RESEARCH Open Access

Intersectional perspectives on gendered adaptation and social hierarchies in agricultural communities of the Indian Himalaya

Akshita Choudhary[1], Michelle Bonatti[2,4*], Stefan Sieber[2,4], Deepali Tewari Pandey[3] and P. K. Joshi[1]

*Correspondence:
Michelle Bonatti
michelle.bonatti@zalf.de
[1]School of Environmental Sciences, Jawaharlal Nehru University, New Delhi 110070, India
[2]The Leibniz Centre for Agricultural Landscape Research (ZALF), 15374 Müncheberg, Germany
[3]Department of Horticulture, KVK Champawat, G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand 263145, India
[4]Humboldt-University of Berlin, 10117 Berlin, Germany

Abstract
The Indian Himalayan states are among the most vulnerable regions to climate change experiencing declines in agricultural production, food security, and livelihood options. However, the importance of socio-economic factors on adaptation within agricultural communities remains largely underexplored. This study examines the effect of gender, social groups and other socio-economic factors influencing adaptation choices using multivariate probit modelling. Using intersectional perspective, the study explores how diverse socio-economic factors interact and affect the adoption of adaptation strategies in response to climate change impacts. Hierarchical clustering was used to create four social groups based on various socio-economic characteristics, such as income, reservation category (based on caste), family size, education, and income level. Using a stratified random sampling technique, primary data was gathered from 298 sample households in the district Almora of Uttarakhand state in the Indian Himalaya. The findings reveal disparities such as female-headed households rely more on social and ecosystem-based strategies to maintain productivity and ensure food security whereas male-headed households are more predominant in technological and institutional strategies. Regardless, lower social groups of male and female-headed households rely more heavily on ecosystem-based approaches to address climate risks, due to their limited access to the technologies and financial resources that are more prevalent in higher social groups. The results highlight how gender and other socio-economic factors interacts and influence the choice of different strategies. The study claims that an intersectional approach can go beyond binary male and female categories and further investigates at the inter-categorical and intra-categorical level of gender intersectionality. The study contributes to effective adaptation planning and polices by understanding how various socio-economic factors intersects to shape differential vulnerabilities and adaptation strategies.

Keywords Adaptation strategies, Intersectionality, Gender, Social group, Multivariate Probit model

1 Introduction

Climate change significantly threatens agricultural sustainability, exacerbates food insecurity and severely impact the livelihoods of millions, particularly in the countries of Global South [49]. Most researchers and organizations now recognize that understanding vulnerability and adaptation strategies of agricultural communities to the effects of climate change is essential to promote sustainable development and resilience. This imperative is particularly evident in geographically sensitive regions like Indian Himalaya, where topographical factors amplify climate-related impacts compared to lowland agricultural zones [52, 63]. Recent evidence indicates that climatic stressors like temperature rise, frequent droughts, and rainfall irregularities have significantly reduced crop yields and increased food insecurity in mountain regions [40, 65].

The physical impacts of climate change are well documented [68, 79], while how these changes affect people at social level is not widely explored [12, 54]. Although, it is quite known that males and females in farming communities perceive and adapt to climate change differently because of their distinct roles and responsibilities [7, 71, 83]. Nevertheless, local knowledge and background of households are rarely taken into account in research and policy making, suggesting that root causes of vulnerability are typically overlooked, as the top-down viewpoint provides only generic database for adaptation policies and programs. Gender inequalities and vulnerabilities to climate impacts are critical considerations in adaptation planning, where smallholder farmers, in particular, face gender-based disparities in rights and responsibilities [42].

Research widely focused on adaptation to climate change in agricultural sector emphasis on environmental, and technical challenges [22], while socioeconomic, and ecological barriers to adaptation planning have received comparatively less attention [18, 34]. However, recent literature does look into diverse social, ecological and institutional vulnerabilities as well as differentiated adaptation strategies to climate change [30, 56, 65]. There still remains a significant need to understand specific factors that contribute to varied, context-specific vulnerabilities and adaptation. People's experiences and perceptions of climate impacts also play a crucial role in shaping their adaptation strategies. Effective planning and policy implementation require a deep understanding of farmers' socio-economic background and knowledge strongly influence their choice of strategies [31, 69]. Incorporating local factors that affect adaptation can lead to more effective strategies, highlighting the essential role farmers' knowledge and skills [22].

Adaptation strategies are more effective when tailored to specific region and context. These strategies vary not only by the gender of the household head but also among different social groups and households' classes [57]. For instance, communities in the Indian Himalaya may benefit from a deeper understanding of how gender interacts with other social factors, such as caste, education, income [28,60]. A simple distinction between male- and female-headed households is insufficient to comprehend the complex interrelationship of factors that create disparities among households [20]. Social, economic, and ecological factors interact with gender to influence adaptation choices, highlighting how and why gender shapes responses to climate change impacts in differently. In this regard, the theory of intersectionality offers a solid foundation to understand the diverse factors that influence the choice of adaptation strategies within male and female-headed households. In this study, intersectionality is operationalized through a multivariate probit model that includes variation across gender, social groups and other socioeconomic factors at inter-categorical and intra-categorical level.

The study aims to investigate the role of various socio-economic factors along with household gender and social groups in determining the differentiated adaptation strategies adopted by agricultural households. It seeks to answer the following questions: i) How do gender dynamics and differences in household shape the landscape of climate adaptation strategies? ii) What is the relative influence of social, economic, and ecological factors in determining households' capacity to adopt and maintain climate adaptation strategies? To address these questions, this study designed an intersectional adaptation framework to determine the factors that influence their adoption in various households' types. While most studies focus on male v/s female gender differences, this study explores how adaptation choices among females (and among males) vary based on various socio-economic factors, while addressing gender intersectionality. The study highlights that a critical intersectional assessment at inter-categorical and intra-categorical level would contribute to effective pathways in the adaptation process by providing a better understanding of how various factors affect their choices. Along with offers policymakers a nuanced perspective on how different households based on their household head gender and social group perceive climate change and adaptation.

1.1 Conceptual framework: intersectional adaptation analysis framework

The theory of intersectionality was introduced by Crenshaw [21] in sociology, it has since become essential for understanding the differentiated nature of vulnerability and adaptation, particularly concerning gender and its interactions [23, 50]. Th article by McCall [50] on intersectionality elaborates the theory by further categorizing it into three approaches, two of them are utilized in this study. The inter-categorical approaches examine diversity between groups, while, intra-categorical approach explores the complexity of experience within a specific social position or groups [11]. The study includes inter-categorical intersectionality by comparing differences between social groups of male and female-headed households and intra-categorical intersectionality brings out the unique experiences or differences within a social group. An intersectional perspective offers a deeper understanding of factors affecting access to adaptation strategies in the agricultural communities.

IPCC defines adaptation as "the process of adjustment to actual or expected climate and its effects" [32]. It further categorized adaptation, which is used in this study, as structural, social and institutional strategies depending on specific needs and the ways communities and government address climate change impacts. By applying an intersectional approach to adaptation strategies, this perspective ensures that local knowledge and roles of socioeconomic and climatic factors are integrated into adaptation planning. The theory of intersectionality provides a holistic framework for understanding how gender intersects with various socioeconomic factors, shaping differential access to resources [25, 38]. The Fig. 1 illustrates how intersectionality is placed at the centre of various social, economic and ecological factors ultimately influencing the choice of adaptation strategies against various climatic and agricultural constraints. The study aims to examine how interactions among multiple socio-economic and environmental factors, that are further elaborated in the methodology section, influence the choice of adaptation strategies in the agricultural communities from an intersectional perspective.

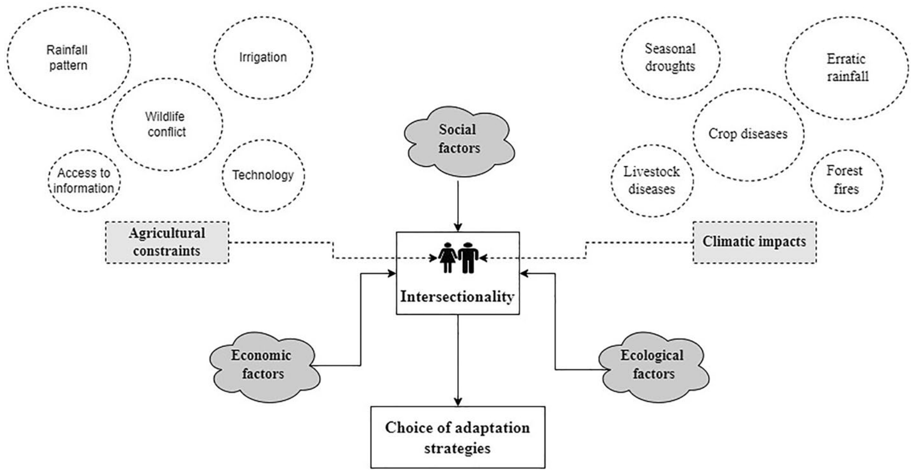

Fig. 1 The conceptual framework of this study shows how intersectionality is placed at the core, interacting with gender and different factors that influence males' and females' choice of strategies

2 Study area

Uttarakhand is a highly vulnerable to extreme climatic events, including erratic rainfalls, flash floods, and recurring droughts, as a result of rising temperatures [69]. Almora, a district in the Kumaon region of Uttarakhand, holds significant agricultural and economic importance. The region is prone to climate change impacts due to its dense population and fragile topography [64]. Over 90% of the population resides in rural areas in the district, where agriculture is the primary source of livelihood. The local economy of the region is mainly dependent on agriculture, horticulture, forestry, tourism and hydropower [77]. The agricultural communities are facing enormous pressure from various social and economic factors intensified by climate change impacts [3, 70].

It is already known that mountain males and females often stick to their culturally defined agricultural roles where females are placed at the center of the agriculture system and males are more involved in off-farm income activities [65]. The changing climate has created extreme conditions for people practicing agriculture; they often seem to abandon their land and seek alternate livelihood sources [42]. The district also faces highest male migration rate (Census of India, 2011), leaving behind females to shoulder additional responsibilities and increase the existing gender inequalities [42].

The district is comprised of nine tehsils and eleven developmental blocks. It encompasses 2289 villages accommodating more than six lakh people. The topography of Almora district ranges from 750 to 2000 m above mean sea level, featuring a landscape of valleys and high mountains. Two developmental blocks, Hawalbagh and Dhauladevi, were selected based on their different elevation ranges (refer to Fig. 2). The selected villages in Hawalbagh lie in the elevation range of 1000–1500 m, while those in Dhauladevi block are at higher elevation ranging from 1500 to 2500 m. Household data was collected from 20 villages, with 10 villages selected from each developmental block.

3 Methodology

3.1 Sampling and data collection

Household data was collected through a stratified random sampling approach using a household survey conducted between April and June 2022. This method was chosen to ensure representative sampling across all reservation categories and gender. In India,

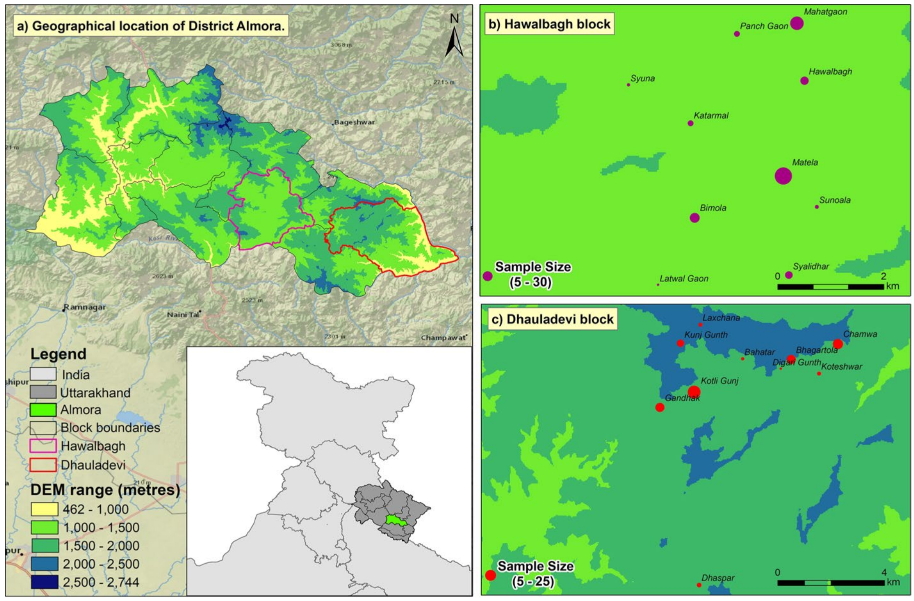

Fig. 2 The study area map, created on ArcMap 10.1 using national and state level boundaries and ASTER digital elevation model (DEM) data at 30 m, shows the location of sample villages in the two blocks of district Almora, Uttarakhand

reservation categories are constitutionally recognized social categories (such as Scheduled Castes, and Other Backward Classes) that have reserved positions in higher education, employment, and government organizations excluding the unreserved or general category [75].

An extensive questionnaire was designed to collect primary data on socioeconomic status, livelihoods information, perception of climate change, farmland size and agricultural adaptation strategies, including access to resources, credit, information, and household food security. The survey includes 298 households that represents both male and female-headed households belonging to different reservation categories. The lead author was responsible for obtaining informed consent from all participants, and the survey was conducted by visiting the households in each village. The author conducted interviews from April to June, 2022 by visiting 6 to 8 households in a day due to rough mountainous terrain. Each interview lasted at least 45 min due to its extensive nature, and the author revisited villages based on the sample households selected. The survey was conducted offline mode and the data was later transcribed and compiled into an excel sheet. The respondent's privacy was protected by following proper confidentiality protocols throughout the data collection.

3.2 Social groups

Social groups were generated using hierarchal clustering based on household's status variables, including total monthly income, education level of the household head, their reservation category as a significant social standing factor [17, 47], and household size. This method was adopted based on its robust nature to include variables measured at different scale and no pre-defined clusters are required. These clusters help reflect social groups within male- and female-headed households, that are most vulnerable and should be prioritized for government assistance [31]. Hierarchal clustering was performed using Ward method, where the distance between clusters is measured by the sum of squares differences across all indicators [27]. Table 1 provides an overview of household, categorized by male- and female-headed into upper, upper middle, lower middle and lower social group.

3.3 Analytical model and tools

A multivariate probit (MVP) model was utilized in this study to assess the impact of various explanatory factors on the adoption of different strategies. The MVP model is appropriate where the binary dependent variables may be correlated or are interdependent [38]. In this case, MVP model is useful as it accounts for correlation between adaptation strategies by exploring the underlying factors that affect decision making where multiple strategies are adopted together. It provides a better methodological framework for examining decision-making and the impact of explanatory variables on the choice of adaptation strategies while accounting for possible correlations between the strategies [55, 59].

The multivariate probit model considers multiple binary dependent variables ($Y_{1,}Y_2,\ldots,Y_M$) that represent different outcomes or choices. Each of these outcomes is modeled as a latent continuous variable Y_i^*

$$Y_i^* = X_i\beta_i + \in_i \; i = 1, 2, \ldots M$$

where, Y_i^* is Latent variable representing the unobserved propensity for outcome iii, X_i is Vector of independent variables (covariates) influencing the outcome, β_i: Coefficient vector for the covariates, and $\in_i$: Error term, which follows a multivariate normal distribution with a mean of 0 and a variance–covariance matrix Σ.

The key feature of the multivariate probit model is the error terms $\in_1$, $\in_2$,.., $\in_M$, are jointly normally distributed, allowing for correlation between them:

$$\in \sim N(0, \Sigma)$$

where Σ is the covariance matrix of the error terms, and the off-diagonal elements capture the correlations between different binary outcomes.

To assess multicollinearity among explanatory on independent factors, Variance Inflation Factors (VIF) was calculated using an Ordinary Least Squares (OLS) regression. The results showed all VIF values below 5 with a mean of 2.33 indicating very less multicollinearity and fit for MVP model. The model is estimated using a maximum likelihood approach. The likelihood function integrates over the joint distribution of the error terms. Given the complexity of the likelihood function, simulation techniques like the Geweke-Hajivassiliou-Keane (GHK) simulator are often used to approximate the likelihood function. Most statistical software packages, such as Stata have built-in functions or packages for estimating MVP models.

Table 1 Total sample households based on the household head's gender and social group

Social group	Gender of household head	
	Male	Female
Upper	35	12
Upper middle	54	37
Lowe middle	56	46
Lower	39	19
Total	184	114

Table 2 The table presents an account of structural strategies identified from literature and pilot survey at the study area

Structural strategies			
Technological	References	Ecosystem based	References
Irrigation (Irr)	Datta and Behera, [22], Kakumanu et al. [37],	Agroforestry (AF)	Datta and Behera, [22], Khatri-Chhetri et al., [43], Pandey et al., [61]
Rainwater harvesting (RWH)	Dey et al., [24], Khatri et al., [43]	Crop diversification (CD)	Ojha et al., [58],Tiwari et al. [77],
New crop varieties (NCV)	Jha, [33], Negi et al., [53]	Mixed Ag livestock (MAgL)	Ravera et al. [65]
High yielding varieties (HYV)	Khatri-Chhetri et al., [43], Negi et al., [53]	Soil conservation measures (SCM)	Dey et al. [42]
		Organic farming (OF)	Negi et al., [53]
		Mixed cropping (MC)	Kumar et al. [44]

Table 3 The table presents an account of social and institutional strategies identified from literature and pilot survey at the study area

Social strategies		**Institutional strategies**	
Strategies	**References**	**Strategies**	**References**
Migration (Mig)	Jha et al., [33]; Negi et al., [53]	Subsidy (Sub)	Chauhan et al., [19], Shukla et al. [70],
Self-help groups (SHG)	Banerjee and Ghosh, [9],Shukla et al., [69],Singh et al. [71],	Crop Insurance (CI)	Singh et al., [74],Dey et al., [24], Khatri-Chhetri et al. [43],
Traditional land-use management (TLUM)	Negi et al., [53]	Training (Tra)	Datta and Behera, [22]
Changing crop calendar (CCC)	Pratap, [62]	Access to credit (Cre)	Karthick and Madheswaran, [39], Singh et al. [74],
Off-farm income (OFID)	Tiwari et al., [78], Khatri-Chhetri et al. [43],	Agricultural extension (AgE)	Shukla et al., [69], Khatri-Chhetri et al. [43]
Land sharing (LS)	Ravera et al. [65]		
Info via internet (Info)	Pandey et al. [61]		

3.4 Selection of variables

3.4.1 Dependent variables

The adaptation strategies were initially identified through a review of literature on the Indian Himalaya context. A pilot survey conducted in the region further refined this list with strategies specific to the study area. During interviews, participants were presented with a list of strategies and asked to choose those they current use. The following table details the identified strategies and their categorization according to IPCC 2014.

The IPCC AR5 categorisation system is the most globally recognised system to cluster adaptation options. It identifies three main categories—structural and physical, social and institutional options. Structural strategies are further divided into two sub-categories [32]. Structural adaptations offer ecosystem based and, technological and infrastructure related solutions, such as agroforestry and improved irrigation techniques respectively. Social adaptations include community practices such as formation of self-help groups (SHGs), while institutional adaptations include the government policies and programs supporting livelihood resilience. Together, these strategies provide a comprehensive adaptation approach, addressing both immediate needs and long-term resilience. Tables 2 and 3 summarise the adaptation strategies included in this study, derived from literature and pilot survey at the ground level.

3.4.2 Independent or explanatory variables

The selection of independent factors is based on a thorough literature review. Previous studies recommend that various socio-economic and demographic factors such as gender, age, education, caste, household size are essential for understanding differences at the household level [22, 38, 65]. Few studies also highlight the significant influence of household decision-maker on adaptation choices [14, 46]. In this study, decision maker is identified as the person who has the primary authority to take decisions in the household [6]. These decisions can be financial, agricultural, education, and any household related expenditure and requirements. The role of decision maker can be shared among household members, in particular to this study, male-headed households may share decision making with females who are more actively involved in agriculture, similarly female-headed households seem to share decisions with their husbands or sons. These decision makers were identified by directly asking respondents who the primary decision maker is and whether the decision is shared with other gender in the household.

Additionally, important factors include access to markets and extension centres, which can also influence strategy choices within a community [8, 51]. Furthermore, perception and understanding of climatic impacts and their variability significantly influence their adoption of adaptation strategies [34, 67]. Table 4 depicts the diverse socio-economic and environmental factors analysed to assess their impact on strategy adoption. It is to be noted that education, income, and household size are used as individual factors in the model, while these variables also contribute to the construction of social group factor. The individual factors represent socio-economic characteristics, and the social group provides a social standing of household background. This allows to study both inter-categorical (between social groups) and intra-categorical intersectionality (explores variation within a social group).

Table 4 The socio-economic and environmental factors utilized in the model as independent variables

Independent indicators	Description	Unit of measurement
Gender	Gender of head of the household is noted	0 = Female, 1 = Male
Age	Age of the household head is considered	Years
Decision maker	The person making decisions regarding major farm and households' responsibilities	Male (0 or 1), Female (0 or 1), Both (0 or 1)
Distance to Ag Ext	Distance to the nearest Ag extension center	Kilometres
Monthly income	The households earning at least 10 thousand Indian rupees and above	0 = less than Rs. 10,000, 1 = Rs. 10,000 and above
Access to market	Distance to the nearest market to the household	Kilometers
Education	Number of years of formal education obtained by the head of the household	Years
Household size	Total number of household members including dependents	Numeric
Social group	Household belong to upper, upper middle, lower middle and lower group based on their income, caste, household size and education	Dummy variables were created for each group
Temperature rise	Households that perceive temperature rise in the last two decades	0 = No change, 1 = Perceive change
Erratic and intensive rainfall	Households that perceive erratic and intensive rainfall episodes have increased	0 = No change, 1 = Perceive change

4 Results

4.1 Household-level socioeconomic profile

Overall, 61.75% of households were male-headed and the remaining were female-headed, mostly due to the absence or permanently migrated males to cities for alternate employment and provide remittance to support their families back home. The average age of household heads are 57.85 years with average household size of 4.6. Both male- and female headed-households have an average land holding size of about 0.26 hectares. Only 9.78% made-headed and 3.59% female-headed households earn more than 20,000 Indian rupees per month. Around 78.5% of all households belong to forward castes in these villages.

The distribution of socio-economic factors across social groups of male- and female-headed households (Table 5) shows that average income range is similar among all social groups for both male- and female-headed households, whereas differences are observed in their average education, household size and the distribution of reservation category under each social group. Average female-headed households obtained no formal education in all social groups, and male-headed households show high school and primary level education in upper and upper middle groups respectively. Average household size in male-headed households increases moving from upper to lower social group, contrastingly the average household size decreases from upper to lower social group in female-headed households. Additionally, reservation category data reveals that female-headed households in lower social groups are predominantly from marginalized castes (OBC and SC), suggesting a compounded disadvantage at the intersection of gender, education and caste.

Adoption of strategies is mostly influenced by the experiences and understanding of decision makers rather than the households' socio-economic status. The study highlights that women are predominantly involved in taking care of their family farms, even if they are not the heads of their household. It is also important to note that not all female-headed households have decision making power in their households. The data show that while men typically make major decisions, such as major household expenditure, buying or selling of farm land and crops, women decide on crop varieties and farm management. Figure 3 highlights the contrast in decision-making dynamics between male- and female-headed households. In male-headed households, men predominantly take decisions on all major expenditures of farm and household, with women having little to no say. In contrast, female-headed households share decision-making with males, where

Table 5 Household-head gender-wise distribution within social groups, reflecting key factors

Factors	Male-headed households				Female-headed households			
	Upper	UM	LM	Lower	Upper	UM	LM	Lower
Income (Rupees)	10,000–15000	5000- 10,000	< 5000	< 5000	10,000–15000	5000-10,000	< 5000	< 5000
Education	High school	High school	High school	Primary	NFE	NFE	NFE	NFE
HH-size (avg)	4.5	4.9	4.3	6	6.2	5.4	3.1	4.4
Reservation category (%)	G: 94.3, OBC: 5.7	G: 96.3, OBC: 1.9, SC: 1.9	G: 98.2, OBC: 1.8	OBC: 23.1 SC: 76.9	G: 100	G: 100	G: 91.7 SC: 8.3	OBC: 52.6 SC: 47.4

Note: UM: Upper Middle; LM: Lower Middle; NFE: No Formal Education; G: General; OBC: Other Backward Castes; SC: Scheduled Castes

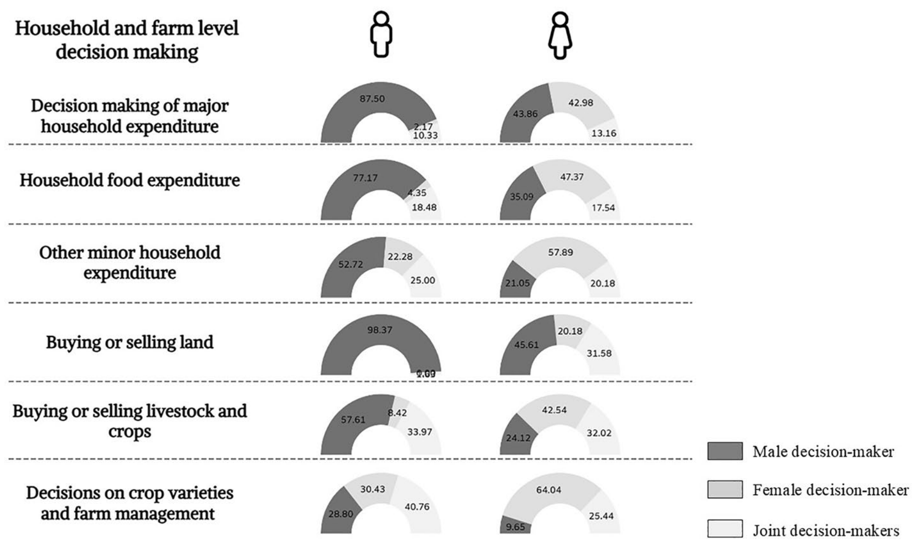

Fig. 3 The nature of household and farm-level decision-making shared between males and females, as reported by the sample households

males often have almost equal decision-making power in major expenditures and decisions related to buying and selling of land. Nevertheless, joint decision-making is more common in male-headed households when it comes to decisions about crop varieties and livestock management. This clearly show that despite females being more involved in agricultural labour, males hold more power in decision-making processes.

4.2 Adaptation strategies across gender and social groups (SGs)

The results of descriptive statistics depict that social and ecosystem-based strategies were more commonly adopted by households compared to technological and institutional ones. Figure 4 illustrates the difference between male- and female-headed households in terms of strategies adopted. Most male- and female-headed households in mountainous region rely on mixed cropping, integrated agriculture-livestock system, traditional soil conservation measures, and crop diversification. Traditional land use practices, such as agroforestry and mixed farming, remain widespread, though crop productivity has been significantly impacted.

The major differences between male- and female-headed households were observed in migration, off-farm income diversification, access to credit and participating in training programs. More than 90 percent of male-headed households have access to credit whereas 72.8 percent of female-headed households have access to credit, meaning male-headed households are 25 percent more likely to get access to credit. Similarly, around 11 percent of male-headed households are more likely to choose off-farm income diversification than female-headed households. Migration is rising due to increase in agricultural challenges due to climate change, more males are moving to lower elevations and urban areas to find alternate income sources. In our study area, 41.3 percent of members from female-headed households are more likely to migrate than male-headed households. With the changing climatic scenarios, adjusting the crop calendar has become a common practice, allowing farmers to align planting and harvesting times with shifting climate patterns to reduce crop failure. There is also a notable shift toward choosing off-farm income diversification as households seek to increase their earnings. The

Fig. 4 The percentage of adoption of different strategies between male- and female-headed households from household survey data

overall scenario of male and female-headed households show that they highly rely on ecosystem-based strategies, followed by social, institutional and least on technological strategies.

The results presented in Table 6 below show the percentage distribution of male-headed and female-headed households adopting different strategies across four social groups: Upper, Upper-Middle (UM), Lower-Middle (LM), and Lower. The results clearly depict that technological strategies are more accessible to male-headed households from upper and upper middle social groups, followed my female-headed households of upper and upper middle groups, male-headed belonging to lower and lower middle and least to female-headed belonging to lower middle and lower social groups. Similar disparities

Table 6 The adoption of different strategies percentages within each social groups of male and female-headed households

Strategies	**Male-headed households**				**Female-headed households**			
Technological	**Upper**	**UM**	**LM**	**Lower**	**Upper**	**UM**	**LM**	**Lower**
HYV	50.00	35.19	38.18	33.33	45.45	37.84	23.40	26.32
NCV	30.56	22.22	14.55	12.82	18.18	21.62	14.89	10.53
RWH	38.89	29.63	16.36	25.64	36.36	37.84	29.79	26.32
WEI	5.56	1.85	1.82	0	0	5.41	0	0.00
Ecosystem-based								
AF	33.33	33.33	7.27	10.26	27.27	18.92	10.64	10.53
CD	75.00	70.37	61.82	79.49	81.82	83.78	63.83	89.47
MAgL	88.89	90.74	94.55	84.62	63.64	83.78	87.23	78.95
MC	72.22	75.93	80	64.10	81.82	72.97	68.09	47.37
OF	11.11	11.11	5.45	15.38	9.09	8.11	4.26	26.32
SCM	86.11	85.19	87.27	74.36	90.91	83.78	74.47	94.74
Social								
CCC	91.67	96.30	94.55	94.87	100	91.89	87.23	94.74
OFID	71.67	72.22	61.82	69.23	72.73	70.27	42.55	52.63
LS	19.44	12.96	9.09	17.95	18.18	13.51	6.38	10.53
Mig	52.78	35.19	40.00	33.33	63.64	27.03	85.11	36.84
SHGs	41.67	59.26	41.82	58.97	72.73	59.46	38.30	57.89
Institutional								
AgExt	36.11	42.59	23.64	25.64	45.45	35.14	17.02	26.32
Sub	25.00	20.37	1.82	10.26	27.03	5.41	2.13	5.26
CI	16.67	20.37	3.64	2.56	27.27	18.92	6.38	5.26
Cre	97.22	90.74	96.36	76.92	81.82	83.78	72.34	47.37
Tra	19.44	9.26	10.91	15.38	9.09	13.51	2.13	0.00

UM-Upper Middle; LM-Lower Middle

are observed under institutional strategies where female-headed households from lower middle and lower social groups have lowest accessibility. Social and ecosystem-based strategies are more or less similarly distributed among males and females, nevertheless, female-headed households predominate adoption of crop diversification, soil conservation measures, migration, join self-help groups (SHGs) and organic farming is more favoured by lower social group female households followed by lower social group male-headed households.

4.3 Multivariate probit model (MVP)—technological strategies

The observed technological strategies in the sampled households are irrigation systems (Irri), rain water harvesting (RWH), and new crop variants (NCV) such as drought and flood resistant crops, and high yielding crops (HYCs). The MVP model results are statistically significant (Wald $\chi2(52) = 114.21$, $p < 0.001$). The results show that gender plays a significant role in adopting some strategies such as female-headed households prefer rainwater harvesting, whereas male-headed households prefer more HYC varieties (Table 7). NCV and HYC were more common among households with higher income range compared to those with lower income range. The findings also show that access to irrigation systems is more common among upper social groups, a clear disparity in resource access based on social groups. The significant correlation coefficient (ρ) of 0.38 between the error terms of the decisions to adopt NCV and WEI signifies a moderate positive correlation. This proves that there are some unobserved factors that increase the likelihood of adopting NCV also affect the likelihood of adopting WEI together.

Table 7 Multivariate probit regression results for technological strategies

Independent factors	WEI	RWH	NCV	HYC
Age	−0.002 (0.008)	−0.010 (0.008)	−0.002 (0.009)	−0.007 (0.008)
Gender	0.057 (0.241)	−0.588*** (0.220)	0.166 (0.268)	0.482** (0.231)
Male—decision maker	0.069 (0.238)	0.350 (0.228)	0.331 (0.282)	−0.289 (0.226)
Female—decision maker	−0.130 (0.309)	−0.296 (0.296)	0.605* (0.363)	−0.080 (0.302)
Income range	−0.202 (0.330)	0.360 (0.300)	0.704** (0.313)	1.254*** (0.339)
Access to market	0.061*** (0.016)	−0.010 (0.015)	0.020 (0.017)	0.019 (0.015)
Formal education (years)	0.010 (0.014)	0.003 (0.013)	0.006 (0.012)	0.019 (0.016)
Household size	−0.049 (0.042)	0.065* 0.039	0.087* (0.043)	0.105*** (0.040)
Temperature change	0.185 (0.456)	0.130 0.390	0.402 (0.630)	−0.233 (0.420)
Rainfall variations	0.253 (0.179)	−0.235 0.168	0.152 (0.199)	0.262 (0.172)
Upper	0.870** (0.429)	0.030 (0.394)	0.108 (0.468)	0.919** 0.433
Upper middle	0.340 0.268	0.100 (0.251)	0.493 (0.340)	1.184*** 0.413
Lower middle	−0.274 0.275	−0.105 (0.251)	0.253 (0.353)	0.179 (0.251)
Constant	−1.550** (0.740)	−0.206 (0.653)	−3.124*** (0.927)	−1.057 (0.673)

Note: Significant levels, *** p ≤ 0.01, ** p ≤ 0.05, * ≤ 0.1

Similarly, the significant coefficient (ρ) between the adoption of NCV and HYC is 0.44 showing a positive correlation in the adoption of NCV and HYC together.

4.4 Multivariate probit model (MVP)—ecosystem strategies

Ecosystem strategies include nature-based solutions like crop diversification (CD), mixed agriculture livestock management (M-Ag-L), organic farming (OF), agroforestry (AF), mixed cropping (MC) and traditional soil conservation measures (SCM) were used to retain water, conserve soil and reduce landslide risks in the mountains. The MVP model is significant at Wald $\chi2(78) = 102.24$, $p = 0.034$.

The results (Table 8) show that crop diversification is less likely to be adopted in lower social groups of both male- and female-headed households, possibly due to larger household sizes and smaller land holdings. Nevertheless, the practice of mixed agriculture and livestock farming is significantly favoured by lower social groups. Organic farming is not widely adopted, but the results indicate that females as primary decision-makers belonging to lower social groups are more likely to choose organic farming, mixed farming and traditional soil conservation measures. This implies a higher likelihood of adopting this practice when females make the agricultural decisions, compared to males or joint decision-making of males and females. Agroforestry is seen to be significantly favoured by both upper middle and lower middle social groups. Soil conservation measures are seen to be more favoured by younger household heads who perceive intensive rainfall as an issue to their farm productivity. The correlation coefficients (ρ) between the error

Table 8 Multivariate probit regression results for ecosystem-based strategies

Independent factors	CD	M-Ag-L	OF	AF	MC	SCM
Age	−0.002 (0.008)	0.014 (0.010)	0.002 (0.010)	−0.006 (0.008)	0.004 (0.007)	−0.018** (0.009)
Gender	−0.361 (0.231)	0.307 (0.282)	−0.160 (0.276)	−0.167 (0.262)	−0.160 (0.242)	−0.333 (0.284)
Male – decision maker	−0.111 (0.234)	−0.017 (0.278)	−0.200 (0.261)	−0.129 (0.245)	−0.298 (0.227)	−0.154 (0.278)
Female – decision maker	−0.229 (0.297)	−0.399 (0.327)	0.644* (0.391)	−0.491 (0.304)	0.598** (0.296)	0.654** (0.331)
Income range	−0.274 (0.312)	−0.052 (0.404)	−0.030 (0.391)	0.088 (0.324)	0.070 (0.328)	0.295 (0.372)
Distance to market	0.020 (0.016)	−0.017 (0.017)	0.004 (0.019)	0.011 (0.015)	0.000 (0.014)	−0.005 (0.017)
Formal education (years)	0.010 (0.016)	0.006 (0.018)	0.002 (0.013)	0.037 (0.024)	0.033 (0.022)	0.021 (0.027)
Household size	0.12*** (0.044)	0.013 (0.045)	−0.039 (0.049)	0.008 (0.037)	−0.022 (0.034)	0.009 (0.042)
Temperature change	0.221 (0.348)	0.228 (0.467)	0.020 (0.550)	0.205 (0.372)	0.220 (0.348)	0.458 (0.352)
Rainfall variations	0.009 (0.170)	−0.218 (0.209)	0.192 (0.224)	0.119 (0.169)	0.395 ** (0.155)	0.324* (0.184)
Upper	−0.118 (0.418)	−0.012 (0.492)	−0.324 (0.488)	0.248 (0.431)	−0.139 (0.414)	−0.042 (0.486)
Upper middle	−0.376 (0.263)	0.229 (0.288)	−0.361 (0.285)	0.303* (0.252)	0.267 (0.236)	0.028 (0.279)
Lower middle	−0.603* (0.249)	0.606** (0.298)	−0.73** (0.304)	0.375* (0.243)	0.432* (0.227)	−0.015 (0.262)
Constant	0.396 (0.655)	0.069* (0.823)	−0.709 (0.911)	0.463 (0.683)	−0.022 (0.606)	1.685** (0.711)

Note: Significant levels, *** $p \leq 0.01$, ** $p \leq 0.05$, * ≤ 0.1

terms of most strategies are positive and statistically significant depicting that there are some unobserved factors that influence households to adopt these strategies together, i.e., most ecosystem-based strategies are practised simultaneously in the households.

4.5 Multivariate

4.5.1 Probit model (MVP)—social strategies

Social adaptation strategies are community level approaches in response to changing climatic conditions. Some of the social strategies households adopted are joining self-help groups (SHGs), and making collective decision, such as changing crop calendar (CCC), migration (Mig) is common among young and middle-aged males to look for alternate income sources, land sharing (LS) is also observed among farmers migrating and leaving their land behind to land-less farmers. Off-farm income diversification (OFID) is also another common practice where households support their income through small businesses, and daily labour.

The MVP model is significant at Wald $\chi2(119) = 264.46$ and $p = 0.000$. The results (Table 9) show that migration appears to be highly influenced by gender and slightly influenced by age, to seek better education and livelihood opportunities. Migration is more prevalent among female-headed households, where female left behind undertake responsibilities of households and farm management. It is also observed that households with male decision makers are less likely to join SHGs, though the likelihood of SHG membership increases with household size. Changing crop calendar (CCC)

Table 9 Multivariate probit regression results for social strategies

Independent factors	Mig	SHG	LS	CCC	OFID
Age	0.029***	−0.012	−0.016*	0.005	−0.012
	0.008	0.008	0.009	0.012	0.009
Gender	−0.418*	0.257	0.161	−0.477	0.314
	0.233	0.231	0.266	0.374	0.256
Male – decision maker	0.057	−0.512**	−0.338	0.563*	−0.917***
	0.223	0.218	0.250	0.321	0.319
Female – decision maker	0.236	0.091	−0.261	−0.332	−0.432
	0.281	0.275	0.325	0.392	0.363
Income range	0.323	0.014	0.368	0.403	6.150
	0.301	0.318	0.371	0.550	100.707
Distance to market	−0.015	0.024*	0.025	−0.018	0.018
	0.015	0.014	0.018	0.019	0.017
Formal education (years)	0.019	−0.021	−0.007	0.024	−0.008
	0.021	0.021	0.014	0.036	0.013
Household size	−0.135***	0.204***	−0.056	−0.026	0.168***
	0.038	0.045	0.047	0.053	0.052
Temperature change	−0.799**	−0.034	−0.593	0.752*	−0.229
	0.399	0.364	0.421	0.420	0.473
Rainfall variations	0.069	−0.238	0.407*	0.013	−0.152
	0.164	0.161	0.216	0.252	0.191
Upper	0.181	−0.182	−0.315	−0.285	−5.344
	0.389	0.404	0.464	0.688	200.6017
Upper middle	−0.296	0.035	−0.280	−0. 107	0.872***
	0.248	0.247	0.286	0	0.288
Lower middle	0.444	−0.154	0.558*	−0.440	−0.253
	0.236	0.232	0.292	0.379	0.236
Constant	−0.413	0.084	0.435	0.933	1.014
	0.654	0.631	0.763	0.906	0.801

Note: Significant levels, *** $p \leq 0.01$, ** $p \leq 0.05$, * ≤ 0.1

is significantly favoured by households with males' decision makers and also by those that perceive rise in temperature as a concern. OFID is favoured by upper middle social groups, but is less favoured in households where males are the primary decision makers. A moderate but significant positive correlation between CCC and OFID show that there are some unobserved factors that adopting CCC tend to increase the likelihood of choosing off-farm income sources as well.

4.6 Multivariate probit model (MVP)—institutional strategies

Institutional strategies refer to the formal policies, and interventions by private or government agencies to manage and reduce climate change impacts. Household have access to institutional provided subsides, crop insurance (CI), training programs, institutional credit, and access to agricultural extension centres (Ag-Ext). The MVP model results are statistically significant (Wald $\chi2(65) = 166.46$, $p = 0.000$) for the effect of explanatory factors on institutional strategies (Table 10).

The results show that households with higher income and with higher education belonging to upper social groups have more access to subsidies and households belonging to lower social groups have less access to subsidies. Access to credit is also positively and significantly affected by education; however, female decision makers have lesser access to institutional credit. Lower middle social groups are more likely to choose government provided credit schemes such as finding livelihoods under National Rural Livelihood Mission, and obtaining credit under Pradhan Mantri Kisan Yojana. Training

Table 10 Multivariate probit regression results for institutional strategies

Independent factors	Subsidy	CI	Training	Credit	Ag-Ext
Age	−0.002	−0.007	−0.021**	0.009	−0.018**
	0.012	0.010	0.010	0.013	0.008
Gender	−0.529	−0.174	0.646*	0.094	0.028
	0.405	0.273	0.336	0.350	0.231
Male – decision maker	−0.188	0.007	0.092	−0.469	−0.177
	0.308	0.283	0.261	0.393	0.218
Female – decision maker	−0.288	−0.127	0.642**	−1.156***	0.053
	0.425	0.354	0.397	0.384	0.277
Income range	1.352***	0.346	−0.375	0.979	0.395
	0.364	0.343	0.432	0.790	0.308
Distance to market	0.045**	0.070***	0.027	0.008	0.044***
	0.023	0.018	0.020	0.020	0.015
Formal education (years)	0.138***	−0.001	0.005	0.057*	0.026
	0.041	0.013	0.013	0.034	0.019
Household size	0.055	0.077	0.068	0.205***	0.069*
	0.054	0.046	0.060	0.066	0.038
Temperature change	0.337	−0.399	−1.055***	0.685	0.570
	0.788	0.481	0.422	0.424	0.464
Rainfall variations	0.274	0.132	−0.016	0.284	−0.025
	0.262	0.230	0.226	0.223	0.166
Upper	1.200**	0.495	−0.674	−0.076	−0.173
	0.536	0.534	0.523	0.842	0.399
Upper middle	−0.497	0.859**	0.114	0.637**	0.227
	0.402	0.399	0.322	0.424	0.245
Lower middle	−1.369**	0.237	−0.148	1.065***	−0.177
	0.574	0.445	0.335	0.313	0.248
Constant	−2.556**	−2.307**	−0.913	−1.746*	−0.990
	1.170	0.912	0.831	0.905	0.707

Note: Significant levels, *** $p \leq 0.01$, ** $p \leq 0.05$, * ≤ 0.1

is more favoured by younger household heads, with male-headed households being more inclined to participate in agricultural trainings than female headed ones. The coefficient of correlation is significant between the subsidy and Ag-Ext stating that these strategies are more like to effect one another. It is also observed that households having higher access to Ag-Ext centres are more likely to participate in trainings than other households.

5 Discussion

Adaptation to climate change in agricultural communities goes beyond economic or technical measures; it is also deeply connected to social measures [38]. Most of the households choose strategies within the context of their socio-economic conditions, and these are mediated by gender, caste, income, education and other factors such as their perception of climate change, decision making and access to resources. 90% of sampled households adopted changing crop calendar to manage shifts in the rainfall season. Due to changing climate patterns, households decide based on their local knowledge to shifts their crop cycles [62, 80]. Verma et al. [81] also noted that agricultural households in Uttarakhand have collectively adjusted their sowing calendar of both rabi and kharif crops due to delay and infrequent winter and monsoon rainfall, respectively.

Most households rely on ecosystem-based strategies like soil conservation measures such as ploughing, terracing, mulching, contour bunding and mixed agriculture and livestock rearing, mixed cropping, and crop diversification. Crop diversification is one of the traditional subsistence strategies mostly adopted by small land holders to ensure food security [16]. Our results show crop diversification is prominent in households belonging to lower social groups. It is a dynamic cropping system that adjusts to changing climatic scenario and enhance productivity and availability of food by incorporating intercropping, crop rotation and mixed cropping over different seasons [11, 29]. Mixed agriculture with livestock rearing is another traditional hilly strategy where households combine crops with livestock to provide additional security at the times of crop failure [45]. Livestock also contributes manure to rainfed agricultural lands, enriching the soil with essential nutrients. However, agroforestry is only practiced by only 30.2% of households; it was found that households on an average with at least 0.4 hectares or more of land opt for it, as farmers with lesser land are unable to adopt because of limited and fragmented farmlands. Nonetheless, integrating trees and shrubs with crops help mitigate soil erosion, improves water retention in rainfed lands and enhance farmer's adaptive capacity of farmers [13,82].

Technological and institutional strategies are among the least adopted by mountainous households. It is primarily due to small land holdings and households solely focused on subsistence farming, which discourage technological interventions. Technologies like efficient irrigation and mechanized farming are widely developed for plains and do not consider the specific needs and tools required by hilly regions [76, 77]. Institutional strategies, such as, access to agricultural extension centres, credit and subsidies, and farmer training are also limited in these regions. Farmers have minimal access to technical knowledge due to underdeveloped extension centres for sustainable agricultural practices [41]. Limited access to institutional strategies like infrequent subsidies and less credit on small farm lands further leads to disregard institutional strategies.

This study further explores the differences between and within gender and social groups to understand the specific needs of households. The following section is divided into two sub-sections to comprehend the underlying factors that leads to differences and adoption of diverse strategies across gender and social groups.

5.1 Adaptation differences between male- and female-headed households.

The nature of adoption of different strategies between male- and female-headed households are influenced by their different roles and responsibilities along with socio-economic variations. For instance, more female-headed households are observed due to rising migration as social norms allows males to migrate but constraints females [35,42]. Male migration is often the primary response to climate change impacts [1], leaving females in charge of household and farmland responsibilities. However, these females who are left behind often face restrictions due to limited land ownership, as well as restricted access to credit, information, and formal training programs [2,66].

HYC are mostly favoured by male-headed households, whereas female-headed households show a strong preference for RWH. Female decision makers also tend to favour more ecosystem-based strategies such as organic farming, mixed cropping and traditional soil conservation methods. It is evident that females usually prefer more traditional methods and favour crop diversification to sustain productivity and food security [15]. It was also noted that households with male decision-makers participate less in self-help groups. However, male-headed households are more adopted to changing crop calendar and more actively participated in training programs than female-headed households. Overall, it becomes clear that male-headed households prefer more technological and institutional strategies while female-headed households rely on ecosystem-based and social strategies. These choices are not standalone gender differences, rather these are the preferred choices based on their household's socio-economic background indicating gender intersectionality with other factors at inter-categorical and intra-categorical level which we will discuss in the next sub-section.

5.2 Major factors affecting choice of strategies within gender and social groups (SGs)

Socio-economic background of households across gender and different social groups significantly influences the choice of strategies. The adoption of technological strategies, such as RWH and NCV are favoured by female-headed households with bigger household size, WEI and HYC by male-headed households are more predominant strategies among upper and upper middle social groups that have more land, better market accessibility, bigger household size and higher income compared to other social groups. Similarly, the adoption of ecosystem-based strategies among female-headed households is more common among lower and lower middle social groups signifying that households with less income, education and belonging lower castes have less accessibility to technological strategies than female-headed households belonging to upper and upper middle social groups. Singh et al. [73] also observed similar findings where wealthier households adapt to climate change better than poor and female-headed households. Nevertheless, social strategies, except migration, are not significantly influenced by household head gender, but rather by the decision maker of the household. The only strategies affected by social groups are land sharing that is prominent in lower social groups and OFID, preferred by households belonging to upper social group due to higher education, income and household support than lower social groups.

Our results highlight how inter-categorical intersectionality between social groups based on their education, income, household size and caste differ and leads to difference in adaptation choices. Lower and lower middle social groups are significantly more dependent on ecosystem-based strategies as they lack access to technologies and financial support that upper social group households do. Another reason being, traditional knowledge is often more prevalent in marginalized communities, plays a crucial role in ecosystem-based adaptation strategies [61, 72]. It is also important to study traditional ecological knowledge of lower social groups that enhances ecosystem-based adaptations. By acknowledging that adaptation also comes from ontological viewpoints, this intersectional pluriverse approach challenges the notion that adaptations are not only scientific, but also culturally and community driven actions [26,48]. This approach promotes theory of intra-categorical intersectionality while assessing and finding effective climate solutions.

While assessing intra-categorical intersectionality within female-headed households of different social groups, the results depict how upper social groups of females have more access to technological and institutional strategies compared to lower and lower middle social groups. Similar disparaties were observed within male-headed households belonging to lower and upper social groups. Recognising these social dynamics is necessary for developing effective adaptation strategies that address both inter-categorical and intra-categorical nature of intersectionality at gender level. By applying an intersectional approach to understand of the interplay between social identities and how these relationships influence vulnerability, decision-making power, and access to land and resources, scholars and policymakers can design equitable and impactful adaptation plans that consider the unique abilities and needs of marginalized groups. The research highlights the importance of integrating gender and its intersectionality as an essential social component into adaptation planning and interventions, developing a more inclusive approach while addressing climate change impacts.

5.3 Limitations and future scope

The intersectional adaptation framework developed in this research includes analysis of various socioeconomic variables including gender and social groups, and enumerate adaptation strategies. However, due to the limited literature that utilize an intersectional analysis, methodological challenges arise when applying intersectionality framework to a quantitative assessment. For instance, complex social relations are reduced to distinct categories, which might not be enough to capture individual experiences and vulnerabilities, that are central to intra-categorical intersectionality. Intersectionality is still understudied despite numerous attempts to consider gender beyond males' v/s females in climate change studies [4, 36]. Future studies might integrate more qualitative data to complement the quantitative findings. In-depth interviews and focus groups could provide richer insights into the lived experiences of households, especially regarding gender dynamics and decision-making processes in adaptation [5, 64].

Another common shortcoming is that primary data is highly dependent on the respondent and it can create biased based on their personal understanding and could lead to different interpretations. Nevertheless, household survey provides firsthand information which can provide valuable information of their socioeconomic status. Secondly, the study covers the minimum required sampling intensity. Lastly, the questionnaire is tailored to collect data on a predefined schema. However, it may be customized for different demographic, geographic and social groups accordingly. In conclusion, while the study has certain limitations, it opens up multiple avenues for further research and contributes to a more nuanced understanding of adaptation strategies from a gender intersectional perspective.

6 Conclusion and recommendations

The study highlights the diverse adaptation strategies employed by male- and female-headed households in response to climate change in a mountainous region. It offers insights into complex and multiple socio-economic factors that differently influence households' strategic choices and recognizes gender-based preferences of different structural, social and institutional adaptation strategies. The study examines the influence of socio-economic factors along with gender and social groups on the adoption of adaptation strategies using MVP model. The results indicate that households majorly adopted ecosystem-based and social strategies, while, less than 50% of the households implement technological and institutional categories.

The results address that gender dynamics and household socio-economic structures play critical roles in shaping climate adaptation strategies. Females often manage household resources and implement adaptation measures like water conservation through rain water harvesting and sustainable agriculture by using traditional methods and crop varieties, but they may face limited access to financial resources, land, decision-making power, and information. Along with these limitations weak socio-economic background such as lesser education, income and belonging to lower castes further constraints their adaptation choices. These factors interact with gender to shape a household's capacity to climate responses.

It becomes clear that adaptation choices are not homogenous in nature and our results from intersectionality perspective reveals that individuals from different social, economic, and cultural backgrounds experience climate impacts differently. Therefore, policy makers and researchers must go beyond one-size-fits-all approach to address these differentiated vulnerabilities. There is a need for intersectional adaptation policies specifically tailored to targeted groups and community-led approaches to be more inclusive of marginalized groups in decision making. Applying and addressing intersectionality framework can offer a deeper and comprehensive understanding of marginalized groups and help contribute to effective policies and programs for the most vulnerable to climate change.

Author Contributions

A.C: conceptualization, methodology, data collection, data analysis, writing the manuscript M.B: conceptualization, supervision, writing the manuscript S.S: supervision, writing the manuscript D.T: supervision, writing the manuscript P.K. J: supervision, writing the manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL. This research have received no funds.

Availability of data and materials

Data Availability Statement The data used in this study originate from primary household surveys conducted as part of the author's PhD research. As the thesis is currently under examination and the dataset includes sensitive personal information for which participant consent for public sharing was not obtained, the dataset cannot be made publicly available.

Declarations

Competing interests

The authors declare no competing interests.

Received: 30 January 2025 / Accepted: 9 June 2025

Published online: 22 July 2025

References

1. Adger, W. N., De Campos, R. S., and Mortreux, C. (2018). Mobility, displacement and migration, and their interactions with vulnerability and adaptation to environmental risks. In: *Routledge handbook of environmental displacement and migration* (pp. 29–41). Routledge.
2. Agarwal B. Gender equality, food security and the sustainable development goals. Curr Opin Environ Sustain. 2018;34:26–32.
3. Aggarwal PK. Global climate change and Indian agriculture: impacts, adaptation and mitigation. Indian J Agric Sci. 2008;78(11):911.
4. Ahmed S, Eklund E. Intersectionality shapes the access to various adaptive resources in climate-vulnerable contexts. Environ Res: Climate. 2024;3(4): 045021.
5. Aldridge J. Working with vulnerable groups in social research: dilemmas by default and design. Qual Res. 2014;14(1):112–30.
6. Anderson CL, Reynolds TW, Gugerty MK. Husband and wife perspectives on farm household decision-making authority and evidence on intra-household accord in rural Tanzania. World Dev. 2017;90:169–83.
7. Arora-Jonsson S. Virtue and vulnerability: Discourses on women, gender and climate change. Glob Environ Chang. 2011;21(2):744–51.
8. Aryal, J. P., Sapkota, T. B., Rahut, D. B., Gartaula, H. N., & Stirling, C. (2022). Gender and climate change adaptation: A case of Ethiopian farmers. In: *Natural Resources Forum* (Vol. 46, No. 3, pp. 263–288). Oxford, UK: Blackwell Publishing Ltd.
9. Banerjee T, Ghosh C. What factors play a role in empowering women? A study of SHG members from India. Gend Technol Dev. 2012;16(3):329–55.
10. Barman, A., Saha, P., Patel, S., & Bera, A. (2022). Crop diversification an effective strategy for sustainable agriculture development. In: *Sustainable crop production-recent advances*. IntechOpen.
11. Bauer GR, Churchill SM, Mahendran M, Walwyn C, Lizotte D, Villa-Rueda AA. Intersectionality in quantitative research: A systematic review of its emergence and applications of theory and methods. SSM-Population Health. 2021;14: 100798.
12. Benevolenza MA, DeRigne L. The impact of climate change and natural disasters on vulnerable populations: A systematic review of literature. J Human Behav Soc Environ. 2019;29(2):266–81.

13. Bhandari, M. S., Shankhwar, R., Meena, R. K., Pandey, S., Kant, R., Barthwal, S., Ginwal, H. S., & Chauhan, J. S. Past and future distribution pattern of Myrica esculenta in response to climate change scenario. Model Earth Syst. Environ. 2021;7:1831–1846.
14. Birkmann, J., Jamshed, A., McMillan, J. M., Feldmeyer, D., Totin, E., Solecki, W., & Alegría, A. Understanding human vulnerability to climate change: A global perspective on index validation for adaptation planning. Sci Total Environ. 2022;803:150065.
15. Bisht, I. S., Mehta, P. S., Negi, K. S., Verma, S. K., Tyagi, R. K., & Garkoti, S. C. Farmers' rights, local food systems, and sustainable household dietary diversification: A case of Uttarakhand Himalaya in north-western India. Agroecology Sustain. Food Systems. 2018;42(1):77-113.
16. Bisht, J. K., Meena, V. S., Mishra, P. K., & Pattanayak, A. (Eds.). (2016). *Conservation agriculture: an approach to combat climate change in Indian Himalaya*. Springer.
17. Bros C. The burden of caste on social identity in India. J Dev Stud. 2014;50(10):1411–29.
18. Casanova-Pérez, L., Martínez-Dávila, J. P., López-Ortiz, S., Landeros-Sánchez, C., & López-Romero, G. Sociocultural dimension in agriculture adaptation to climate change. Agroecology Sustain. Food Systems. 2016;40(8):848–862.
19. Chauhan N, Shukla R, Joshi PK. Assessing inherent vulnerability of farming communities across different biogeographical zones in Himachal Pradesh. India Environ Dev. 2020;33: 100506.
20. Choudhary, A., Ajgaonkar, H., Chauhan, N., Kaechele, H., & Joshi, P. K. (2025). Methodological and empirical insights from gender vulnerability and adaptation responses to climate change in South Asia–a systematic review. *Climate and Development*, 1–12.
21. Crenshaw K. Mapping the margins: intersectionality, identity politics, and violence against women of color. Stanford Law Rev. 1991;43(6):1241–99.
22. Datta P, Behera B. Climate change and Indian agriculture: A systematic review of farmers' perception, adaptation, and transformation. Environ Chall. 2022;8: 100543.
23. Davis K. Intersectionality as buzzword: A sociology of science perspective on what makes a feminist theory successful. Fem Theory. 2008;9(1):67–85.
24. Dey NC, Saha R, Parvez M, Bala SK, Islam AS, Paul JK, Hossain M. Sustainability of groundwater use for irrigation of dry-season crops in northwest Bangladesh. Groundw Sustain Dev. 2017;4:66–77.
25. Erwin A, Ma Z, Popovici R, O'Brien EPS, Zanotti L, Zeballos EZ, Bauchet J, Calderon NR, Larrea GRA. Intersectionality shapes adaptation to social-ecological change. World Dev. 2021;138: 105282.
26. Escobar, A. (2018). Designs for the Pluriverse: Radical Interdependence, Autonomy, and the Making of Worlds. Duke University Press.
27. Ghimire YN, Shivakoti GP, Perret SR. Household-level vulnerability to drought in hill agriculture of Nepal: implications for adaptation planning. Int J Sust Dev World. 2010;17(3):225–30.
28. Goodrich, C. G., Prakash, A., & Udas, P. B. Gendered vulnerability and adaptation in Hindu-Kush Himalayas: Research insights. Environ Dev. 2019;31:1–8.
29. Gururani K, Sood S, Kumar A, Joshi DC, Pandey D, Sharma AR. Mainstreaming Barahnaja cultivation for food and nutritional security in the Himalayan region. Biodivers Conserv. 2021;30(3):551–74.
30. Huyer, S., Gumucio, T., Tavenner, K., Acosta, M., Chanana, N., Khatri-Chhetri, A., ... & Simelton, E. (2021). From vulnerability to agency in climate adaptation and mitigation. *Advancing gender equality through agricultural and environmental research: Past, present, and future*, 261. CGIAR.
31. Huyer S, Loboguerrero AM, Chanana N, Spellman O. From gender gaps to gender-transformative climate-smart agriculture. Curr Opin Environ Sustain. 2024;67: 101415.
32. Intergovernmental Panel on Climate Change. (2014). *Climate Change 2014: Synthesis Report (Longer Report)*. Intergovernmental Panel on Climate Change. Retrieved from: https://www.ipcc.ch/report/ar5/syr/.
33. Jha UC. Current advances in chickpea genomics: applications and future perspectives. Plant Cell Rep. 2018;37:947–65.
34. Jha CK, Gupta V. Farmer's perception and factors determining the adaptation decisions to cope with climate change: An evidence from rural India. Environ Sustain Ind. 2021;10: 100112.
35. Joshi B. Recent trends of rural out-migration and its socio-economic and environmental impacts in Uttarakhand Himalaya. J Urban Reg Stud Contemporary India. 2018;4(2):1–14.
36. Kaijser A, Kronsell A. Climate change through the lens of intersectionality. Environ Polit. 2014;23(3):417–33.
37. Kakumanu KR, Kaluvai YR, Nagothu US, Lati NR, Kotapati GR, Karanam S. Building farm-level capacities in irrigation water management to adapt to climate change. Irrig Drain. 2018;67(1):43–54.
38. Kandel GP, Bavorova M, Ullah A, Kaechele H, Pradhan P. Building resilience to climate change: examining the impact of agro-ecological zones and social groups on sustainable development. Sustain Dev. 2023;31(5):3796–810.
39. Karthick V, Madheswaran S. Access to formal credit in the Indian agriculture: does caste matter. J Soc Inclus Stud. 2018;4(2):169–95.
40. Kaul V, Thornton TF. Resilience and adaptation to extremes in a changing Himalayan environment. Reg Environ Change. 2014;14:683–98.
41. Kaur K, Kaur P. Agricultural extension approaches to enhance the knowledge of farmers. Int J Curr Microbiol App Sci. 2018;7(2):2367–76.
42. Khandekar, N., Gorti, G., Bhadwal, S. and Rijhwani, V. Perceptions of climate shocks and gender vulnerabilities in the Upper Ganga Basin. Environ Dev 2019;97-109.
43. Khatri-Chhetri, A., Poudel, B., Shirsath, P. B., & Chaudhary, P. (2017). Assessment of climate-smart agriculture (CSA) options in Nepal. *CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), New Delhi, India*.
44. Kumar, N., Mrunalini, K., Patnaik, G. P., & Behera, B. (2023). Efficient Diversified Cropping Systems of Field and Horticultural Crops for Livelihood Security. In *Integrated Pest Management in Diverse Cropping Systems* (pp. 1–29). Apple Academic Press.
45. Kumar P, Sharma PK, Kumar P, Sharma M, Butail NP. Agricultural sustainability in Indian Himalayan region: Constraints and potentials. Indian J Ecol. 2021;48(3):649–61.
46. Lawson ET, Alare RS, Salifu ARZ, Thompson-Hall M. Dealing with climate change in semi-arid Ghana: understanding intersectional perceptions and adaptation strategies of women farmers. GeoJournal. 2020;85(2):439–52.
47. Lerche J, Shah A. Conjugated oppression within contemporary capitalism: class, caste, tribe and agrarian change in India. J Peasant Stud. 2018;45(5–6):927–49.

48. Martínez-Torres ME, Rosset PM. Diálogo de saberes in La Vía Campesina: Food sovereignty and agroecology. J Peasant Stud. 2014;41(6):979–97.
49. Mbow, C., C. Rosenzweig, L.G. Barioni, T.G. Benton, M. Herrero, M. Krishnapillai, E. Liwenga, P. Pradhan, M.G. Rivera-Ferre, T. Sapkota, F.N. Tubiello, and Y. Xu, 2019: Food security. In *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Intergovernmental Panel on Climate Change.
50. McCall L. The complexity of intersectionality. Signs: J Women Cult Soc. 2005;30(3):1771–800.
51. Nagar A, Nauriyal DK, Singh S. Determinants of farmers' access to extension services and adoption of technical inputs: Evidence from India. Univ J Agric Res. 2021;9(4):127–37.
52. Negi GCS, Samal PK, Kuniyal JC, Kothyari BP, Sharma RK, Dhyani PP. Impact of climate change on the western Himalayan Mountain ecosystems: an overview. Trop Ecol. 2012;53(3):345–56.
53. Negi, V. S., Maikhuri, R. K., Pharswan, D., Thakur, S., & Dhyani, P. P. Climate change impact in the Western Himalaya: people's perception and adaptive strategies. J Mt Sci. 2017;14(2):403–416.
54. Ngcamu BS. Climate change effects on vulnerable populations in the Global South: a systematic review. Nat Hazards. 2023;118(2):977–91.
55. Nhemachena C, Hassan R, Chakwizira J. Analysis of determinants of farm-level adaptation measures to climate change in Southern Africa. J Dev Agric Econ. 2014;6(5):232–41.
56. Nong HTT, Gan C, Hu B. Climate change vulnerability and adaptation in Vietnam from a gender perspective: a case study of Northern province of Vietnam. Int J Soc Econ. 2020;47(8):953–72.
57. Nyantakyi-Frimpong H. Unmasking difference: Intersectionality and smallholder farmers' vulnerability to climate extremes in Northern Ghana. Gend Place Cult. 2020;27(11):1536–54.
58. Ojha HR, et al. Is South Asian agriculture adapting to climate change? Evidence from the Indo-Gangetic Plains. Agroecol Sustain Food Syst. 2014;38(5):505–31.
59. Ojo TO, Adetoro AA, Ogundeji AA, Belle JA. Quantifying the determinants of climate change adaptation strategies and farmers' access to credit in South Africa. Sci Total Environ. 2021;792: 148499.
60. Ogra, M. V., & Badola, R. (2014). Gender and climate change in the Indian Hindu-Kush Himalayas: global threats, local vulnerabilities. *Earth System Dynamics Discussions*, *5*(2).
61. Pandey R, Kumar P, Archie KM, Gupta AK, Joshi PK, Valente D, Petrosillo I. Climate change adaptation in the western-Himalayas: Household level perspectives on impacts and barriers. Ecol Ind. 2018;84:27–37.
62. Pratap, D. (2015). Climate Change Impacts and Adaptation by Communities in a Tribal Region of Central Himalaya: A Study from Uttarakhand Himalaya India. In: *international conference on commons*, 1–16.
63. Rani S, Kumar R, Maharana P. Climate change, its impacts, and sustainability issues in the Indian Himalaya: an introduction. In: Climate Change: Impacts, Responses and Sustainability in the Indian Himalaya. Cham: Springer International Publishing; 2022. p. 1–27.
64. Rao N, Lawson ET, Raditloaneng WN, Solomon D, Angula MN. Gendered vulnerabilities to climate change: insights from the semi-arid regions of Africa and Asia. Climate Dev. 2019;11(1):14–26.
65. Ravera F, Iniesta-Arandia I, Martin-Lopez B, Easter U, Bose P. Gender perspectives in resilience, vulnerability and adaptation to global environmental change. Ambio. 2016;45:235–42.
66. Rijhwani, V., Sharma, D., Khandekar, N., Rathod, R., & Govindan, M. (2021). Gender dynamics and climate variability: Mapping the linkages in the Upper Ganga Basin in Uttarakhand, India. In Engendering Climate Change, Routledge India. pp. 201–225.
67. Sam AS, Padmaja SS, Kächele H, Kumar R, Müller K. Climate change, drought and rural communities: Understanding people's perceptions and adaptations in rural eastern India. Int J Disaster Risk Reduct. 2020;44: 101436.
68. Shivanna KR. Climate change and its impact on biodiversity and human welfare. Proc Indian Natl Sci Acad. 2022;88(2):160–71.
69. Shukla R, Agarwal A, Sachdeva K, Kurths J, Joshi PK. Climate change perception: an analysis of climate change and risk perceptions among farmer types of Indian Western Himalayas. Clim Change. 2019;152:103–19.
70. Shukla R, Sachdeva K, Joshi PK. Inherent vulnerability of agricultural communities in Himalaya: A village-level hotspot analysis in the Uttarakhand state of India. Appl Geogr. 2016;74:182–98.
71. Singh C, Deshpande T, Basu R. How do we assess vulnerability to climate change in India? A systematic review of literature. Reg Environ Change. 2017;17:527–38.
72. Singh P, Tewari P, Verma D. Status of self-help groups in Uttarakhand. Int J Basic Appl Agric Res. 2017;15(3):242–7.
73. Singh RK, Zander KK, Kumar S, Singh A, Sheoran P, Kumar A, Hussain SM, Riba T, Rallen O, Lego YJ, Padung E, Garnett ST. Perceptions of climate variability and livelihood adaptations relating to gender and wealth among the Adi community of the Eastern Indian Himalayas. Appl Geogr. 2017;86:41–52.
74. Singh NP, Anand B, Khan MA. Micro-level perception to climate change and adaptation issues: a prelude to mainstreaming climate adaptation into developmental landscape in India. Nat Hazards. 2018;92:1287–304.
75. Soren C. Reservation in India: rhetoric and reality. Int J Adv Res. 2021;9(7):1234–40.
76. Tiwari PC. Land-use changes in Himalaya and their impact on the plains ecosystem: need for sustainable land use. Land Use Policy. 2000;17(2):101–11.
77. Tiwari PC, Joshi B. Natural and socio-economic factors affecting food security in the Himalayas. Food Secur. 2012;4:195–207.
78. Tiwari KR, Rayamajhi S, Pokharel RK, Balla MK. Determinants of the climate change adaptation in rural farming in Nepal Himalaya. Int J Multidiscipl Curr Res. 2014;2(1):2321–3124.
79. Tracker, C. A. (2021). *Warming projections global update*. Climate Analytics and New Climate Institute.
80. Tripathi A, Mishra AK. Knowledge and passive adaptation to climate change: an example from Indian farmers. Clim Risk Manag. 2017;16:195–207.
81. Verma T, Bhardwaj DR, Sharma U, Sharma P, Kumar D, Kumar A. Agroforestry systems in the mid-hills of the north-western Himalaya: a sustainable pathway to improved soil health and climate resilience. J Environ Manage. 2023;348: 119264.
82. Verma, A., Kumar, M., & Bisht, S. (2022). Changing patterns of agriculture in Uttarakhand state from 2010–2020. *IOSR Journal of Economics and Finance (IOSRJEF)*, 1–10.

83. Yadav SS, Lal R. Vulnerability of women to climate change in arid and semi-arid regions: The case of India and South Asia. J Arid Environ. 2018;149:4–17.

Publisher's Note