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RESEARCH ARTICLE

Agriculture diversification in Jammu region: Status and determinants

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Abstract

Agricultural diversification refers to the shift from the dominance of one crop to production of a number of crops on a farm or in a region, to meet the ever-increasing demand for food. It is crucial for enhancing food security and reducing climate risks, yet small-scale farmers in rain-fed regions face challenges in adopting diversified farming systems. The main objectives of the study were to assess the present status of crops, livestock, integrated crop-livestock diversification in vulnerable and non-vulnerable villages and identify key determinants influencing agricultural diversification. The baseline survey was conducted in 51 villages of Bhalwal block of Jammu district (2016-17) and identified 25 villages as climate-vulnerable villages. In these 25 vulnerable villages, project entitled "Climate Resilient Sustainable Agriculture in Rain-fed Farming Areas of Jammu Region" has been implemented since 2016-17 in the said block. Therefore, for the present study, 300 farmers were selected randomly from the 25 vulnerable villages that are covered under under the said project. For comparison, 100 farmers were selected randomly from the adjoining non-vulnerable villages which were not covered under the said project. The results revealed that non-vulnerable villages exhibited slightly higher crop diversity (0.67) than vulnerable villages (0.63), while livestock diversity was higher in vulnerable villages (0.40) compared to non-vulnerable villages (0.37). Integrated crop-livestock diversification was also greater in vulnerable villages (0.88) than in non-vulnerable villages (0.82), highlighting the prevalence of integrated farming systems. Key drivers of crop diversification in vulnerable villages included access to irrigation, adoption of drought-tolerant crops and participation in training programs, which played a significant role in diversification. Strengthening diversification drivers particularly irrigation, resilient crops and capacity-building programs can enhance agricultural resilience. Policies should promote integrated farming systems to mitigate climate risks and stabilize farm incomes.

Keywords

agricultural diversification; crop diversity; livestock diversity; integrated farming systems; climate resilience

Introduction

Agriculture serves as the backbone of economies by ensuring food security and livelihoods. However, agricultural production faces significant uncertainties due to price volatility, climate variability, soil degradation and challenging terrain (1). These factors create income instability for farmers as market conditions and environmental factors fluctuate annually (2), making farming inherently risky. To enhance business sustainability, farmers must adopt effective risk management strategies, with diversification emerging as a crucial approach (3). Agricultural diversification involves transitioning from monoculture to cultivating multiple crops or integrating crops with livestock to enhance food security, income stability and climate resilience (4, 5). It encompasses three phases: (1) shifting from monoculture, (2) adopting multiple crops/livestock to meet market demands and (3) implementing mixed farming systems for optimal resource use (6, 7). This paper primarily focuses on the second and third phases of diversification. Thus, crop diversification refers to the cultivation of two or more crops with the available productive resources. Crop diversification, which contrasts with crop specialization, reflects the distribution and balance of different crops within a region (8). It plays a crucial role in agricultural land use studies and is a key aspect of regional crop geography (9). As a scientific tool, crop diversification helps analyze spatial relationships among crops in agricultural geography and land utilization. Ultimately, it facilitates the transition from low-value to high-value agriculture, contributing to increased agricultural productivity and economic growth while supporting Sustainable Development Goals (SDGs) 2 (Zero Hunger) and 8 (Decent Work and Economic Growth) (10). Crop diversification has been widely studied as a strategy for risk management and income enhancement (11). Similarly, livestock diversification is the rearing of two or more livestock types by the farmers given their available resources. Crop-livestock diversification is defined as the production of one or more crops and livestock with the available resources. Globally, integrated crop-livestock systems contribute to approximately half of the world's food production (12), promote efficient resource utilization and long-term sustainability. These systems align with SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) by optimizing agricultural inputs, reducing environmental impact and enhancing climate resilience (13). These systems integrate crop and livestock production within the same farmland, improving efficiency and sustainability.

Thus, agricultural diversification serves as a critical strategy for enhancing farm resilience, offering three key benefits: (1) expanded revenue streams through multiple enterprises, (2) reduced vulnerability to single commodity price fluctuations and (3) stabilized annual income (14). This approach mirrors financial portfolio theory, where diversifying across uncorrelated assets mitigates risk-in agriculture, spreading production across crops and livestock buffers against climatic and market shocks (15-17). Particularly in developing economies, integrated crop-livestock systems enhance food security while optimizing resource use through nutrient cycling. However, intensification without conservation risks soil degradation (18), requiring balanced approaches that combine diversification with sustainable practices.

The study on agricultural diversification in the Jammu region of Jammu & Kashmir (J&K) is critical due to the unique agro-climatic, socioeconomic and environmental challenges faced by the farmers. Agriculture in Jammu region is characterized by small landholdings (averaging 0.59 ha vs. the national average of 1.14 ha) (19), limited irrigation facility and vulnerability to climate change, alongside high population density and underdeveloped rural infrastructure. Despite these challenges, the region holds significant potential for agricultural development and diversification. The region's strengths, such as varied agro-climatic zones, ranging from subtropical plains to temperate hills, provide ideal conditions for cultivating a wide range of crops, including high-value and off-season varieties. The region's temperate climate in higher altitudes supports the growth of fruits like apples, cherries and walnuts, while the subtropical plains are conducive to growing vegetables, aromatic plants and medicinal herbs. Moreover, the region's distinct seasons enable the cultivation of off-season crops, giving farmers a competitive advantage in markets and also offer opportunities for enhancing farmers' incomes and improving food security. However, the lack of empirical evidence on current diversification patterns and their determinants hinders effective policy formulation. This study addresses this gap by assessing the status of crop, livestock and integrated crop-livestock diversification and identifying key drivers to inform strategies for boosting agricultural resilience and economic growth in the region.

Conceptual framework

The study's conceptual framework is adapted from the two-compartment network model of Stark et al. (20), which examines input-output flows within integrated crop-livestock farms. This study modifies the framework to reflect the two-way interaction between crop farming (System 1) and livestock farming (System 2). System 1 consists of diverse crops such as cereals, legumes, fodder crops, oilseeds and vegetables, while System 2 includes livestock such as large, small ruminants and poultry (Fig. 1). These integrated systems enhance farm productivity, improve household food security and lower production costs through economies of scope (21).

In the present study, diversification indices were constructed using approximately 20 different crop types and 7 livestock species in this study. There were three types of cereals (wheat, rice, maize) four types of fodder crops (sorghum, bajra, oats, berseem), three types of legumes (chickpea, mash, horse gram), two types of oilseeds (mustard, sesame), seven types of vegetables (tomatoes, okra, cauliflower, potato, radish, knol khol, ridge gourd) and one type of flower (marigold). The livestock, on the other hand, included two types of large ruminants (local cows and improved cows, buffaloes, ox), two types of small ruminants (goats and sheeps) and poultry birds. This broad spectrum of crops and livestock highlights the extent of diversification in the study area, providing valuable insights into how farmers integrate different agricultural enterprises to enhance resilience, optimize resource use and improve food security.

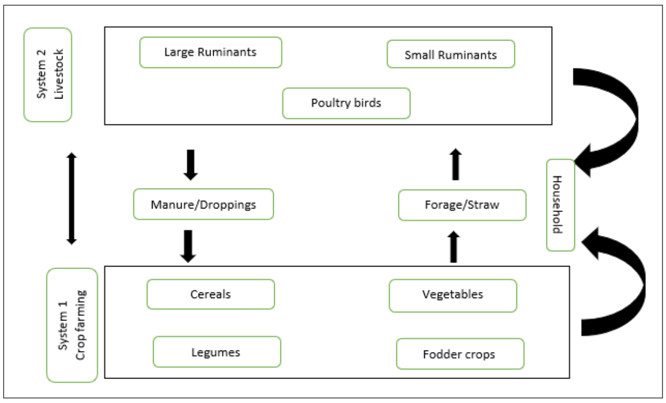

Fig. 1. The conceptual framework adapted from Stark et al. (10).

Materials and Methods

Materials

This study was conducted in the Bhalwal block of Jammu district, Union Territory (UT) of Jammu and Kashmir (J&K). The selection of Bhalwal block was based on the key criteria that, it was officially designated by the Department of Agriculture, Jammu as the implementation site for the "Climate Resilient Sustainable Agriculture in Rain-fed Farming Areas of Jammu and Kashmir" project. This ongoing initiative, operational since 2016-17, focuses on enhancing agricultural sustainability in rain -fed ecosystems, making it an ideal location for examining agricultural diversification patterns and outcomes.

Research design

The present study used an ex post facto (with/without) research design to compare agricultural diversification patterns between 300 farmers from 25 climate-vulnerable villages (VI: 0.64-0.79) and 100 farmers from 25 non-vulnerable villages (VI: <0.64) in study area.

Selection of villages

The study villages were selected through a systematic process beginning with a 2016-17 baseline survey that assessed climate vulnerability across 51 villages in Bhalwal block, Jammu district, using a standardized vulnerability index. From this survey, 25 villages with vulnerability index scores ranging from 0.64 to 0.79 (22) were identified as highly climate-vulnerable and selected as primary study sites due to their demonstrated exposure to climatic risks and need for adaptation interventions. For comparative analysis, an additional 25 adjacent non-vulnerable villages (with index scores below 0.64) were selected as control sites, matched on key agro-ecological and socioeconomic parameters to isolate the effects of climate vulnerability while controlling for regional contextual factors. This paired-village approach, combined with rigorous sample size calculations from the vulnerable villages, ensures robust comparisons while maintaining focus on communities most affected by climate change in this rain-fed agricultural region. For calculating the sample size from vulnerable villages, Slovin's formula (Equation 1) given by Yamane (23) was employed to select the sample of farmers.

$$n = \frac{N}{(1 + Ne^2)} \qquad \text{Eq. 1}$$

Where,

n = required sample size

N = the total number of farmers (N =1250)

e = adjust margin of error at level of significance 5 %.

Selection of respondents

From vulnerable villages, 12 farmers were selected from using random sampling technique. Thus, the sample size from vulnerable villages was 300. For comparison, 100 farmers were selected from the villages where the project was not implemented. Here onwards, these villages will be named as non-vulnerable villages. Thus, total sample size was 400 (300 farmers from villages covered under the project + 100 farmers from the villages who were not covered under the project). The data used for this study was exclusively from primary source and were collected with the help of a interview schedule designed and administrated at the household level through face-to-face interview. The analysis focused on descriptive and comparative assessments of diversification patterns to strengthen causal inferences. The sampling design ensured representation of both project-implemented (vulnerable) and non-project (non-vulnerable) villages, providing a basis for evaluating agricultural diversification under different climate-risk conditions.

Methods applied for diversification and determinants of diversification

Diversification index : Simpson index was used to assess the crop and livestock diversification and Margalef index was used to assess the integrated crop-livestock diversification index. The Simpson Index was employed to measure crop and livestock diversification due to its proven effectiveness in agricultural studies, combining richness (number of species/activities) and evenness (distribution across activities) into a single metric (ranging from 0 to 1) while being less sensitive to rare entries-critical for analyzing smallholder systems with dominant staple crops. For integrated crop-livestock diversification, the Margalef Index was chosen as it specifically quantifies system complexity by accounting for both the variety of components (crops + livestock) and their functional interactions (e.g., crop residues feeding livestock, manure fertilizing crops), aligning with the study's focus on synergies in mixed farming systems. These complementary indices were selected over alternatives (e.g., Shannon-Wiener) because they respectively: (1) prioritize robustness in skewed distributions (Simpson) and (2) capture interdependencies unique to integrated systems (Margalef), thereby addressing the dual objectives of assessing standalone enterprise diversity (crop/livestock) and their combined linkages-a methodological advance over prior studies using single indices.

Simpson index : It is the most suitable index for measuring diversification of crops in a particular geographical region and is calculated by Equation (2):

$$DI_j = 1 - \sum_{i=1}^{N} Pi\,2 \qquad \text{Eq. 2}$$

Where,

DI_j = diversification index of the jth component {j = crps (area) and livestock (in no.)}.

$P_i = \frac{A}{\Sigma Ai}$ = the proportion of the ith activity (crop/livestock) in their respective total).

If DI_j is near zero, it indicates that the zone or region is near to the specialization in growing of a particular crop and if it is close to one, then the zone is fully diversified in terms of crops.

Magalef index (MI) **:** The study expands the conceptual framework by incorporating the Margalef index to quantify diversification indices for crops (System 1), livestock (System 2) and an integrated crop-livestock diversification index that combines both systems (Table 1). The Margalef index was selected due to its superior ability to differentiate diversification levels and its suitability compared to other diversity indices (13). It effectively captures variations in crop and livestock species, making it a reliable measure for assessing agricultural

Table 1. Margalef index by dimension, diversity portfolios and units

Dimension	S	N
Crop (system 1)	Number of crop types planted	Total area planted overall crop types
Livestock (system 2)	Number of livestock types raised	Total number of livestock over all types
Crop-livestock (1 and 2)	Number of crop and livestock types planted and raised	Total number of all livestock species and cropland area

diversification (24). The Margalef index is given as:

$$Di = \frac{Si - 1}{\ln (ni)} \quad \text{Eq. 3}$$

Where,

Di denotes diversification,

Ni is the total number of household-managed system of diversity options in the sample and

Si is the number of household managed system of diversity for the ith household.

A higher Margalef index value signifies greater diversification within a system, whereas a lower value indicates increased specialization and reduced diversity. A zero Margalef index value suggests very limited crop species per unit of land or a low number of livestock species within the population (25).

Determinants of agricultural diversification

***Multiple linear regression*:** Multiple linear regression is a statistical method used to model the relationship between a dependent variable (also called the outcome or target variable) and one or more independent variables (also called predictors or features). The goal of multiple linear regression is to find the best-fitting line (in the case of one independent variable) that minimizes the differences between the observed data and the model's predicted values. In the present study, multiple linear regression model is used to identify the determinants of agricultural diversification.

The formula for linear regression is:

$$Y = \beta_0 + \beta_1 X_1 + \beta_1 X_1 + \ldots\ldots \beta_n X_n + \varepsilon \quad \text{Eq. 4}$$

Where

Y is the dependent variable.

$X_1, X_2, \ldots X_n$ are the independent variable.

β_0 is the intercept.

$\beta_1, \beta_2, \ldots\ldots, \beta_n$ are the coefficients of the independent variables.

ε is the error term (the difference between the observed and predicted values).

- ***Descriptive statistics for variable used in linear regression model:*** The list of the variables which were used in the regression model was described in Table 2.

Results and Discussion

The results indicate that farmers in vulnerable villages are making strides toward achieving the diversification levels observed in non-vulnerable villages, aided by targeted interventions under the project on "Climate resilient sustainable agriculture in rain-fed farming areas of Jammu region".

Crop and livestock diversification

The Simpson's Index for crop diversification was 0.63 in vulnerable villages and 0.67 in non-vulnerable villages, indicating greater crop diversity in non-vulnerable areas (Table 3). This findings aligns with the studies in critical role of irrigation in enabling diverse cropping systems (26). However, it contrasts with studies in Ethiopia it reported higher crop diversification in more vulnerable areas, where diversification serves as a risk-coping mechanism in response to climate variability (27). The discrepancy suggests that Jammu's smallholder farmers face distinct constraints-particularly limited irrigation access (only 28 % of vulnerable villages have assured irrigation) and small landholdings (average 0.59 ha)-that may limit their capacity to diversify crops despite climate risks. Despite these challenges, farmers in vulnerable villages are actively narrowing the diversification gap through the cultivation of drought-tolerant crops, adoption of climate-resilient varieties and participation in capacity-building programs. The study suggests that project interventions-including the provision of drought-resilient crop varieties, training on sustainable agricultural practices and the

Table 2. Descriptive statistics for variables used in linear regression model

Variables	Measurement	Mean	
		Vulnerable villages (n = 300)	Non-vulnerable villages (n = 100)
Age	Years	52.77	57.57
Education	Number of formal schooling years completed	6.82	8.14
Farmer experience	Years	22.24	23.24
Family size	Number of family members	5.28	5.55
Operational land	In ha	0.84	0.94
Irrigation facility	1 = yes, 0 = no	0.09	0.61
On farm occupation	1 = yes, 0 = no	0.99	0.96
Availed Kisan Samman Nidhi Yojana	1 = yes, 0 = no	0.25	0.45
Adoption of cultivation of drought tolerant crops	1 = yes, 0 = no	0.92	0.70
Adoption of drought tolerant varieties	1 = yes, 0 = no	0.45	0.69
Participation in training	1 = yes, 0 = no	0.31	-
Availed crop insurance	1 = yes, 0 = no	0.03	0.16
Distance to market	km	6.41	4.83
Distance to veterinary hospital	km	5.20	3.09

promotion of mixed farming systems-are gradually improving farmers' ability to diversify crops and maintain productivity under changing climatic conditions. These measures enable climate-adaptive diversification strategies, helping to mitigate environmental and economic shocks, consistent with findings by Kassie et al. (18) who demonstrated that targeted interventions accelerate diversification in resource-poor farming communities.

The Simpson's Index for livestock diversification stood at 0.40 in vulnerable villages and 0.37 in non-vulnerable villages (Table 3), indicating a modestly higher level of diversification in vulnerable communities. This suggests that farmers in vulnerable areas are increasingly relying on livestock diversification as a strategy to manage risks and complement their crop-based adaptation measures. As shown in Fig. 3, the average livestock diversification index is slightly higher in vulnerable villages, with a standard error of 0.020, while non-vulnerable villages show a somewhat lower index and a larger standard error of 0.038. This pattern aligns with the broader literature on climate resilience, where diversification into livestock-particularly small ruminants and poultry-has been recognized as an effective risk management strategy (28). Previous studies Feyisa et al. (29) and Thornton et al. (30) have reported that small ruminants and poultry significantly improve household income and food security, especially among lower-income households. However, our study advances this understanding by demonstrating the specific role of project interventions-such as subsidized livestock distribution and breed improvement programs-in facilitating this diversification pathway in Jammu. These initiatives have not only increased livestock ownership among smallholders but also improved productivity, reducing farmers' vulnerability to climate and market shocks. This evidence reinforces the argument by Ngigi et al. (31) that institutional support plays a crucial role in shaping adaptive diversification strategies.

Overall, while non-vulnerable villages exhibit greater crop diversity, vulnerable communities are compensating through livestock diversification, supported by targeted interventions. These findings highlight the need for continued investment in irrigation expansion and livestock support programs to further enhance diversification and build long-term resilience in marginal farming environments

Integrated crop-livestock diversification

The Margalef index for integrated crop-livestock diversification was higher in vulnerable villages (0.88) compared to non-vulnerable villages (0.82) (Table 3), indicating that farmers in more at-risk areas are actively adopting integrated farming systems to enhance food security and stabilize their incomes. Fig. 4 further illustrates that the mean diversification index is slightly higher in vulnerable villages, with a standard error of 0.052, whereas non-vulnerable villages exhibit a marginally lower index with a higher standard error of 0.064. This trend underscores the increasing reliance on diversified farming practices in vulnerable communities, aligning with global findings that integrated crop-livestock systems serve as a crucial climate adaptation strategy by optimizing resource use and improving farm resilience (13). The higher Margalef index in vulnerable villages suggests that smallholders in these areas are adopting integrated systems not only as a climate adaptation mechanism but also as a means to cope with resource limitations. This supports the work of Santermo (32), who emphasized that biological synergies in diversified systems enhance resilience, particularly in low-resource environments. Moreover, the 7.3 % higher diversification level in vulnerable villages compared to non-vulnerable ones exceeds the integration levels reported by Aryal et al. (28) in Nepal, suggesting that targeted project interventions have played a pivotal role in accelerating adoption. These results also provide empirical validation for Thornton and Herrero's (13) theoretical framework, which posits that integrated systems are particularly beneficial for resource-constrained farmers in climate-stressed regions. Contrary to their conclusions, farmers in Jammu's vulnerable villages have achieved synergies through cost-effective practices such as crop residue utilization and diversified fodder sourcing. This suggests that institutional support, rather than capital intensity, can drive integration, aligning with Danso-Abbeam et al. (33), who argue that targeted interventions can compensate for weak market linkages. Furthermore, integrated crop-livestock systems have been

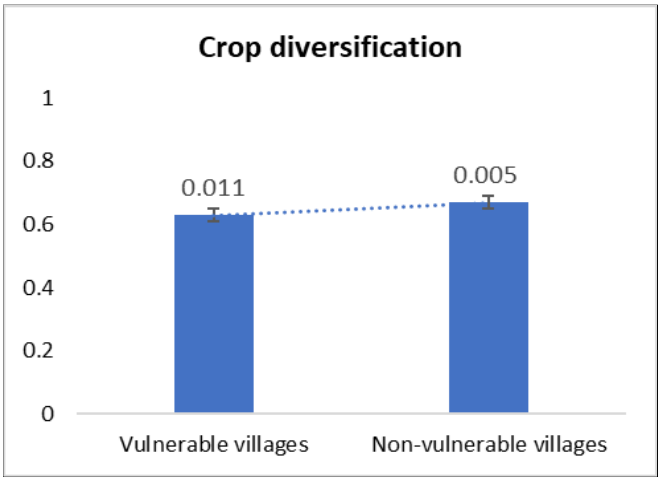

Fig. 2. Pattern of crop diversification index.

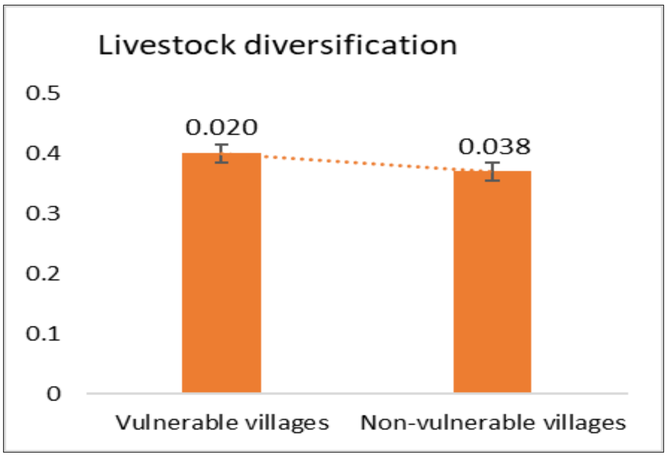

Fig. 3. Pattern of livestock diversification index.

Table 3. Level of agriculture diversification

	Vulnerable villages (n = 300)		Non-vulnerable villages (n = 100)	
	Crop diversification	Livestock diversification	Crop diversification	Livestock diversification
Simpsons index	0.63	0.40	0.67	0.37
	Integrated crop-livestock diversification			
Margalef index	0.88		0.82	

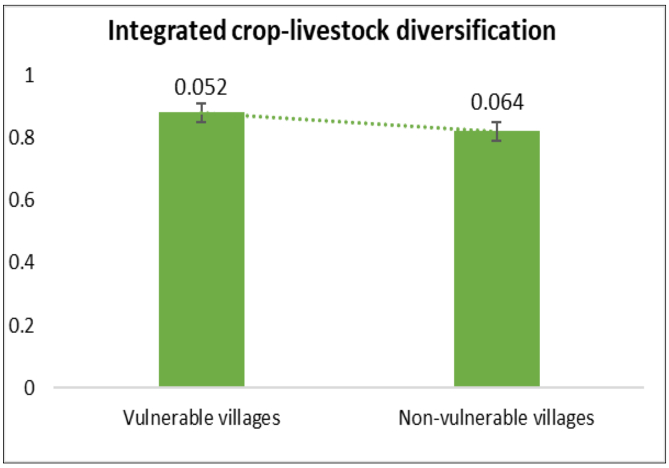

Fig. 4. Pattern of integrated crop-livestock diversification.

widely recognized for their environmental benefits, including enhanced biodiversity and more efficient nutrient cycling (31), reinforcing the sustainability of these practices.

Project interventions-including the promotion of mixed farming, capacity building and sustainable agricultural techniques-have been instrumental in fostering diversification. The narrowing gap in diversification levels between vulnerable and non-vulnerable villages (from 0.07 to 0.06) indicates that these interventions are successfully building resilience and enabling vulnerable communities to catch up. However, continued efforts to improve water access and livestock breed enhancement could further accelerate progress, offering a replicable model for other marginal environments where conventional diversification approaches face constraints.

Overall, these results highlight the effectiveness of climate-resilient agricultural interventions in enhancing farmers' adaptive capacity and long-term sustainability. While challenges remain, the shrinking gap in crop-livestock diversification demonstrates that targeted support can significantly strengthen vulnerable farming communities, positioning them on a more sustainable trajectory.

Determinants of crop diversification

The relationship between crop diversification and various independent variables namely age, education, farmer experience, family size, operational land holding, irrigation facility, on-farm occupation, availed Kisan Samman Nidhi Yojana, adoption of cultivation of drought tolerant crop, adoption of drought tolerant variety, participation in training programs, availed crop insurance, distance to market and distance to veterinary hospital distinguishing between vulnerable and non-vulnerable villages are presented in Table 4.

In vulnerable villages, irrigation access (B = 0.053, $p \leq 0.05$), on-farm occupation (B = 0.54, $p \leq 0.05$), adoption of drought-tolerant crops (B = 0.086, $p \leq 0.05$) and participation in training programs (B = 0.065, $p \leq 0.05$) showed significant positive associations with crop diversification. These findings align with Asfaw et al. (34), who demonstrated that irrigation access and climate adaptation practices significantly enhance resilience and diversification in drought-prone regions of Ethiopia. The role of irrigation can be attributed to its biochemical impact on soil moisture availability, reducing physiological stress on crops and enabling a broader range of cultivars. Similarly, the farmer participation in training programs increased their willingness to diversify, reinforcing the idea that knowledge dissemination enhances farmers' capacity to adopt diversified systems (35). Training programs likely facilitate the uptake of integrated soil fertility management, conservation agriculture and water-efficient cropping strategies, which improve soil structure and microbial activity, further supporting diversification. The adjusted R^2 value of 0.383 suggests that these factors explain a moderate proportion of the variance in crop diversification, emphasizing their role in livelihood resilience under climatic vulnerability.

In non-vulnerable villages, irrigation facilities (B = 0.081, p = 0.002) and the adoption of drought-tolerant crops (B = 0.055, $p \leq 0.05$) were also significantly associated with crop diversification. The well-irrigated regions encourage higher cropping intensity and reduced climate risks, facilitating diversification the findings supports the study (26). The lower adjusted R^2 value of 0.188, however, suggests that in less vulnerable areas, diversification is influenced by additional factors such as market access, credit availability and mechanization rather than climatic stressors alone. The relatively lower explanatory power indicates that in such settings, diversification may be a response to economic opportunities rather than a necessity for resilience. Interestingly, family size (B = -0.004, $p \leq 0.05$) showed a negative relationship with crop diversification in non-vulnerable villages, suggesting that larger households may face resource constraints that hinder diversification efforts. This aligns with

Table 4. Determinants of crop diversification

Variables	Vulnerable villages			Non-vulnerable villages		
	Unstandardized Beta	Standardized Beta	t (Sig.)	Unstandardized Beta	Standardized Beta	t (Sig.)
(Constant)	-0.010		0.132 (0.895)	0.624		0.256 (0.972)
Age	0.000	-0.020	0.336 (0.737)	0.001	0.065	0.516 (0.607)
Education	0.001	0.040	0.550 (0.583)	-0.001	-0.069	0.122 (0.903)
Farmer experience	0.000	0.050	0.964 (0.336)	-0.001	-0.069	0.620 (0.537)
Family size	-0.003	-0.069	1.457 (1.46)	-0.004	-0.078	0.746 (0.458)
Operational land holding	0.002	0.028	0.538 (0.591)	0.010	0.115	1.070 (0.288)
Irrigation facility	0.053	0.164	3.247* (0.001)	0.081	0.356	3.206* (0.002)
On farm occupation	0.54	0.339	7.205* (0.000)	-0.075	-0.133	1.280 (0.204)
Availed Kisan Samman Nidhi Yojana	0.006	0.029	0.544 (0.587)	0.011	0.051	0.479 (0.633)
Adoption of cultivation of drought tolerant crop	0.086	0.249	5.106* (0.000)	0.055	0.227	2.129* (0.036)
Adoption of drought tolerant variety	0.024	0.129	1.843 (0.066)	0.007	0.030	0.291 (0.772)
Participation in training programs	0.065	0.324	6.647* (0.000)	-	-	-
Availed crop insurance	0.029	0.055	1.102 (0.271)	-0.018	-0.058	0.543 (0.589)
Distance to market	0.002	0.069	1.445 (0.150)	0.005	0.161	1.541 (0.127)
R^2		0.410			0.433	
Adjusted R^2		0.383			0 .188	

findings argued that larger families increase subsistence pressure, limiting investment in diverse cropping systems (36). The contrasting trend, where larger households facilitated diversification due to greater labor availability has been observed (37). This discrepancy could be attributed to regional variations in labor utilization-while some households may distribute labor across diversified activities, others might prioritize staple crops for subsistence, reducing diversification potential. Surprisingly, education and farmer experience did not show significant effects in either group. This contradicts studies which found a strong positive link between education and diversification (27). The lack of significance in this study may suggest that institutional and infrastructural constraints in the region overshadow the role of education, limiting farmers' ability to leverage knowledge for diversification. This underscores the need for complementary support mechanisms, such as financial incentives and market access, to translate education into actionable diversification strategies.

Overall, these results emphasize the critical role of irrigation, climate-resilient practices and training participation in promoting crop diversification, particularly in vulnerable villages where farmers face heightened climate risks. The findings also highlight how socioeconomic constraints, such as household size, influence diversification differently across vulnerability contexts. Strengthening irrigation infrastructure, expanding training opportunities and promoting drought-tolerant crops can serve as crucial strategies for enhancing agricultural resilience. Further, addressing institutional barriers—such as access to finance and markets—can further support diversification efforts, particularly in non-vulnerable villages where economic drivers play a more pronounced role.

Determinants of integrated crop-livestock diversification

The integrated crop-livestock diversification index, comparing its determinants in vulnerable and non-vulnerable villages are presented in Table 5. In vulnerable villages, operational landholding ($B = 0.121$, $p \leq 0.05$), adoption of drought-tolerant crops ($B = 0.317$, $p \leq 0.05$), participation in training programs ($B = 0.170$, $p \leq 0.001$) and proximity to markets ($B = 0.024$, $p \leq 0.05$) exhibit significant positive associations with diversification. These findings suggest that larger landholdings create opportunities for diversified cropping and livestock integration, while training programs provide essential knowledge for optimizing resource use within mixed farming systems. The critical role of land availability and capacity-building programs in fostering diversification in mixed farming systems (13). Moreover, the findings demonstrated that exposure to agricultural training enhances farmers' ability to integrate livestock with cropping systems, leading to improved resilience in drought-prone environments (34). The biochemical and physicochemical mechanisms underlying these relationships are multifaceted. For instance, diversified cropping improves soil organic matter content, microbial diversity and nutrient cycling, which collectively enhance soil fertility and resilience against environmental stresses. Similarly, the integration of livestock contributes to nutrient recycling through manure application, improving soil structure and increasing water retention capacity. Access to markets further facilitates diversification by reducing transaction costs and incentivizing the production of high-value crops and livestock products. In contrast, the adoption of drought-tolerant varieties ($B = -0.208$, $p \leq 0.05$) and greater distance to veterinary hospitals ($B = -0.024$, $p \leq 0.05$) show significant negative relationships with diversification. The negative association of drought-tolerant varieties suggests that farmers relying primarily on climate-resilient crop varieties may prioritize monocropping over diversification, viewing these varieties as a risk-mitigation strategy rather than a complement to integrated systems. This finding is consistent while drought-tolerant crops improve climate resilience, they may discourage diversification if perceived as a standalone adaptation measure (38).

Moreover, the limited availability of veterinary services constrains livestock productivity, thereby reducing the feasibility of crop-livestock integration. Veterinary care is essential for maintaining livestock health, preventing disease outbreaks and ensuring optimal growth rates. The inadequate veterinary support significantly hampers livestock adoption in smallholder systems, which, in turn, limits diversification potential has been reported (39). The adjusted R^2 value of 0.294 suggests that these factors explain a moderate to substantial proportion of the variation in diversification in vulnerable villages.

In non-vulnerable villages, operational landholding ($B = 0.091$, $p \leq 0.05$), irrigation facilities ($B = 0.288$, $p \leq 0.05$) and adoption of drought-tolerant crops ($B = 0.358$, $p \leq 0.05$) emerge as significant determinants of diversification. The strong positive effect of irrigation facilities on diversification is consistent with the studies (26), it demonstrated that irrigation access enhances fodder production, enabling greater livestock integration. The physicochemical interactions in irrigated systems contribute to increased biomass production, improved soil moisture retention and reduced water stress, which together create favorable conditions for diversification. The positive relationship between drought-tolerant crops and diversification also aligns with findings (18), suggesting that resilient cropping systems provide economic and ecological stability, allowing farmers to expand into complementary enterprises such as livestock production. This stability reduces income volatility, encourages investment in diversified systems and enhances overall farm resilience. The adjusted R^2 value of 0.273 suggests that while diversification in non-vulnerable villages is influenced by similar factors as in vulnerable villages, the presence of better infrastructure, institutional support and lower climatic risks provides a more stable foundation for integration.

Overall, these findings emphasize the critical role of land availability, irrigation, climate-resilient practices and institutional support in fostering crop-livestock diversification. However, challenges such as limited veterinary access in vulnerable villages may hinder the full realization of diversification benefits. Policies aimed at strengthening diversification should prioritize expanding veterinary services, improving irrigation infrastructure and enhancing farmer training programs, particularly in vulnerable regions where external constraints are more pronounced. Furthermore, promoting drought-tolerant crops as a complementary strategy rather than a substitute for diversification could further support resilience-building efforts.

Table 5. Determinants of integrated crop-livestock diversification

Variables	Vulnerable villages			Non-vulnerable villages		
	Unstandardized Beta	Standardized Beta	t(Sig.)	Unstandardized Beta	Standardized Beta	t(Sig.)
(Constant)	-0.147		0.408 (0.684)	0.671		1.375 (0.173)
Age	-0.001	-0.024	0.386 (0.700)	-0.008	-0.189	1.569 (0.120)
Education	0.009	0.096	1.223 (0.222)	-0.016	-0.127	1.090 (0.279)
Farmer experience	0.001	0.033	0.59 (0.556)	0.002	0.053	0.492 (0.624)
Family size	0.010	0.050	0.991 (0.323)	-0.011	-0.043	0.419 (0.676)
Operational land holding	0.121	0.326	5.826* (0.000)	0.091	0.227	2.222* (0.029)
Irrigation facility	0.070	0.049	0.863 (0.389)	0.288	0.276	2.492* (0.015)
On farm occupation	0.461	0.066	1.303 (0.194)	0.268	0.103	1.020 (0.310)
Availed Kisan Samman Nidhi Yojana	0.065	0.070	1.230 (0.220)	0.078	0.077	0.745 (0.458)
Adoption of cultivation of drought tolerant crop	0.317	0.210	4.022* (0.000)	0.358	0.322	3.073* (0.003)
Adoption of drought tolerant variety	0.208	0.258	3.432* (0.001)	0.043	0.039	0.395 (0.694)
Participation in training programs	0.170	0.196	3.749* (0.000)	-	-	-
Availed crop insurance	0.057	0.024	0.453 (0.651)	0.012	0.009	0.084 (0.933)
Distance to market	0.024	0.218	2.851* (0.005)	0.008	0.056	0.381 (0.704)
Distance to veterinary hospital	-0.024	-0.187	2.372* (0.018)	0.051	0.243	1.507 (0.136)
R^2		0.327			0.522	
Adjusted R^2		0.294			0.273	

Conclusion and recommendations

This study evaluated the impact of the project *"Climate Resilient Sustainable Agriculture in Rain-fed Farming Areas of Jammu and Kashmir"* on agricultural diversification in vulnerable villages. The results indicate that while non-vulnerable villages exhibited slightly higher crop diversity (0.67) compared to vulnerable villages (0.63), livestock diversity was marginally greater in vulnerable villages (0.40) than in non-vulnerable villages (0.37). Moreover, integrated crop-livestock diversification was higher in vulnerable villages (0.88) than in non-vulnerable villages (0.82), highlighting the prominence of integrated farming systems in areas facing greater climate risks. Key determinants of crop diversification in vulnerable villages include access to irrigation, adoption of drought-tolerant crops and participation in training programs, all of which significantly enhance resilience and flexibility in farming practices. Similarly, integrated crop-livestock diversification is driven by operational landholding, adoption of drought-tolerant crops, training programs and market proximity in vulnerable villages, whereas in non-vulnerable villages, operational landholding, irrigation access and adoption of drought-tolerant crops play a crucial role. The findings reinforce the importance of climate-resilient interventions such as promoting drought-tolerant crops and varieties, expanding irrigation infrastructure, organizing capacity-building programs and improving market access to enhance diversification in vulnerable areas. However, limited access to veterinary services negatively impacts diversification, underscoring the need to strengthen livestock support systems. Given that the identified drivers collectively explain nearly 30 % of agricultural diversification, targeted policy measures that support diversification can serve as an effective strategy for mitigating climate risks and improving income stability among farmers in vulnerable regions. By prioritizing these interventions, policymakers can enhance the resilience of smallholder farmers and promote sustainable agricultural development in rain-fed farming areas.

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Authors' contributions

C carried out the primary data collection, analysis of data, participated in the sequence alignment and drafted the manuscript. RS participated in the design of the study, supervised the whole research and helped in compiling and finalization of the manuscript. LKS also participated in the design of the study and helped in compiling the manuscript. JK participated in finalization and compiling manuscript. MKS supervised the statistical analysis of the research. NPT also participated in finalization and compiling manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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