resilience and vulnerability profiles among households in the study area, offering valuable insights for your research work.

A two-step quantitative approach was employed to assess the influence of household livelihood strategies on their vulnerability and resilience aspects in semi-arid regions of India. First, a multivariate linear regression model was estimated, where two dependent variables HLVI and HRI were regressed simultaneously on a common set of thirteen livelihood strategies as shown in the Equation 8. Multivariate linear regression was selected as continuous dependent variables

TABLE 1 Major and sub-components under HLVI.

Major component	Sub-components	Unit of measurement	Functional relationship	Explanation
Socioeconomic demographic profile (SDP)	Dependency ratio	Ratio	Positive	Proportion of population aged <18 and >65 to population aged 19–64 (Sam et al., 2016; Ha-Min et al., 2020).
	Household head gender	Binary (male/female)	Negative	Households led by female are regarded as more vulnerable (Aiswarya et al., 2023).
	Education levels of households head	Ordinal (illiterate, primary, secondary, graduate and above)	Negative	Higher education enhances adaptive capacity (Brody et al., 2008; Sam et al., 2016).
	Social category of the households	Categorical (forward/backward)	Negative	Marginalized groups are more at risk because they do not have limited access to resources (Kuchimanchi et al., 2019; Sam et al., 2016).
	Housing structure	Categorical (kutcha/semi-pucca/pucca)	Negative	Poor housing quality increases vulnerability to shocks (Sam et al., 2016).
Livelihood strategies (LS)	Diversification of the livelihood	Index	Negative	Diversified livelihoods reduce vulnerability (Sam et al., 2016).
	No. of members of family dependent on agriculture	Count	Positive	Vulnerability increases with greater dependence on agriculture (Sam et al., 2016).
	No. of members of family migrated	Count	Negative	Migration reduces vulnerability by diversifying sources of income (Banerjee et al., 2018; Jha et al., 2018)
	Diversification of the livestock	Index	Negative	Vulnerability can be reduced through multiple livestock varieties (Sam et al., 2016).
	Diversification of the assets	Index	Negative	Asset diversity improves coping capacity by reducing vulnerability (Carter and Barrett, 2006; Habib et al., 2023).
Social networks (SN)	Assistance from the NGO's/SHG's	Binary(yes/no)	Negative	Access to external support reduces vulnerability (Demon, 2022).
	Formal and informal credit institutions access/time	Binary (yes/no)	Positive	Available credit sources reduces the households vulnerability (Ghosh, 2020).
	Access/time to banks for households	Minutes (one-way)	Positive	Vulnerability increases with the average time it takes to reach to the nearest bank (Ghosh, 2020).
	Households access/time to school	Minutes (one-way)	Positive	Average time taken to reach schools increases household vulnerability in the long term (Sam et al., 2016; Das and Das, 2023).
Health (H)	Households encountering drought-related diseases	Binary (yes/no)	Positive	More diseases caused by drought increase households vulnerability (Tiwari et al., 2022).
	Public health center access/time	Minutes (one-way)	Positive	Households are more vulnerable as time taken to reach health centers increases (Weiss et al., 2020).
	Health insurance for households	Binary (yes/no)	Negative	Households without health insurance are more susceptible to illness-related financial shocks (Reshmi et al., 2021).
	Monthly average health expenditure for households	INR	Positive	Households that spend more on health care are more susceptible to financial strain (Xu et al., 2003).

(Continued)

TABLE 1 (Continued)

Major component	Sub-components	Unit of measurement	Functional relationship	Explanation
Water (W)	Households depending on the public resources for household activities	Percent	Negative	Dependency on public resources signals that there aren't adequate secure private sources. (Sam et al., 2016).
	Households depending on the natural resources for household activities	Percent	Positive	Climate fluctuation makes households who depend on natural sources more vulnerable (Sam et al., 2016).
	Households access water for household activities	Percent	Negative	Secure water access reduces vulnerability (Sam et al., 2016).
	Households access water for irrigation	Percent	Negative	Higher irrigation access lowers vulnerability (Sam et al., 2016).
Food (F)	Households consume insufficient food over a period of a year	Binary (yes/no)	Positive	Insufficient food consumption indicates vulnerability to food insecurity (Coates et al., 2007).
	Average number of months that households struggles in affording food	Count	Positive	More months of struggle for affording food indicates higher vulnerability (Coates et al., 2007).
	Average monthly household food expenditure	INR (continuous)	Negative	Lower food expenditure reflects weaker purchasing capacity and higher vulnerability (Coates et al., 2007).
	Households that rely on their own farm food	Percent	Positive	Own farms protect against market food price fluctuations but run the risk of crop failure (Sam et al., 2016).
	Household reliant on the public distribution system	Percent	Negative	PDS reduces food insecurity (George and McKay, 2019).
Drought (D)	Diseases due to drought	Binary (yes/No)	Positive	Diseases due to drought and high temperatures increase household vulnerability (Tiwari et al., 2022).
	Yield reduction due to drought	Percent	Positive	Greater yield reduction by drought increases household vulnerability (Leng and Hall, 2019).
	Reported increment of average temperatures	Binary (yes/no)	Positive	Households perceiving increased temperatures are more vulnerable (Jha and Gupta, 2021).
	Reported variation in average rainfall	Binary (yes/no)	Positive	Households perceiving rainfall variation are more vulnerable (Jha and Gupta, 2021).

TABLE 2 Major and sub-components for HRI.

Major component	Sub-components	Unit of measurement	Functional relationship	Description
Income and food access (IFA)	Total income of the households	INR/year	Positive	Increased income enhances resilience, recovery and coping (Ramilan et al., 2022).
	Per capita expenditure of the households	INR/person	Positive	Higher per capita spending improves household resilience and lowers food insecurity (Ramilan et al., 2022).
Access to public services (APS)	Time taken to nearest health center	Minutes (one-way)	Negative	Longer travel times result in reduces timely care and worse during climate-related health events (Srivastava et al., 2003).
	Time taken to nearest health school	Minutes (one-way)	Negative	Time and distance limits reduce educational opportunities, weakening human capital, a fundamental resilience capacity (Das and Das, 2023).
	Time to the closest veterinary center	Minutes (one-way)	Negative	Lack of access to vets compromises livestock-based resilience by delaying treatment and preventive treatments (Ahuja et al., 2003).
	Time taken to nearest market center	Minutes (one-way)	Negative	Improved transportation connectivity improves channel choice and price realization strengthening income buffers (Negi et al., 2018).
	Access to early warning systems	Binary (yes/no)	Positive	EWS and preparedness at the household level reduce disaster losses and allow for proactive measures (Sahana et al., 2023).
Social safety nets (SSN)	Food from Government or NGO's	Binary (yes/no)	Positive	PDS transfers increase household food resilience by cushioning consumption during shocks (George and McKay, 2019).
	Remittances of the households	INR/year	Positive	Remittances diversify income and economic adaptation (Banerjee et al., 2017; Banerjee et al., 2018)
	Households cash-for-work	Binary (yes/no)	Positive	Public works reduce risk and facilitate consumption; NREGA responds counter-cyclically to heat/drought (Patwardhan and Tasciotti, 2022).
Adaptive capacity (AC)	Households herds composition change	Binary (yes/no)	Positive	Diversifying species and breeds is an adaptation that protects against diseases and climate shocks (Singh and Kerven, 2023).
	Households mobility and herd splitting	Binary (yes/no)	Positive	Mobility and splitting are traditional drought-coping strategies for maintaining herds and income (Louhaichi et al., 2015).
	Households combining livestock production with crop farming	Binary (yes/no)	Positive	Higher and more steady incomes, food security are the outcomes of integrated systems that diversify outputs and recycle resources (Shanmugam et al., 2024).
	Households access to extension services	Binary (yes/no)	Positive	Extension enhances adoption of adaptive practices (Jha and Gupta, 2021).
	Households education level	Ordinal	Positive	Education reliably predicts adaptation capacity in Indian farm studies (Jha and Gupta, 2021).
	Number of income sources of the households	Count	Positive	Diversification (farm/non-farm) buffers shocks observed for Indian agriculture (Birthal and Hazrana, 2019).

(Continued)

TABLE 2 (Continued)

Major component	Sub-components	Unit of measurement	Functional relationship	Description
Assets (A)	Farm equipment and improved seed supply for the households	Count	Positive	Improved seeds and farm equipment increase resilience by increasing production and lowering yield losses spurred on by climate change (Sahoo et al., 2025).
	Adult labor	Count	Positive	Greater labor endowment expands coping/adaptation options (Ramilan et al., 2022)
	Livestock owned	Count	Positive	Livestock serves to smooth income and provide collateral and savings (Ramilan et al., 2022)
	Access to irrigation water	Binary (yes/no)	Positive	Access to irrigation is often associated with greater resilience to rainfall shocks (BIRTHAL, 2022).
	Households access to credit	Binary (yes/no)	Positive	When shocks hit, credit allows for adaptation and consumption moderation (Chosh, 2020).
Stability (S)	Farm land owned by the households	Acres	Positive	In Indian farming systems, land is a critical productive resource that supports the resilience of food and income (Ramilan et al., 2022).
	Livestock Loss	Binary (yes/no)	Negative	Preserving vital livelihood assets through preventing livestock loss maintains resilience (Mekuyie et al., 2018).
	Market (price, supply and demand) shocks due to drought	Binary(yes/no)	Negative	Crop failures weaken resilience by upsetting farmer terms of trade and local agri-markets (David et al., 2023).
	Death of family member's due to climate shock	Binary (yes/no)	Negative	When households are able to cope with climate-related mortality shocks, household resilience increases (Mekuyie et al., 2018).

(HRI, HLVI) need to be regressed by several livelihood strategies. Second, a multinomial logistic regression model was applied to predict four quadrant membership based on livelihood strategies, considering the interaction between vulnerability and resilience by using Equation 9. To account for nonlinear relationships, multinomial logistic regression was utilized to model categorical transitions across quadrants.

$$\begin{bmatrix} HLVI_i \\ HRI_i \end{bmatrix} = \begin{bmatrix} \beta_{oV} \\ \beta_{oR} \end{bmatrix} + \sum_{k=1}^{13} \begin{bmatrix} \beta_{kV} \\ \beta_{kR} \end{bmatrix} LS_{ik} + \begin{bmatrix} \epsilon_{iV} \\ \epsilon_{iR} \end{bmatrix} \quad (8)$$

Where LS_{ik} is the Adoption status of the k^{th} livelihood strategy by household i , β_{kV}, β_{kR} were the coefficients representing the marginal impact of each strategy and $\epsilon_{iV}, \epsilon_{iR}$ were the error terms allowing correlation between HLVI and HRI.

$$\ln \left(\frac{P(Y_i = j)}{P(Y_i = 2)} \right) = \alpha_j + \sum_{k=1}^{13} \theta_{jk} \cdot LS_{ik} + e_{ij} \quad (9)$$

Where Y_i is quadrant membership for household i , α_j intercept for category j , θ_{jk} coefficient of the k^{th} livelihood strategy for category j and e_{ij} random error term.

3 Results

The MMK test results shown strong proof of substantial shifts in climate in the study districts as shown in the Table 3. In Coimbatore, both T_{max} and T_{min} showed statistically significant upward trends which means that the temperature is consistently rising. Rainfall on the other hand did not show any significant trend. Jaipur showed a strong positive trend in both rainfall and T_{min} . This means that the amount of rain gets unpredictable as the minimum temperature rises. However, the latter was only close to being significant in one test. There was substantial increase in both rainfall and temperature in Wanaparthi with T_{min} showing the strongest signal ($Z = 8.34$). The Sen's slope estimates provide these patterns greater depth by showing that temperatures are rising steadily across districts ($0.010-0.021^\circ C/yr$) and that rainfall was only modestly rising (up to 1.6 mm/yr). These Sen's slopes along with the MMK results shown clear signs of climate change in the study areas such as rising temperatures and changes in precipitation that were specific to each region. Plots illustrating these trends were also provided in the Supplementary materials.

3.1 Household livelihood vulnerability and household resilience indices for semi-arid regions of India

Table 4 presents the seven components that were used to build the HLVI: livelihood strategies (LS), socioeconomic demographic profile (SDP), social networks (SN), water (W), food (F), health (H) and drought (D). Analysis results reveal a moderate level of vulnerability throughout the semi-arid zones with an all-India HLVI value of 0.517. Among components, livelihood strategies (0.113) contributed significantly to the national HLVI suggesting continued dependence

TABLE 3 Modified Mann-Kendall and Sen's slope test for the climatic variables of the study districts.

District	Variable	Trend	p _value	Z	Tau	S	VarS	Sen Slope
Wanaparthy (Telangana)	Rainfall	Increasing	0.022	2.283	0.139	1,058	214375.3	1.069
	T _{max}	Increasing	0.000	8.342	0.492	1,329	25342.87	0.016
	T _{min}	Increasing	0.002	3.033	0.248	669	48521.59	0.005
Coimbatore (Tamil Nadu)	Rainfall	No trend	0.111	1.592	0.097	738	214375.3	0.735
	T _{max}	Increasing	0.000	5.956	0.608	1,641	75807.33	0.019
	T _{min}	Increasing	0.032	2.143	0.357	963	201491.9	0.010
Jaipur (Rajasthan)	Rainfall	Increasing	0.000	4.114	0.184	1,400	115648.9	1.599
	T _{max}	No trend	0.057	1.905	0.164	443	53822.21	0.007
	T _{min}	Increasing	0.000	4.735	0.476	1,287	73750.13	0.021

TABLE 4 Household livelihood vulnerability index for semi-arid regions of India.

State	SDP	LS	SN	H	W	F	D	HLVI
Telangana	0.101	0.115	0.039	0.036	0.064	0.079	0.090	0.525
Tamil Nadu	0.094	0.114	0.027	0.040	0.047	0.071	0.095	0.487
Rajasthan	0.090	0.111	0.075	0.036	0.045	0.071	0.105	0.533
India	0.094	0.113	0.050	0.037	0.051	0.073	0.097	0.517

on climate-sensitive agricultural livelihoods. Drought (0.097) also emerged as a major vulnerability driver, reflecting chronic exposure to water scarcity and environmental stressors. SDP (0.094) which highlighted poor housing structure, low education levels, high dependency ratio, gender of the household, social category and other critical component food (0.073). The marginal role of social networks (0.050) and health (0.037) indicated declining informal coping mechanisms and poor health infrastructure.

Estimates across the study states revealed significant differences in the vulnerability profile. Rajasthan had the highest overall vulnerability of all the states investigated with the highest HLVI score of 0.533. Food (0.071), livelihood strategies (0.111), drought (0.0105), SDP (0.090) and social networks (0.075) were the strongest indicators in Rajasthan. Water (0.045), health (0.036) and were the other dimension scored in Rajasthan. Focused analysis of regional vulnerability clusters was based on those values which represent the varying stress levels across different domains. With an HLVI of 0.525 Telangana placed in second in terms of overall vulnerability. Of the three states, it had the LS score (0.115), a higher score in the livelihood strategies component. SDP (0.101), drought (0.090), food (0.079), water (0.064), social networks (0.039) and health (0.036) were additional significant factors that influenced Telangana's HLVI. Among the three states, Tamil Nadu had the lowest HLVI value (0.487) suggesting a relatively lower level of risk. Livelihood strategies (0.114), drought (0.095), SDP (0.094), food (0.071), water (0.047), health (0.040) and social networks (0.027) were the component-wise scores for Tamil Nadu. In comparison to Telangana and Rajasthan, Tamil Nadu displayed slightly lower scores in the social networks and water components. The livelihood strategies score in all three states were high and fairly steady ranging from 0.111 in Rajasthan to 0.115 in Telangana. Telangana had the lowest drought component (0.090), while Rajasthan had the highest (0.105). Telangana's SDP was 0.101 while Rajasthan's was with 0.090. With values ranging from 0.036 to 0.040 in every state health vulnerability stayed low and

TABLE 5 Household resilience index for semi-arid regions of India.

State	IFA	APS	SSN	AC	A	S	HRI
Telangana	0.004	0.114	0.079	0.121	0.082	0.049	0.448
Tamil Nadu	0.005	0.139	0.072	0.116	0.103	0.067	0.501
Rajasthan	0.016	0.120	0.053	0.119	0.130	0.070	0.509
India	0.009	0.124	0.067	0.119	0.108	0.063	0.489

closely emphasized. Telangana had the highest food component (0.079) despite it being moderately high across every state. In social networks the difference was more pronounced with Tamil Nadu having the lowest value (0.027) and Rajasthan having the highest (0.075).

National average HRI score of 0.489 which was shown in Table 5 indicated a moderate level of household resilience across India's semi-arid regions. Access to public services (APS) had the highest value at 0.124 closely followed by adaptive capacity (AC) at 0.119 and assets (A) at 0.108. The lowest national average score was for income and food access (IFA) 0.009, stability (S) 0.063 and 0.067 for social safety nets (SSN). Rajasthan had the greatest HRI of 0.509 at the state level which was supported by its strongest score in adaptive capacity (0.119), asset ownership (0.130) and stability (0.070). Other component values were IFA (0.016), SSN (0.053) and APS (0.120). Tamil Nadu with an HRI score of 0.501 ranked in second. APS contributed the most to Tamil Nadu's component values (0.139) the highest of the three states indicating effective delivery of public services performance. Following APS, assets (0.103), AC (0.116), stability (0.067), SSN (0.072) and IFA (0.005) were the contributions to the resilience. Tamil Nadu's resilience pattern was comparatively consistent due to its often balanced scores in all six components particularly in APS and SSN. Telangana, on the other hand holds the lowest HRI (0.448) which indicated that it was less resilient across

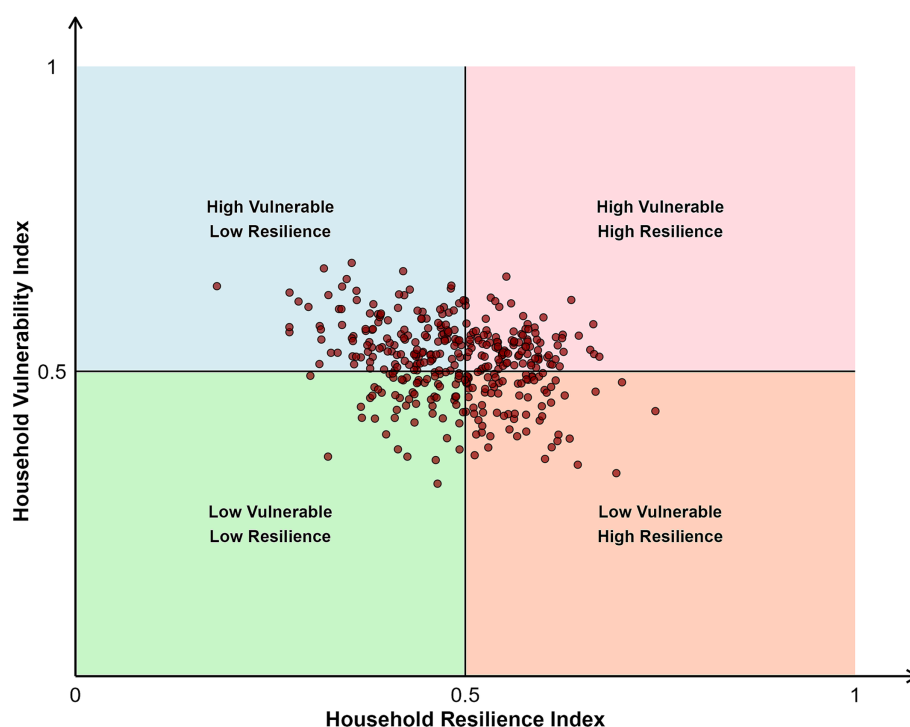


FIGURE 3

Distribution of households across four vulnerability-resilience quadrants based on HLVI and HRI across semi-arid regions of India.

many areas of interest. Telangana had the lowest IFA score of all the areas examined at 0.004 which suggests that there is limited access to food and steady income. Among the most significant components to Telangana's resilience structure were APS (0.114) and AC (0.121); other scores included assets (0.082), stability (0.049) and SSN (0.079). Telangana's low IFA and moderate assets limited the overall resilience index even if its APS and AC values are similar to the national average.

3.2 Household vulnerability and resilience interplay

The quadrant analysis in Figure 3 and Table 6 highlighted the complex interplay between vulnerability and resilience demonstrating that these concepts were not always inversely related. A significant percentage of households 37.07 percent were in the most critical group, termed as the high vulnerability and low resilience (HVLR) quadrant. These households lack the resources or support networks necessary to absorb or adapt to economic and climatic shocks and they were structurally weak and economically unstable. On the other hand, the low vulnerability and high resilience (LVHR) quadrant covers 19.20 percent of households. These households benefit from relatively secure livelihoods, better access to public services and adaptive assets that support both long-term development and short-term shock absorption. It's significant that 27.47 percent of households classified into the high vulnerability & high resilience (HVHR) category. Households in LVLR quadrant represent 16.27 percent of total households. Although the structural conditions and exposure levels of these households are currently better, their resilience systems were weak or underdeveloped.

TABLE 6 Percentage of households by vulnerability-resilience quadrants.

Quadrant	Symbol	Percentage (%)
High vulnerability and low resilience	HVLR	37.07
Low vulnerability and high resilience	LVHR	19.20
High vulnerability and high resilience	HVHR	27.47
Low vulnerability and low resilience	LVLR	16.27

Such households could fall into the HVLR category in the event of right after shocks specifically systemic or prolonged events.

3.3 Livelihood strategies impacts on combined vulnerability and resilience indices

The multivariate linear regression was employed to investigate the combined impacts of multiple livelihood strategies (LS) on vulnerability and resilience at the household level as shown in Table 7. The HRI and the HLVI two dependent variables were regressed against 13 livelihood strategies simultaneously. By the deployment of this two-dimensional analysis we can determine whether a specific approach effectively enhances resilience in along with reducing vulnerability. The model significantly explains changes in both HLVI and HRI based the results of the multivariate test statistics (Wilks'

TABLE 7 Multivariate linear regression of the impact of livelihood strategies on combined vulnerability and resilience indices.

Livelihood strategies	Multivariate tests				Tests of between-subject effects		Parameter estimates	
	Pillai's Trace	Wilks' Lambda	Hotelling's Trace	Partial Eta squared	Partial Eta Squared (effect sizes)		β_{HLVI}	β_{HRI}
					HLVI ^a	HRI ^b		
Intercept	0.854***	0.146***	5.828***	0.854***	0.778***	0.573***	0.533***	0.343***
H&DR	0.023**	0.977**	0.024**	0.023**	0.005	0.014**	0.009	0.016**
CD&CR	0.004	0.996	0.004	0.004	0.003	0.002	−0.007	0.005
LSD	0.066***	0.934***	0.071***	0.066***	0.003	0.057***	0.005	0.021***
C&LSI	0.010	0.990	0.010	0.010	0.003	0.008*	−0.004	0.007*
DLS	0.015*	0.985*	0.015*	0.015*	0.001	0.015**	−0.003	0.014**
DIS	0.059***	0.941***	0.063***	0.059***	0.043***	0.029***	−0.015***	0.013***
T/PM	0.012	0.988	0.012	0.12	0.001	0.012**	−0.003	0.008**
HCL	0.033***	0.967***	0.034***	0.033***	0.006	0.031***	0.005	−0.013***
ACMF	0.014*	0.986*	0.014*	0.014*	0.006	0.005	−0.006	0.006
RWH	0.022**	0.978**	0.023**	0.022**	0.013**	0.014**	−0.008**	0.008**
GCC	0.000	0.1	0.000	0.000	0.000	0.000	0.002	0.001
GFMC	0.003	0.997	0.003	0.003	0.003	0.000	0.007	−0.001
ASD	0.019**	0.981**	0.019**	0.019**	0.011**	0.011**	−0.011**	0.011**

*, ** and *** significant at 10, 5 and 1% levels.

^aR Squared = 0.120.

^bR Squared = 0.500.

Lambda = 0.146 and Pillai's Trace = 0.854; both significant at 1%). Most of the livelihood strategies appear to have a greater impact on household resilience than vulnerability as evidenced by the explained variance R^2 which is 12 percent for HLVI and 50 percent for HRI. This difference draws emphasis to the complexity of vulnerability which may have deeper roots in environmental and structural factors whereas resilience may be more directly impacted by resource mobilization and proactive household strategies.

Among the livelihood strategies that were investigated, livestock diversification (LSD) showed the most significant overall impact on the combined variation in HRI and HLVI. At the 1 percent significance level its partial eta squared value was the highest of all variables at 0.066. LSD's β value for HRI was 0.021 indicating that its influence was more pronounced in improving household resilience despite its 0.005 parameter estimate (β) for HLVI. With a partial eta squared of 0.059 diversification of income sources (DIS) placed in second. Significant relationships between DIS and both dependent variables were found with DIS having a positive impact on HRI ($\beta = 0.013$) and a negative impact on HLVI ($\beta = -0.015$) suggesting an impact that spans across the vulnerability-resilience spectrum. Also the partial eta squared value of 0.033 for household working as casual labor (HCL) was significant. It demonstrated a significant negative relationship ($\beta = -0.013$) for HRI and a positive but negligible β value ($\beta = 0.005$) for HLVI suggesting a distinct role for resilience and vulnerability. The partial eta squared for hybrid and drought-resistant varieties (H&DR) was 0.023. It had a statistically significant favorable effect on HRI ($\beta = 0.016$) and a marginal effect on HLVI ($\beta = 0.009$). Rainwater harvesting (RWH) had a statistically significant effect on both HLVI and HRI with β values of -0.008 and 0.008 , respectively, with the partial eta square value of 0.022. Adjusting Sowing or planting dates

(ASD) had a partial eta squared value of 0.019 and demonstrated a similar dual effect with a negative β value of -0.011 on HLVI and a positive value of 0.011 on HRI each significant at the 5 percent level.

A moderate amount of combined impact can be seen by crop and livestock insurance's (C&LSI) insignificant partial eta squared of 0.010. While its effect on HRI was favorable and significant ($\beta = 0.007$) its effect on HLVI was negative but not significant ($\beta = -0.004$). At the 10 and 5 percent levels, respectively, the distribution of livestock (DLS) at various places showed a partial eta squared of 0.015 with minor impacts on HLVI ($\beta = -0.003$) and a slightly greater positive effect on HRI ($\beta = 0.014$). Only the HRI achieved significance with β values of 0.008 on HRI and -0.003 on HLVI while temporary or permanent migration (T/PM) had an insignificant partial eta squared of 0.012. Other factors, such as access to community microfinance (ACMF) also showed significance impact with the partial eta squared value of 0.014, but the HRI (0.006) and HLVI (-0.006) had non-significant β values. Crop rotation and crop diversification (CD&CR) had a minor impact recording β values of 0.005 for HRI and -0.007 for HLVI, with a partial eta squared of 0.004. The β value for growing fast-maturing crops (GFMC) was 0.007 for HLVI and -0.001 for HRI indicating a very tiny effect size of partial eta squared 0.003. Growing commercial crops (GCC) had β values of 0.002 for HLVI and 0.001 for HRI indicating no substantial influence and a partial eta squared of almost zero (0.000).

To investigate the effects of various livelihood strategies on the probability that households fall into one of the four vulnerability-resilience quadrants the multinomial logistic regression was employed. The reference category which was the high vulnerability and low resilience (HVLRL) group as represented in Table 8. The model demonstrated a good overall fit with Cox and Snell $R^2 = 0.454$,

TABLE 8 Multinomial logistic regression of livelihood strategies on household vulnerability-resilience quadrants.

LS	HVHR		LVLR		LVHR	
	θ	Exp(θ)	θ	Exp(θ)	θ	Exp(θ)
Intercept	-5.063***		-1.747***		-4.588***	
H&DR	0.673*	1.960	-0.265	0.768	0.402	1.495
CD&CR	0.173	1.189	0.231	1.260	-0.171	0.843
LSD	0.376*	1.457	-0.183	0.832	0.356	1.428
C&LSI	0.432**	1.541	0.364*	1.439	0.493**	1.638
DLS	0.440	1.553	-0.293	0.746	0.407	1.503
DIS	0.134	1.143	0.307	1.359	0.740***	2.095
T/PM	-0.025	0.975	-0.215	0.807	0.248	1.281
HCL	-0.709***	0.492	-0.093	0.911	-0.334*	0.716
ACMF	0.065	1.067	-0.038	0.963	-0.343	0.709
RWH	-0.037	0.964	0.081	1.084	0.487**	1.628
GCC	0.011	1.012	-0.139	0.870	-0.265	0.768
GFMC	0.381	1.464	0.031	1.032	-0.368	0.692
ASD	0.613**	1.847	0.469*	1.599	1.141***	3.131

HVLR is the reference category. *, ** and *** significant at 10, 5 and 1% levels. Cox and Snell $R^2 = 0.454$; Nagelkerke $R^2 = 0.488$ and McFadden $R^2 = 0.227$.

Nagelkerke $R^2 = 0.488$ and McFadden $R^2 = 0.227$ suggesting that the livelihood strategies collectively explain a substantial proportion of variance in the household vulnerability-resilience interaction.

With an emphasis on the HVHR category a number of livelihood strategies considerably enhanced the likelihood that a household would move from the HVLR base category to HVHR. Adjusting sowing or planting dates was found as a significant predictor ($\theta = 0.613$, $\text{Exp}(\theta) = 1.847$, $p < 0.05$) implying that households adopting timely sowing strategies had a 1.85 times more likely to fall in this quadrant or high chances of transitioning the households from the most vulnerable group or reference group (HVLR) to this quadrant (HVHR) which was highly resilient in spite of risk factors. Additionally there was a positive relationship between HVHR and crop and livestock insurance (C&LSI) ($\theta = 0.432$, $\text{Exp}(\theta) = 1.541$, $p < 0.05$) indicating that households with C&LSI were 43.2% more likely to remain resilient under vulnerability. Adoption of hybrid and drought-resistant varieties (H&DR) also showed a statistically significant contribution ($\theta = 0.673$, $\text{Exp}(\theta) = 1.960$, $p < 0.1$) effectively doubling the chances that the households reaching the HVHR quadrant from most vulnerable reference category (HVLR). Livestock diversification (LSD) significantly improved the odds of HVHR inclusion ($\theta = 0.376$, $\text{Exp}(\theta) = 1.457$, $p < 0.1$). Household casual labor (HCL) on the other hand had a significant negative impact ($\theta = -0.709$, $\text{Exp}(\theta) = 0.492$, $p < 0.01$) reducing these households chances of moving from most vulnerable HVLR to HVHR by more than half by depending on casual labor for their livelihoods. This suggests that unstable and low-quality employment serves as an obstacle to resilience.

In the case of LVLR which represents households that have evaded high vulnerability but were still low in resilience, ASD was again the most significant positive driver with an $\text{Exp}(\theta)$ of 1.599 ($\theta = 0.469$, $p < 0.1$) indicating households that adopted to adjusting sowing dates had a roughly 1.6 times higher chance of moving from most vulnerable

reference category HVLR to this LVLR quadrant. Crop and livestock insurance (C&LSI) confirmed the protective role of risk-transfer mechanisms in this case as well ($\theta = 0.364$, $\text{Exp}(\theta) = 1.439$, $p < 0.1$). Access to community microfinance (ACMF) and crop diversification & crop rotation (CD&CR) were marginally positively associated ($\text{Exp}(\theta) = 1.067$ and 1.260 respectively) but they were not statistically significant. At the same time distribution of livestock (DLS) at different places, LSD and temporary/permanent migration (T/PM) showed marginally negative coefficients. These directional shifts suggest the partial influence of these strategies on reducing vulnerability even if they do not build sufficient resilience. HCL again showed a negative association ($\theta = -0.093$, $\text{Exp}(\theta) = 0.911$) reinforcing that such insecure employment continues to limit household adaptive outcomes even in lower vulnerability conditions.

Multiple livelihood strategies had a strong relationship with LVHR, the most desirable quadrant. The strongest predictor was adjusting sowing dates ($\theta = 1.141$, $\text{Exp}(\theta) = 3.131$, $p < 0.01$) suggesting that adjusting sowing dates practices increased the likelihood of shifting the households to best category LVHR by more than three times from the most vulnerable quadrant HVLR. Followed immediately after was diversification of income sources ($\theta = 0.740$, $\text{Exp}(\theta) = 2.095$, $p < 0.01$) suggesting that households with an array of non-farm revenue sources had a greater than twofold likelihood of achieving both high resilience and low vulnerability from low resilience and high vulnerable reference quadrant. The probabilities of switching to LVHR were also considerably raised by C&LSI ($\theta = 0.493$, $\text{Exp}(\theta) = 1.638$, $p < 0.05$) and rainwater harvesting ($\theta = 0.487$, $\text{Exp}(\theta) = 1.628$, $p < 0.05$). These findings highlight how ecological infrastructure and financial instruments work together to improve adaptive outcomes and minimize climatic sensitivity. Despite being statistically insignificant, LSD ($B = 0.356$, $\text{Exp}(\theta) = 1.428$) and T/PM ($\theta = 0.248$, $\text{Exp}(\theta) = 1.281$) both shown favorable effects indicating additional functions in resilience-building. HCL showed a significant negative relationship again ($\theta = -0.334$, $\text{Exp}(\theta) = 0.716$, $p < 0.1$) indicating that the use of unskilled labor remains an obstacle to developing holistic adaptive capacity. In all three transition categories, a number of other livelihood strategies including growing commercial crops (GCC), growing fast-maturing crops (GFMC) and CD&CR were statistically insignificant. Their $\text{Exp}(\theta)$ values were nearly equal suggesting that they had little effect on changing the vulnerability-resilience position of households. Although ACMF was beneficial in HVHR and LVLR, it was negative in LVHR ($B = -0.343$, $\text{Exp}(\theta) = 0.709$) supporting the idea that microfinance alone may not always result in better household resilience outcomes when it is not accompanied by institutional and knowledge support.

4 Discussion

The findings show that in semi-arid India, climate vulnerability was still a structural problem. Telangana and Rajasthan's high HLVI levels result of their dependency on rainfed agriculture, socioeconomic limitations and long-standing exposure to severe droughts. These findings resonate with earlier studies (Kumar and Mohanasundari, 2025) and various reports discovered that livelihood dependency and climate exposure were the main factors influencing vulnerability in dry areas. Strong contributions to the vulnerability were made by LS, SDP, D, and F. Rural households continue to rely heavily on rainfed

agriculture and seasonal wage labor which were particularly unstable and highly susceptible to climate shocks. Despite numerous governmental and non-governmental efforts promoting livelihood diversification, a significant proportion of the rural population remains locked into low-return, insecure forms of employment such as agricultural wage labor. These forms of labor were often characterized by irregularity, low pay and lack of social protection thereby increasing household vulnerability and constraining their capacity to build resilience (De Haan and Zoomers, 2005; Sam et al., 2016). Several studies have affirmed that households engaged primarily in casual labor tend to experience higher exposure to risk and reduced ability to absorb or adapt to stressors, due to limited asset accumulation and constrained agency over livelihood choices (Narayanan and Gerber, 2016; FAO, 2018).

The SDP components in relation with high vulnerability was a reflection of ongoing structural problems in rural India, such as large dependency ratios, poor housing structure and low levels of education (Brenkert and Malone, 2005; Sam et al., 2016). Despite the presence of public distribution systems, the food index indicates continuing food insecurity suggesting potential inadequacies in continuity, access and targeting for the most vulnerable populations (Kattumuri, 2011). The high drought value highlighted how climatic stressors were persistent, how semi-arid households were chronically exposed to water scarcity and crop failure and how rural households were exposed to recurrent droughts and have limited coping mechanisms, particularly when their primary sources of income were climate-dependent. In regions that were prone to drought, where inadequate infrastructure and groundwater depletion have grown prevalent, water insecurity was particularly problematic reducing the agricultural output pushing households toward food insecurity despite existing welfare systems which suggested significant food insecurity leading to the high HLVI (Shah et al., 1998; Sam et al., 2016). These intersecting deficits highlight the need for integrated drought and food security strategies. The marginal value for social networks suggests some potential buffering through informal support systems though their weakening raises concerns about community based coping capacities. The comparatively low the score, despite this, could suggest a weakening of community-based support networks, which were sometimes undermined by societal shifts, migration or financial stress (Sam et al., 2016). Despite being lower than the others, the health component still highlights significant gaps in rural health infrastructure, especially during drought years when access to medical services becomes more challenging due to an increase in waterborne diseases (Dewi et al., 2024; Mani et al., 2024).

With the highest HLVI Rajasthan was shown to be the most vulnerable state mainly as a result of social networks deteriorating and an extended drought exposure. Household vulnerabilities have increased as a result of persistent water scarcity and insecure agriculture which have weakened traditional coping mechanisms including community collaboration (Singh et al., 2018). Because of limited diversification of livelihoods and the food insecurity in arid districts, Rajasthan exhibits fairly high susceptibility in terms of livelihood strategies and food insecurity. Structural limitations continue to undermine household resilience in spite of continuous state-led investments in rural employment and water harvesting. Telangana, the second most vulnerable state, exhibits the highest livelihood strategy vulnerability among the three indicating a greater reliance on climate-sensitive agriculture with insufficient income

diversification. The profile reveals that vulnerability spreads across several dimensions among semi-arid households in Telangana with livelihood-related fragility being especially evident. The large number of seasonal labor and smallholder farmers particularly in areas with inadequate irrigation infrastructure, might be the root cause of this. The drought vulnerability of Telangana was still fairly high which fuels a cycle of agrarian distress. Food insecurity and the socioeconomic demographic profile were other factors that indicated ingrained disparities in access to resources and services (Sam et al., 2016). Household-level vulnerability persists despite initiatives like Rythu Bandhu and Mission Kakatiya because of implementation flaws and limited access to the most vulnerable. Tamil Nadu on the other hand had a lower HLVI which is indicative of comparatively superior public services and diversified livelihoods. The relatively better performance can be attributed to more diversified rural livelihoods, improved irrigation infrastructure and stronger access to social welfare schemes. Despite this considerable drought vulnerability was continuing to be recorded for Tamil Nadu, highlighting the ongoing water stress in several semi-arid districts (Varadan and Kumar, 2015; Balaganesh et al., 2020). The state's higher health vulnerability also indicated difficulties in providing rural health services in the last mile, particularly in remote tribal areas. For further investigation on resilience interactions and strategies for adaptation at the regional and national levels these HLVI information offer a quantitative basis for investigation.

The composite HRI value which was comprised up of component scores offers insight into the spectrum of external support networks and household capabilities that were available for climate resilience. Institutional access, assets and adaptive capacity all play significant effects on resilience as determined by HRI. Stronger effectiveness in expanding public healthcare, education and extension services, in addition to boosting adaptive behaviors like improved agricultural practices was reflected in higher scores in these areas. In terms of resilience building, Tamil Nadu in particular fared better because to its high-quality public infrastructure. In the same way comparatively high adaptive capacity score indicates that some households were adopting improved agricultural practices engaging in community training programs or having access to climate-relevant knowledge that facilitates increased preparedness. Rajasthan's resilience positioned was significantly influenced by its improved asset ownership and able to adapt. Land, livestock and savings were among the assets that significantly improved resilience, highlighting the importance of asset accumulation in rural adaptation. Because it builds internal buffers against disruptions in income or food supplies, asset accumulation was especially crucial in areas with limited legally binding safety nets (Ansah et al., 2022; Ackerl et al., 2023). The superior performance of Tamil Nadu and Rajasthan confirms that the climatic vulnerability can be offset by adaptive capability especially asset-based resilience. On the other hand, access to food and income remained extremely limited, leaving rural households vulnerable to persistent food insecurity and economic shocks. The analysis shows that many households remain economically vulnerable and nutritionally insecure despite owning land or accessing services making them less likely to recover back quickly from shocks like drought or market failure. Low IFA in all regions indicated food insecurity and systemic income, supporting the findings of Narayanan and Gerber (2016), who identified economic vulnerability as a major barrier to climate adaptation. Mixed outcomes were also seen by social safety nets.

Although there are programs like PDS, MNREGA and pensions their efficacy differs by location. Access to safety nets alone does not provide resilience unless these systems are adequate in scope, timely and well-targeted (Narayanan and Gerber, 2016).

States' social safety nets differed greatly from one another; Telangana had better access but less resilience overall, indicating that having safety nets was not enough unless they were strong and functional. Rural households find it more difficult to make long-term decisions in an unstable external environment where income, prices and service delivery fluctuate. This was reflected in the moderate stability component which stands for consistency of livestock, market price volatility and institutional reliability. It also reflects a moderate but vulnerable position across semi-arid regions and retarded resilience (Mekuyie et al., 2018; Dawid et al., 2023). The system lacks robust shock-absorbing mechanisms and households continue to face serious disruptions to their means of livelihood. The decreased HRI in Telangana is extremely alarming. Its resilience, especially in IFA and assets, was poor despite its moderate HLVI. This indicated that rural households here face greater income instability and weaker asset buffers limiting their ability to recover from shocks even if public service access and adaptive efforts show promise. These results highlight the fact that resilience was more than just the lack of vulnerability; rather, it calls for proactive mechanisms, strategies and support to enable households adapt and recover back (Cutter et al., 2008; Zhai and Lee, 2024). Even though some states have achieved progress, the semi-arid regions of India urgently require economic stabilization, targeted nutrition interventions and stronger institutional mechanisms due to limited income access and inadequate safety nets.

The quadrant analysis challenges the binary framing of vulnerability and resilience. The presence of households in HVLR, HVHR & LVHR revealed that high resilience can exist even under high vulnerability. The distribution of households across the four quadrants demonstrated that, depending on contextual and structural circumstances, resilience and vulnerability can coexist to varying degrees contradicting the widely held belief that they were simply opposites. This support to the conceptual model put forth by Cutter et al. (2008) which posits that resilience was a function of both internal and external systems rather than just the absence of vulnerability. The significance of internal risk reducing strategies including access to institutions, education, diversified income, assets and social networks highlighted by the coexistence of high vulnerability and high resilience seen in some households (Manyena et al., 2011; Nunes, 2021). Households in the low vulnerability-low resilience quadrant were also indicative of latent fragility which occurs when favorable current situations conceal a lack of adaptive systems, leaving these households vulnerable to shocks in the future (Nunes, 2021). Policy must shift from one-size-fits-all strategies to focused quadrant-specific initiatives in view of this diverse reality. While high-resilience but vulnerable households need measures to mitigate external stressors, strengthening their capacities through inclusive governance, knowledge-sharing platforms and ecologically based innovations such as watershed development and livelihood diversification helps replicate their resilience across broader communities. High-vulnerability, low-resilience households worst category those trapped in a poverty-vulnerability quadrant require foundational support such as basic infrastructure, strengthened social safety nets and enhanced livelihood diversification pathways (Singh

et al., 2019). This detailed understanding informs tailored micro-contextual solutions that are crucial for developing inclusive and effective climate adaptation mechanisms in semi-arid regions. Therefore, policies need to distinguish between enhancing resilience and minimizing exposure.

Majority of the livelihood strategies have a greater influence as depicted by the multivariate regression analysis. In line with previous research (Barrett et al., 2001; Kumar et al., 2020; Ramilan et al., 2022) which claimed that diversification of economic activities lowers vulnerability and improves adapting capacity, DIS and LSD showed as the most dominant methods. Multiple-income households, particularly those involved in non-farm activities were better able to develop long-term adaptation capacities and function as a buffer against climate hazards. Diversified livestock holdings, such as rearing multiple species or breeds significantly increase household resilience by providing a buffer against climate shocks, food diversity and income stability. The significance of ASD, RWH and C&LSI were also consistent with the findings of other researchers (Kangalawe and Lyimo, 2013; Panwar et al., 2023; Roy et al., 2024) who found that insurance schemes and early agronomic interventions greatly improve household adaptive behavior in dryland areas. Although the significantly improved HRI, resistant varieties (H&DR) indicated that these seeds have agronomic ability for promoting adaptive farming, it also raises the possibility that access challenges or agro climatic incompatibilities may affect actual uptake and performance (Louwaars and Manicad, 2022). Favorable coefficients for rainwater harvesting (RWH) highlight its relevance as an inexpensive, natural adaptation method. RWH was a nature-based approach that enhances water security and reduces exposure to drought especially in dryland farming systems (Sikka et al., 2022; Sharma et al., 2022; Jain et al., 2024). Even though livestock and crop insurance (C&LSI) does not change structural vulnerability, it nonetheless plays a crucial role in stabilizing income post a shock. Adjusting sowing or planting dates reaffirmed its significance in preventing terminal drought stress and synchronizing crop growth stages with the most optimal available precipitation (Tripathi and Mishra, 2017).

The fact that HCL had a negative impact on resilience in every strategy highlights structural employment insecurity. The informal, unstable nature of such employment which provides few chances for asset building or upward mobility was probably the cause of this. Casual labor markets make households susceptible to shocks since they were unable to generate steady income or accumulate assets (Kelly and Adger, 2000; De Haan and Zoomers, 2005; Datey et al., 2023). Therefore, generating employment alone will not be enough if quality and stability are neglected. The insignificant statistical significance of strategies such as CD&CR, GFMC and ACME, despite their directionality suggested that institutional support was necessary for these interventions to become transformative.

Our findings support the main idea of the adaptation triangle which holds that vulnerability, resilience and livelihood strategies perform best together to explain adaptation outcomes rather than each component alone. The multinomial logistic regression's findings provided a sophisticated and situation-specific information of how livelihood strategies influence shifts the households in each of the vulnerability-resilience quadrants. According to Cutter et al. (2008) and Bahadur et al. (2015) the analysis backs up the claim that resilience was a distinctive, actionable construct that was influenced by both structural and adaptive factors rather than just being the

absence of vulnerability. The persistent impact of early planting or adjusting sowing dates in all quadrants particularly in facilitating transitions from the most critical category HVLR to more favorable conditions was one of the most notable findings. The importance of proactive agronomic timing in climate adaptation was highlighted by the significantly greater probability of reaching the LVHR group for households who adopted adjustments in the sowing dates. This was consistent with research (Tripathi and Mishra, 2017; Begum and Mahanta, 2017; Paramesh et al., 2022; Patel et al., 2023) which shown that adjusting sowing dates increases agricultural resilience in semi-arid areas and reduces yield losses during erratic precipitation periods. In the same way DIS became a game-changing strategy that significantly enhanced household potential of achieving LVHR. This was in line with the findings (Wan et al., 2016; Jalal et al., 2021; Kumar and Mohanasundari, 2025) who highlighted that livelihood diversification protects households against systemic risks like weather variability and market failures and minimizes reliance on climate-sensitive sectors. The greater shift toward non-farm rural livelihoods, which has emerged as an essential path for resilience in developing nations was also reflected in DIS (FAO, 2016a, 2016b; Barrett et al., 2001; Zhang et al., 2023). The significance of risk transfer mechanisms was highlighted by the strength of C&LSI in influencing movement toward LVHR and HVHR particularly in areas where shocks like drought were frequently encountered (Aina et al., 2024a; Aina et al., 2024b; Biglari et al., 2019; Beula and Kumaar, 2024). In addition to mitigating financial losses, insurance allows households to take economic risks, like investing in irrigation or seeds without fearing about catastrophic failure (Birthal et al., 2022; Greatrex et al., 2015).

Also RWH made a substantial contribution to the build-up of resilience especially for LVHR households. This result confirms findings from sub-Saharan Africa and India showing that decentralized water management enhances year-round water availability encourages crops diversification and reduces vulnerability to dry spells (Rockström et al., 2003; Panwar et al., 2023; Jain et al., 2024; Singh et al., 2025). LSD although less potent than ASD and DIS, offered notable gains in both HVHR and LVHR transitions. Particularly in ecologically vulnerable areas livestock serve as resilience assets by safeguarding against crop failures and supplying a consistent supply of food and income (Sekaran et al., 2021; Bonilla-Cedrez et al., 2023; Bashiru and Oseni, 2025; Sahoo et al., 2025). HCL's negative impact on transitions in all resilience quadrants highlights the systemic constraints of rural informal employment. The lack of ability of casual labor to provide social protection, stability or asset accumulation often contributes to vulnerability traps (De Haan and Zoomers, 2005; Narayanan and Gerber, 2016; Dodman et al., 2023). Migration has been identified here as a constructive coping mechanism, especially when it was organized and facilitated by skill development or remittances despite the fact that it was frequently perceived as a distress response (Deshingkar and Start, 2003; McLeman and Hunter, 2010; Jha et al., 2018). The idea that well-supported migration can increase resilience and reduce dependence on fragile local ecosystems was a component of the "migration-as-adaptation" (Tacoli, 2009; Warner, 2010; Foresight, 2011).

These findings reflect the fundamental idea of the adaptation triangle which stated that livelihoods, vulnerability and resilience must all be addressed simultaneously. Strategies such as adjusting sowing dates, income diversification and rainwater harvesting significantly helped households transition from HVLR to adaptive

quadrants, enhancing resilience while reducing exposure. Households depending on casual work on the other hand, enhanced vulnerability and reduced resilience. These differentiated outcomes showed that one-size-fits-all policies were ineffective. Instead, micro-contextual interventions must combine safety nets, risk-reduction tools and adaptive livelihood support, ensuring households at varying positions on the adaptation continuum receive tailored responses aligned with their specific resilience and vulnerability profiles.

5 Conclusions and policy recommendations

The study analyzed household vulnerability and resilience in India's semi-arid areas with the HLVI and HRI indices within the adaptation triangle framework. The results indicate a moderate vulnerability and a low resilience with 37% of households residing in the most critical HVLR quadrant. Livelihood strategies including income and livestock diversification, rainwater harvesting, crop and livestock insurance and adjusting sowing dates significantly improved resilience and lowered vulnerability. On the other hand, depending on casual agricultural labor sustained structural vulnerability, income insecurity and low adaptive capacity. Migration, although frequently driven by distress, exhibited potential when bolstered by institutional support. These findings highlight the critical importance for context-specific, strategic adaptation interventions. A variety of intricate and fact-based short- and long-term policy recommendations were derived from these thorough findings, which were rooted in the adaptation triangle. Some of these short-term strategies include to reduce the dependency on casual labor, increasing access to skill training, microenterprises and rural non-farm employment particularly in Telangana. Expand and streamline crop and livestock insurance, offering smallholders discounted rates and enhance awareness and claim settlement procedures. Use extension networks to promote drought-resistant crop varieties and provide timely agromet advisories on adjusting planting and sowing dates. Expand farm ponds and decentralized rainwater harvesting under MGNREGS, especially in districts of Rajasthan that were vulnerable to drought. Instead of allowing distress-driven movement, promote safe and planned migration by offering skill certification and portable social protection (PDS, pensions) to increase resilience. Long-term strategies include to address the systemic vulnerability of casual laborers, formalizing rural employment, creating sector-specific rural labor markets and offering wage protection during climate shocks particularly in rural labor intensive states like Tamil Nadu. To stabilize output and minimize exposure to drought, strengthen irrigation systems, watershed development and agro-ecological resources. Encourage women-led producer organizations, savings plans and livestock diversification to improve household resilience and adaptive capacity. Investments in social protection programs including employment guarantees and food distribution, should be recalibrated to support resilience outcomes, not just relief.

5.1 Suggestions for future research

Although this study offers valuable insights into the relationship among livelihood strategies, resilience and household vulnerability,

some limitations draw attention to the need for further studies. First, it is difficult to make causal inferences about long-term adaptation because the analysis is based on cross-sectional household data. Longitudinal panel data should be used in future research to document dynamic shifts in resilience and vulnerability over time, particularly as households repeat climate shocks and modify their livelihood portfolios. Second, combining socioeconomic data at the household level with climate trend analyses may strengthen the connection between adaptation at the micro level and climate variability at the macro level. Third, to evaluate the adaptation triangle framework's transferability and policy relevance, future research could test it in a variety of agro-ecological zones outside of India's semi-arid regions. Lastly, future research need to adhere to the IPCC-AR6 framework by using longitudinal datasets, incorporating regional climate forecasts and socio-economic vulnerability evaluations.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Author contributions

BM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. SK: Conceptualization, Supervision, Writing – review & editing. VK: Conceptualization, Project administration, Supervision, Writing – review & editing. PP: Project administration, Supervision, Writing – review & editing. EK: Data curation, Visualization, Writing – review & editing. AY: Investigation, Validation, Writing – review & editing. PD: Software, Visualization, Writing – review & editing. RM: Data curation, Formal analysis, Methodology, Writing – review & editing.

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Supplementary material

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