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Climate change vulnerability among pineapple agroforestry farmers in the Indian sub-Himalayas

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Abstract
The Hmar community of the Indian sub-Himalayas has shifted from traditional shifting agriculture to economically viable pineapple-based (*Ananas comosus*) agroforestry, helping manage economic crises while providing environmental benefits. However, the functioning and essential ecosystem services of these systems are under increasing threat from climate change, jeopardising food and livelihood security. Understanding the ecological, economic, and social dimensions of vulnerability at the micro-level is essential for identifying stressors and ensuring sustainable agroforestry practices. To assess socio-ecological vulnerability, 122 households were surveyed across five villages using the IPCC climate vulnerability framework, complemented by focus group discussions to understand community-level adaptive strategies. Principal Component Analysis identified key components, followed by aggregation to measure exposure, sensitivity, and adaptive capacity. The entropy method was applied to assign village-level weights for sensitivity and adaptive capacity to construct a composite vulnerability index. Most households lived in semi-pakka houses and a nucleated family structure. Farmers' education levels ranged from primary to matriculation, with an average monthly income of about US$120. Villages with higher climate susceptibility experience erratic temperature and precipitation patterns and frequent extreme events, negatively impacting pineapple productivity, further exacerbated by the lack of irrigation infrastructure. Households heavily reliant on pineapple cultivation are more vulnerable to climate change disruptions. These factors contribute to higher climate sensitivity in Saisel Punjee (0.35) and Lobonkhal (0.32), reflecting greater socio-ecological vulnerability. Villages lacking strong social networks, sufficient infrastructure, and diversified income sources show reduced adaptive capacity. In contrast, villages implementing resilient farm management strategies, such as diverse tree integration, erosion control, reduced tillage, proper residue handling, pest and disease control, and optimised crop density, function as effective Nature-based Solutions (NbS) and reduce climate vulnerability. Adaptive capacity was stronger in Kolom Punjee (0.27) and Hmarkhawlein (0.28), leading to lower vulnerability. Strengthening resilience requires supportive policies, expanded market access, promotion of small-scale enterprises, alternative livelihoods, and investments in education, rural infrastructure, and ecosystem restoration.

Keywords Adaptability, Ecosystem services, Extreme events, Sensitivity, Shifting agriculture

1 Introduction

The social, economic, ecological, and political systems are jeopardized by the complex crisis posed by global climate change [1], leading to uneven disruptions across sectors and regions [1]. In developing countries, communities reliant on natural and land-based livelihoods are often impoverished and marginalised, and therefore experience greater climate vulnerability [2]. India is ranked as the 7th most vulnerable country to extreme events of climate change [3], resulting in annual losses of US$9 to 10 billion [3]. Likewise, the Indian Himalayan regions face diverse risk from extreme climate events [4]. The farming practices of mountain communities reflect their socio-cultural traditions; however, the goods and ecosystem services of these systems are being severely affected by changing climatic conditions [5].

Shifting agriculture, locally called "Jhum," practised by different ethnic communities in the Indian East Himalayas, sustains the livelihoods of approximately 0.44 million indigenous people [6, 7]. Over time, extended cultivation practices and shortened fallow periods (from 20 years to 3–5 years) have degraded the long-term viability of this system. Rapid human population growth and shrinking landholdings at the individual level have further intensified these changes [8]. Such changes also disrupt the ecological balance within socio-cultural systems, making communities more vulnerable to climate change [9].

The impact of climate change on shifting agricultural sites in northeast India could increase soil erodibility by up to 60% due to shorter fallow cycles if global temperatures increase by 3 °C [10]. The rising temperatures has major impacts on tree mortality, seed germination and dispersal, pest attacks, growth of invasive species, phenological alterations, crop yield, and animal productivity [11]. Moreover, variations in temperature and rainfall directly affect agricultural productivity, and the lack of irrigation facilities in the region further threatens food security and rural livelihoods [12]. The complex challenges posed by climate change to shifting agriculture can push farmers toward extreme poverty.

Agroforestry has become a key strategy for restoring degraded landscapes by integrating forestry and agricultural practices to enhance ecosystem services and improve the climate resilience of rural communities. Some tribal communities in the Indian sub-Himalayas have shifted their shifting agricultural lands to cash crop plantations, such as pineapple (*Ananas comosus*) agroforestry systems [13]. The Hmar community in this region has been cultivating pineapple for centuries [14]. This land-use transition has accelerated over the past four decades due to growing market demand, promoting sustainable land management by integrating crops and trees. Traditional agroforestry systems contribute to reducing poverty and lowering the risks associated with monoculture practices by providing higher incomes [15], while also improving soil fertility through enhanced nutrient cycling, increased water retention, carbon sequestration, and support biodiversity within the system [16]. These systems also support access to nutritious food by aligning crop diversity with local diets and cultural traditions, and accelerate rural economies through a sustainable, food-based approach rooted in local knowledge

[17]. Integrating Local Ecological Knowledge (LEK) into agroforestry practices can further enhance adaptive capacity while empowering communities through participation in decision-making, thereby strengthening local governance structures [18].

However, a study on socio-economic vulnerability in Mizoram, India, showed that the services of traditional agroforestry systems are severely threatened by climate change [19]. Farmers with smaller landholdings, frequent crop losses, higher disease outbreaks, and limited livelihood options are more vulnerable, often resulting in economic losses at the household level [20]. Furthermore, climate vulnerability is exacerbated by food insecurity, low income, land-use change, agricultural limitations, high dependency ratios, and gender disparities [21]. Similarly, pineapple farmers are increasingly affected by global climate change by reduced productivity, changes in fruit quality, and increased pest attacks [22, 23]. Extreme climate events also disrupt pineapple export chains, leading to reduced farm income in Ghana [22]. Therefore, understanding both non-climatic and climatic factors is essential to avoid disruptions in pineapple cultivation [24].

Understanding the extent of climate change vulnerability among pineapple agroforestry farmers is crucial to sustain livelihoods and protect cultural values. Climate change vulnerability is defined as to the "degree of exposure to extreme climate events, sensitivity to their impacts, and the capacity to adopt resilient strategies" [25, 26]. This vulnerability is closely linked to socioeconomic factors and policy-making and differs across regions [27]. Assessing the key drivers of climate change and identifying areas most at risk are important for effective planning and resource management [28]. Furthermore, understanding the farm-level climate-adaptive strategies of pineapple agroforestry farmers is crucial for advancing climate-resilient approaches and for providing opportunities to develop a sustainable, food-based economy grounded in traditional knowledge systems [17].

Although several studies have highlighted the contribution of pineapple agroforestry in southern Assam and the Indian sub-Himalayas, it has emerged as a key strategy to accelerate land productivity in hilly regions [13]. It also acts as a natural approach to restore degraded landscapes and supports rural livelihoods [29]. Research has reported total vegetation carbon storage ranging from 28.23 to 71.80 Mg ha^{-1} and a soil organic carbon sequestration rate of 1.52 Mg ha^{-1} yr^{-1}, highlighting the influence of stand age on tree density, basal area, and aboveground carbon stock in the Cachar district of Assam, India [14]. Furthermore, previous studies have highlighted that integrating tree species such as *Hevea brasiliensis*, *Mangifera indica*, *Tectona grandis*, *Parkia timoriana*, *Eucalyptus globulus*, and *Azadirachta indica* into pineapple agroforestry systems substantially diversifies farm income and improves soil health management in the Indian Himalayan region [13, 30, 31].

Despite the growing global concern over climate change, a comprehensive understanding of the socioeconomic and ecological aspects of climate change vulnerability among pineapple agroforestry farmers is lacking; this gap persists even in the global context. Most studies focus on the evaluation of the economic and ecological benefits of pineapple agroforestry systems [13, 14, 29, 32], with relatively less attention given to their socio-ecological vulnerability under changing climatic conditions. Evaluating climate vulnerability at the village level is important for increasing adaptive capacity and addressing the challenges posed by climate variability within agroecological systems. Therefore, an in-depth understanding of the effects of climate change on farming communities is key to support pineapple agroforestry in a sustainable approach and to provide key inputs for effective policy interventions [13].

This research helps promote sustainable management and support long-term resilience against global climate change. Additionally, identifying specific indicators of climate change vulnerability among traditional farming communities would provide a baseline for future scientific exploration of climate risk and vulnerability assessment in other similar agrarian systems. Additionally, it is essential to assess the socio-economic conditions of farmers to inform pertinent policy interventions. Accordingly, the present study focuses on understanding the socio-ecological factors affecting the climate change vulnerability, the impacts of extreme climate events on traditional pineapple agroforestry farmers, and the effectiveness of various traditional farm management strategies to mitigate climate risks across the villages. Therefore, the specific objectives were to: (i) evaluate the socio-economic settings of pineapple agroforestry farmers in the study region; (ii) evaluate perception of climate exposure among pineapple agroforestry farmers and analyse climatic trends; and (iii) examine differences in village-level climate sensitivity and adaptive capacity, and derive a composite socio-ecological vulnerability using the Intergovernmental Panel on Climate Change (IPCC) framework.

2 Materials and methods

2.1 The profile of the study region

The Sub-Himalayan range, extends from the Indian state of Punjab to Assam and is commonly referred to as the Himalayan foothills, this region.

The study was conducted in the Cachar district of Assam, encompassing an area of 3786 square kilometres (Fig. 1), with elevation ranging from 22 masl (metres above sea level) in the eastern part to 1657 masl in the north [13]. This district is located in the Indo-Burma biodiversity hotspot. This region includes a diverse ecosystem, including

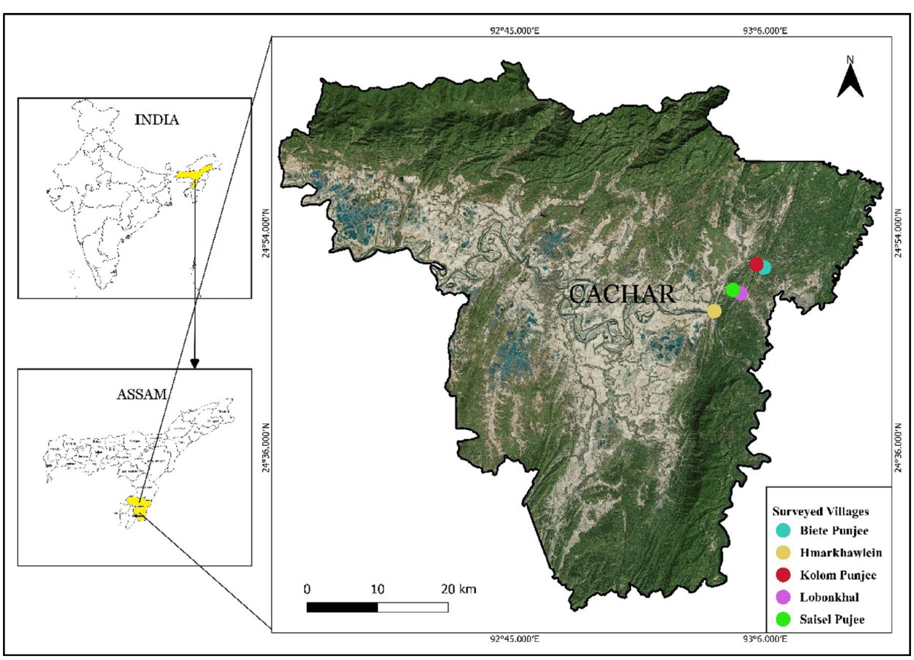

Fig. 1 Map of the surveyed villages with pineapple agroforestry farmers in the Indian sub-Himalayas

plains, undulating terrain, hillocks, and waterlogged lands [33]. The primary river flowing through this area is the Barak.

The study region receives an average annual rainfall of about 2290 mm [13], with atmospheric temperatures ranging from 9.4–15°C in winter to 35°C and 40°C in summer [14]. The average annual relative humidity is 76% [14]. The dominant soil types in this zone are "sandy clay loam" and "sandy loam", both classified as "Inceptisols" of the Barak series under the United States Department of Agriculture (USDA) classification system. According to the World Reference Base for Soil Resources (WRB), these soils correspond to "Cambisols" [34]. The vegetation is dominated by "Cachar tropical evergreen (1B/C3)" and "semi-evergreen (2B/C2)" forests [35], characterised by diverse plant species.

2.2 The study community

The Hmar ethnic group, a subgroup of the broader "Mizo-Kuki-Chin" ethnic cluster in India, is demographically vulnerable due to its small population [36]. The Hmar people are among the various tribes that live in the northeastern states of India, including Assam, Manipur, Meghalaya, Mizoram, and Tripura, as well as the Chittagong Hill tracts of Bangladesh and the upper Myanmar region, and speak a "Tibeto-Burman" language. They lack written historical evidence [37], and the name Hmar remains unfamiliar to most Indians. Despite their rich history and cultural heritage, the Hmar people have largely remained unknown, primarily due to the scarcity of documentation and limited scholarly work addressing their identity [36]. The Hmar population shows a strong dependence on agriculture for their livelihood, as the majority of the population is associated with shifting agriculture [36]. Furthermore, owing to modern economic and environmental pressures, land is transitioning to horticulture-based agroforestry systems and monoculture plantations, which are prominent among the Hmar community [29]. There is no recent official census data of the Hmar population in Cachar district. However, according to the Barak Valley Hill Tribes Development Council (2007), the Hmar population in the district was calculated at 36,684, comprising 5216 households across 99 villages [32, 38].

2.3 Data collection

Primary data on the ethnic Hmar community, livelihood opportunities, land-use practices, the impact of extreme climate events, and adaptive mechanisms to climate challenges were collected during initial visits to the study region. A schematic illustration of the transitional changes in pineapple agroforestry managed by the Hmar community is shown in Fig. 2. An indicator-based questionnaire was developed using information from literature review, field observations, and peers' discussions to analyse the causes and nature of climate change vulnerability (Table S1). This approach is widely used to evaluate climate change vulnerability of stakeholders by providing relevant knowledge into the social, economic, and ecological settings of the systems and the communities that rely on them [20, 28, 39, 40]. The questionnaire comprised 77 indicators covering social context, demographic features, economic settings, ecological features, climate trends, livelihood patterns, and agricultural management practices (Table S1). A total of 26 components were formed by grouping indicators according to their association with

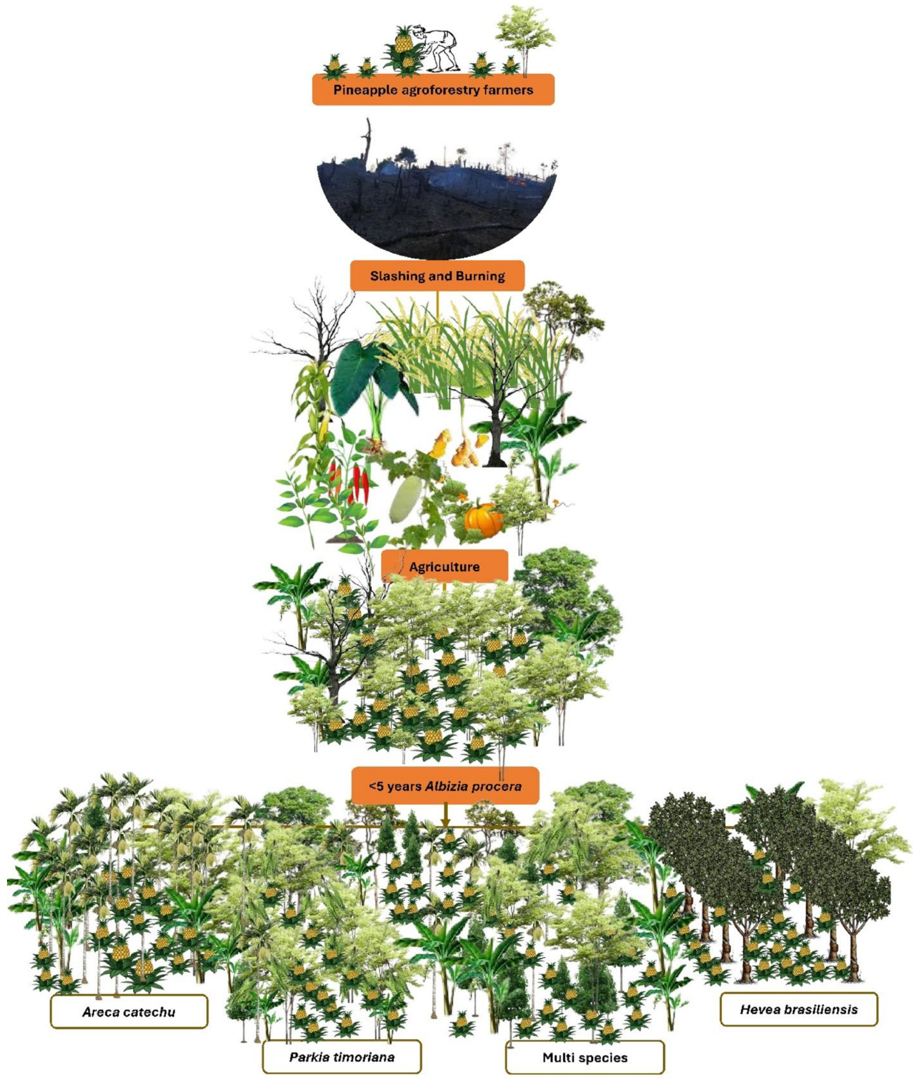

Fig. 2 Schematic representation of pineapple agroforestry system in the study region

climate change vulnerability (Table S1). The questionnaire was revised after a pretest, and the final version was used for household interviews.

2.3.1 Selection of the indicators

Evaluating climate exposure based on eight key components highlighted region-specific fluctuations in temperature and rainfall regimes, along with the intensity and frequency of extreme climate events like rainfall, water stress, landslides, incidences of disease, pest, and weed and invasive plants' growth over the past 20 years [40–42] (Table S1). Additionally, climatic data including annual mean maximum temperature, annual mean minimum temperature, annual mean temperature, and annual rainfall for the period 1985–2024 were collected from NASA's Data Access Viewer (https://power.larc.nasa.gov/data-access-viewer/) to assess long-term trends in temperature and rainfall in the study region. This online portal provides access to globally gridded datasets derived from satellite observations and reanalysis products, facilitating the extraction of point-specific climate data.

Sensitivity was determined using eight components including (unavailability of land, the impact of extreme events on crop productivity, farm sensitivity, farm health, water availability in farmland, natural capital, livestock sensitivity, and livelihood dependency) (Table S1). Limited land availability poses risks by reducing crop productivity and limiting farmers' adaptive capacity [42]. Extreme climate events increasingly affect agrarian productivity, with greater impacts reflecting increased vulnerability [41]. Soil fertility, soil erosion, and wildlife depredation are closely linked to productivity and may create challenges that can be worsen under global climate change scenarios [28, 43]. Water scarcity reduces soil moisture and increases farmers' crop management costs [42]. High reliance on natural resources for energy and self-sufficiency can lead to deforestation, threaten ecosystem services and increase vulnerability [28]. Disease outbreaks can impact the livestock population, an integral component of homegardens, and may lead to disruptions in farmers' supplementary earnings [44]. Livelihood dependency reflects the extent to which households rely on agroforestry for economic livelihoods, time commitments, and family involvement. Climate change vulnerability can be further exacerbated by declines in farm productivity resulting from extreme climate events, particularly among households that rely heavily on farm activities for their livelihoods [20]. Higher values for these components indicate greater sensitivity among farmers, thereby contributing to increased socio-ecological vulnerability.

Adaptive capacity was assessed using ten key components (including household infrastructure, social networking, benefits from cultivation, access and suitability of farmland, adjustment in cultivation schedule, livestock maintenance and support, crop maintenance and support, homegarden management, availability of household assets, and decision-making) (Table S1). A linear dendrogram was created using RAWGraphs 2.0 to illustrate the farmers' efficient adaptive strategies [45]. Household assets and infrastructure reflect economic resilience, and adequate infrastructure helps reduce climate change vulnerability [46]. Assistance from government or community participation as social networking plays a key role during the crisis that helps mitigate the effects of extreme climate events [20]. In addition, household socio-economic stability can be measured by the benefits derived from their cultivation practices [20]. Adjustment in planting and harvesting schedules enable farmers to maintain agricultural productivity [47]. Crop and livestock management techniques adopted by farmers helps protect their livelihoods [40]. Decision-making abilities are linked to the management of available resources, land-use conversion, and engagement in alternative livelihood activities that support household sustenance [46]. The management of homegardens further contributes to ensuring food availability and provides farmers with supplementary income [48]. Higher scores for these components indicate greater adaptive capacity, thereby contributing to reduced socio-ecological vulnerability.

2.3.2 Scaling of indicator

To evaluate the extent of exposure, sensitivity, and adaptive capacity, the individual indicators were measured using various scales, including Likert-type, binary, and percentage-based depending on their relationship to vulnerability. For example, perception of seasonal temperature changes over the past 10–20 years was assessed using a scale where "No Change" = 0, "Decrease" = 1, "Highly Decrease" = 2, "Increase" = 3, and "Highly Increase" = 4, reflecting their expected impact on vulnerability. Water availability was coded as "No Change" = 0, "Extremely High" = 1, "High" = 2, "Low" = 3, and "Highly Low" = 4, with higher values indicating greater vulnerability. Binary responses such as access to extension services were coded as 1 for "Yes" and 0 for "No." Access to agricultural communication channels was recorded on a scale as 0% = 0, 25% = 1, 50% = 2, 75% = 3, and 100% = 4.

2.3.3 Identification and selection of villages

There are no official records exist on the villages practising pineapple-based agroforestry systems within the study district. Preliminary information on the Hmar villages dependent on pineapple cultivation was collated based on existing peer-reviewed and grey literature. The Hmar population is primarily concentrated in the Lakhipur sub-division of the Cachar district. After consultations with government officials and local informants, five distinct villages, viz., Biete Punjee, Hmarkhawlein, Kolom Punjee, Lobonkhal Punjee, and Saisel Punjee were selected for household interviews.

Preliminary discussions with the village heads yielded the following household numbers: 77 (Biete Punjee), 43 (Kolom Punjee), 117 (Lobonkhal Punjee), and 37 (Saisel Punjee), all households engaged in pineapple-based agroforestry systems. In contrary, Hmarkhawlein, a semi-urban area with more than 1000 households, had about 133 households practising pineapple agroforestry systems. These estimates are based on local administrative knowledge and were used because official records were unavailable. The purposive selection of villages in this study was based on the following criteria: (i) villages that were easy to access, (ii) those that had been long-established (over 100 years old) and were largely dependent on pineapple agroforestry systems for their livelihoods, and (iii) prior permission from the village head for data collection.

A total of 122 households were selected for face-to-face interviews using a simple random sampling strategy, representing at least 30% of the households practising pineapple cultivation in each village. This relatively high sampling proportion was considered sufficient to ensure adequate representation of village-level variability in socio-economic conditions and climate vulnerability. Previous studies on climate change vulnerability have relied on considerably smaller sample sizes, highlighting that the depth of questionnaires, the duration of interviews, and the representativeness of the data are more critical than large sample sizes [28]. Interviews were conducted primarily in the local dialect, "Sylheti," after obtaining informed consent from each respondent and clearly explaining the purpose of the study. Additional assistance from local interpreters was provided when necessary. Each interview lasted approximately one hour.

2.3.4 Focus group discussions

To complement the household survey data and to obtain a deeper understanding of farm-level adaptive strategies, focus group discussions were conducted in each village. The discussions were based on the indicators of adaptive capacity from the questionnaire. These interactions lasted over two-three hours. Farmland management strategies, infrastructural conditions, and other farm-level adaptive responses to extreme climate events were the key discussion topics aimed at developing a detailed understanding of the adaptive capacity of pineapple agroforestry farmers. Ten participants were selected from each village. The headmen (village head) served as the formal representative of the village, along with other villagers, and women representatives. The headman served as a key informant due to their leadership role and their overall knowledge of existing agricultural practices. All participants were chosen based on their experience and active involvement in pineapple agroforestry systems, to gather diverse and reliable information during the discussions. A similar approach was employed to assess the climate adaptability in rural Bangladesh [49].

2.4 Data analysis

2.4.1 Socio-economic data analysis

Socio-economic data were entered into Microsoft Excel (2019), with binary responses coded as 0 and 1 and numerical values recorded directly. The data were then compiled and analysed using descriptive statistical methods, and the results were presented as percentages and in tabular form for clear interpretation.

2.4.2 Climate trend analysis

Temperature and rainfall data collected from NASA's Data Access Viewer (https://power.larc.nasa.gov/data-access-viewer/*)* were used to perform the Mann-Kendall (MK) test to evaluate trends in temperature and rainfall. This test identifies consistent trends in time series data without requiring normal distribution [50]. In addition, Sen's slope estimator, a nonparametric approach, was applied to estimate the magnitude of the trends [51].

2.4.3 Normalization of indicators

The indicators for assessing the household climate change vulnerability were measured on different scales. Therefore, indicators were normalised to a uniform scale ranging from 0–1. Normalisation was carried out employing the equation as follows [52]:

$$I_{xi} = \frac{I_i - I_{min}}{I_{max} - I_{min}} \tag{1}$$

where:

"I_{xi} = normalised index score for the i^{th} indicator"
"I_i = actual (observed) value of the i^{th} indicator"
"I_{min} = minimum value of the indicator across all households"
"I_{max} = maximum value of the indicator across all households"

2.4.4 Aggregation of indicators

The indicators were grouped into a total of 26 components representing exposure, sensitivity, and adaptive capacity, to assess the climate change vulnerability [41], using the following equation:

$$S_v = \frac{\sum_{i=1}^{n} I_{xi}}{n} \tag{2}$$

where:

"S_v = index of component v"
"I_{xi} = normalised value of the i^{th} indicator within component v"
"n = total number of indicators in component v"

2.4.5 Principal component analysis

Principal Component Analysis (PCA) was applied to reduce the dimensionality of the dataset and identify the key components of exposure, sensitivity, and adaptive capacity. PCA with varimax rotation was performed using jamovi (version 2.3.26) to transform correlated variables into a set of uncorrelated principal components, thereby retaining the most relevant information in the dataset [53]. Principal components with eigenvalues ≥ 1 were retained for further analysis, following Kaiser's criterion [54], as they explain a significant proportion of the total variance. Variables with factor loadings ≥ 0.60 were retained for exposure and sensitivity, while those with factor loadings ≥ 0.50 were retained for adaptive capacity. A slightly lower threshold for adaptive capacity was adopted due to context-specific datasets. The component scores derived from PCA were subsequently aggregated to estimate the indices of exposure, sensitivity, and adaptive capacity of the farmers [28].

2.4.6 Entropy method for weighing dimensions for each village

The degree of dispersion among the variables can be effectively measured by this method [55]. Therefore, the entropy method was used to calculate the weights of sensitivity and adaptive capacity for each village. The greater variability/dispersion in the data indicates lower entropy values [56]. The weights of the dimensions were calculated using the equations as follows:

$$\mathrm{P_{ij}} = \frac{\mathrm{X_{ij}}}{\sum_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{X_{ij}}} \tag{3}$$

where:

"P_{ij} = specific gravity value for each Xij"

"Xij = normalised and aggregated value of the *j-th* component"

"i = evaluation object or village"

"j = component within a given dimension"

"n = total number of components within that dimension"

$$e_j = -K \sum P_{ij} ln(P_{ij}),\ K = \frac{1}{ln\,(n)} \tag{4}$$

where, n is the number of households in that village, and the value of e_j lies ($0 \leq e_j \leq 1$).

The entropy coefficient (g_j) for the dimensions was estimated as:

$$\mathrm{g_j} = (1 - e_j) \tag{5}$$

The weight of the dimensions was calculated using the following equation:

$$\mathrm{W_i} = \frac{\mathrm{g_j}}{\sum_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{g_j}} \tag{6}$$

Finally, the socio-ecological vulnerability of these farmers was calculated for each village by multiplying the dimensions' values with their corresponding weights.

2.4.7 Socio-ecological vulnerability index

According to the IPCC (2012) [57], the climate change vulnerability of a system is considered independent of physical events, with exposure treated as a spatial and external concept. The measurement of exposure specifically helps evaluate the magnitude of extreme climate events in a given region. Thus, the IPCC's fifth assessment report [58] highlighted the concept of climate change vulnerability as an "interplay between the extent of sensitivity and the resilient adaptive strategies of systems". The socio-ecological vulnerability index was designed by adopting the "Manush Approach", following the structure of the "Human Development Index" [59]. This approach is based on the idea of displaced ideals, emphasising the variability of parameters and proposing that systems closer to the worst-case (ideal vulnerable) scenario are the most vulnerable. Since vulnerability is considered a negative attribute, the least resilient system, lacking adaptive capacity, served as the reference point. The score for sensitivity (SE_v) was determined by calculating the squared distance from this ideal, while for adaptive capacity, the squared distance $(AC_v)^2$ from the ideal represented the lack of adaptive strategies. Indices of climate sensitivity and adaptive capacity were considered to estimate the socio-ecological vulnerability. Therefore, the socio-ecological vulnerability across the villages was measured based on a proposed vulnerability index (SEVI) as outlined in (Eq. 7) [20]. A higher value of the Socio-Ecological Vulnerability Index (SEVI) indicates greater proximity to high climate change vulnerability.

$$\mathrm{SEVI} = 1 - \sqrt{\frac{(1-\mathrm{SE_v})^2 + \mathrm{AC_v^2}}{2}} \tag{7}$$

3 Results

3.1 Socio-economic settings of the pineapple agroforestry farmers

The present investigation highlighted the predominance of male family representatives, accounting for 88.7% of the surveyed participants, while females accounted for the remaining 11.3% of households. The ages of respondents ranged from 22–87 years. Table 1 shows differences in socio-economic conditions among households practising pineapple agroforestry systems across the villages.

The majority of households live in Semi-pakka and Kaccha houses and are predominantly nucleated families. Hmarkhawlien, in particular, was characterised by a dominance of Semi-pakka (75%) and Pakka (5%) house types. Access to electricity was widespread across households, and a few also use supplementary sources such as rooftop solar panels and solar-powered portable lights. Drinking water was reportedly scarce, with most households relying on ring wells, springs, and mud wells, while only a few relied on government-provided water supplies.

The demographic makeup was predominantly adults aged 19 to 36 years. Most of the village population had educational levels ranging from primary to matriculation. A higher percentage of illiterate males (12.24%) and females (9.62%) was observed in Saisel Punjee.

Agricultural activities served as the primary source of income, while non-agricultural activities were more prominent in Kolom Punjee (36.36%) and Hmarkhawlein (32.50%). Furthermore, Saisel Punjee showed a greater extent of cultivated land on average (3.34 ± 0.90 ha) (Table 1). Both male and female household members proactively engaged

Table 1 Socio- economic profile of pineapple agroforestry farmers in the study region

Variables	Villages of pineapple farmers				
	Biete Punjee	**Hmarkhawlein**	**Kolom Punjee**	**Lobonkhal**	**Saisel Punjee**
Family type (%)					
Nuclear	78.26	92.5	76.92	74.29	63.64
Joint	21.74	7.5	23.08	25.71	36.36
Average family size	5.65 ± 1.92	5.08 ± 2.12	5.15 ± 1.28	5.71 ± 1.61	9.18 ± 5.58
Sex ratio					
(Adult male: Adult female)	977:1000	918:1000	958:1000	913: 1000	914:1000
House type (%)					
Pakka	8.70	20	7.69	14.29	0
Semi-Pakka	52.17	75	61.54	68.57	54.55
Kaccha	39.13	5	30.77	17.14	45.45
Education of male population (%)					
Illiterate	4.48	3.88	2.86	4.81	12.24
Primary Level	49.25	26.21	28.57	42.31	55.10
High School (10th Standard)	17.91	25.24	34.29	26.92	8.16
Higher Secondary (12th Standard)	17.91	23.30	22.86	18.27	12.24
Bachelor and above	10.45	21.36	11.43	7.69	12.24
Education of female population (%)					
Illiterate	4.50	5.10	3.33	6.74	9.62
Primary Level	42.46	44.90	26.67	44.94	69.23
High School (10th Standard)	30.30	27.56	36.67	24.72	7.69
Higher Secondary (12th Standard)	18.18	12.24	20.00	17.98	7.69
Bachelor and above	4.56	10.20	13.33	5.62	5.77
Occupation of family head (%)					
Agriculture	78.26	67.50	63.64	71.43	81.82
Wage labour	0	2.50	0.00	0	0
Govt. service	13.04	17.50	9.09	17.14	9.09
Business	8.70	7.50	18.18	8.57	9.09
Private	0	5.00	9.09	2.86	0
Area under cultivation (ha)	1.28 ± 0.71	2.49 ± 1.40	1.77 ± 0.86	1.41 ± 0.80	3.34 ± 0.90
Livestock in households (%)					
Chickens	73.8	73.63	70.00	64.57	70.11
Pig	23.3	11.79	11.82	17.88	22.99
Cow	0	0	4.55	3.31	2.30
Pigeons	2.91	0.56	3.64	0.66	0
Goats	0	0.84	2.73	2.65	0
Ducks	0	13.18	7.27	10.93	4.60

in cultivation activities, contributing to total household income, with most households earning an average monthly income of over US$120. Livestock rearing was common across the villages, with chickens and pigs being the predominant livestock.

3.2 Principal component analysis

Four key components were identified by PCA, each for exposure, sensitivity, and adaptive capacity, collectively accounting for 61.3%, 61.6%, and 56.7% of the variance, respectively. Based on factor loadings of 0.60 and above, 6 out of 8 components for exposure (Table S2), 7 out of 8 for sensitivity (Table S3), whereas 9 out of 10 components for adaptive capacity (Table S4) were selected based on factor loadings of 0.50 and above for further statistical analysis and subsequently calculating socio-ecological vulnerability.

3.3 Assessment of exposure among pineapple agroforestry farmers

The magnitude of climate exposure was evaluated based on their perceptions of climatic patterns observed over the past 20 years. Farmers at Kolom Punjee (0.54), Biete Punjee (0.53), and Lobonkhal (0.53) experienced heightened climatic exposure, attributed to variations in temperature, erratic rainfall patterns, and severity of extreme climate events during this period (Table 2). High rainfall intensity and frequent water stress have become major challenges for pineapple agroforestry farmers, particularly in Saisel Punjee and Lobonkhal Punjee. In addition, weed and invasive plants' growth in farmlands has become more severe in recent years.

Climatic trends, temperature and rainfall variations from 1985 to 2024 in the study region are shown in Fig. 3. The Mann-Kendall test showed non-significant decline in annual mean temperature ($\tau = -0.08$, $p = 0.48$). While, Sen's slope showed a very small decrease of − 0.0027 °C per year (95% CI: − 0.010 to 0.006 °C/year). The analysis revealed a statistically significant negative trend ($\tau = -0.25$, $p = 0.0238$) for annual mean maximum temperature, with Sen's slope estimating a decline of − 0.0489 °C per year (95% CI: − 0.0886 to − 0.0089 °C/year), indicating a significant downward trend. In contrast, the annual mean minimum temperature showed a positive but non-significant trend ($\tau = 0.17$, $p = 0.12$), with Sen's slope indicating an increase of 0.020 °C per year (95% CI: − 0.0045 to 0.047 °C/year), suggesting a gradual but uncertain warming. The Mann-Kendall test showed a statistically significant increasing trend ($\tau = 0.618$, $p < 0.001$) for annual rainfall, and Sen's slope examine an average increase of 26.7 mm per year (95% CI: 17.2–35.3 mm/year), indicating a strong upward trend in rainfall over the years.

3.4 Assessment of sensitivity among pineapple agroforestry farmers

Land stewardship among tribal communities is associated with community ownership, responsibility and participation. The selection of cultivation plots is usually monitored by the village's chief, elders, households, or, in some cases, the community as a whole.

Table 2 Estimated values of normalized indicators and components for exposure across the villages of pineapple farmers of the study region (component values are highlighted in bold), higher value indicates higher exposure

Component	Village of pineapple farmers				
	Biete Punjee	Hmarkhawlein	Kolom Punjee	Lobonkhal	Saisel Punjee
Temperature variation	**0.75**	**0.71**	**0.71**	**0.72**	**0.68**
Cold months	**0.36**	**0.41**	**0.35**	**0.42**	**0.48**
Erratic rainfall	**0.66**	**0.53**	**0.67**	**0.67**	**0.48**
Intensity of extreme events	**0.58**	**0.62**	**0.62**	**0.67**	**0.37**
Intensity of rainfall	0.51	0.56	0.50	0.48	0.61
Intensity of water stress condition	0.26	0.17	0.31	0.36	0.45
Intensity of cold wave	0.22	0.37	0.21	0.38	0.21
Intensity of landslides	0.32	0.21	0.21	0.21	0.39
Intensity of Cloudburst	0.38	0.38	0.37	0.42	0.15
Intensity of disease infestation	**0.28**	**0.20**	**0.38**	**0.17**	**0.23**
Intensity of weed and invasive plants' growth	**0.52**	**0.55**	**0.50**	**0.50**	**0.68**
Exposure	***0.53***	***0.50***	***0.54***	***0.53***	***0.49***

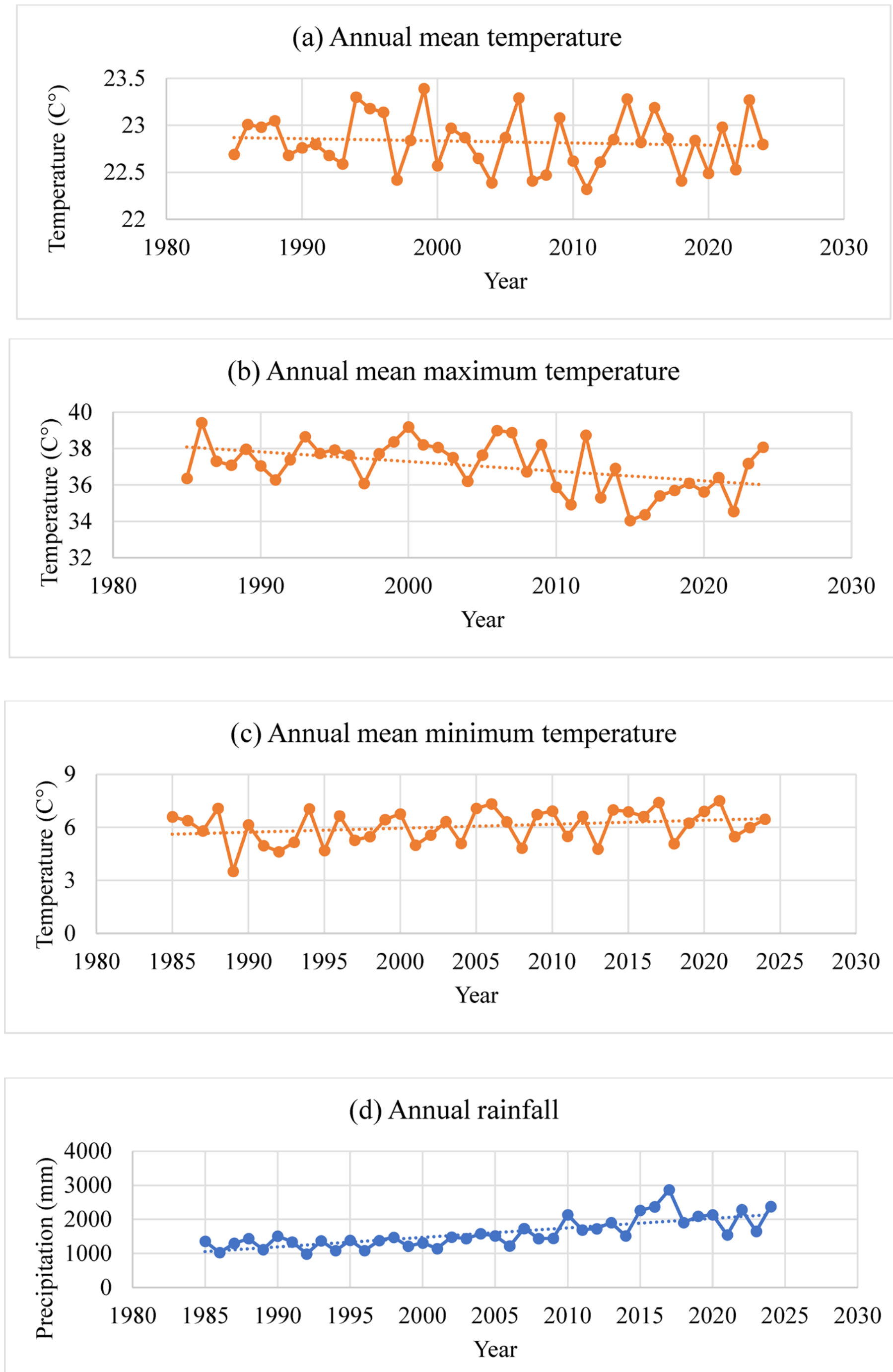

Fig. 3 Trend of temperature and rainfall (1985–2024) in the study region. (*Source*: https://power.larc.nasa.gov/data-access-viewer/); **a** annual mean temperature, **b** annual mean maximum temperature, **c** annual mean minimum temperature, **d** annual rainfall

Household land ownership varied across the villages. Biete Punjee and Lobonkhal had smaller landholdings and high unsuitable land for pineapple cultivation.

The impact of extreme climate events on crop productivity was more pronounced in Lobonkhal (0.56) and Hmarkhawlein (0.55), wherein erratic rainfall and frequent water stress incidences posed a critical challenge for pineapple cultivation. Issues related to soil fertility and erodibility contributed to heightened aggregated farm sensitivity score, particularly evident in Lobonkhal (0.49) and Hmarkhawlein (0.43). Furthermore, pineapple farmers have been experiencing the risk of wildlife depredation, particularly in Hmarkhawlein (0.31) and Saisel Punjee (0.23), which intensifies the threat of agricultural losses. Lower water availability and soil moisture in the farmland was particularly evident in Hmarkhawlein (0.72) and Lobonkhal (0.71).

A greater reliance on natural capital, particularly for harvesting timber, fodder, and fuelwood for household use from agroforestry and nearby forest, was comparatively higher in villages Saisel Punjee (0.61), Lobonkhal (0.52), and Biete Punjee (0.51) (Table 3).

Livestock rearing was a common practice in all the villages. Variability in rainfall and temperature has greatly affected the livestock productivity. Moreover, increasing outbreaks of pests and disease on livestock have further intensified the difficulties faced by farmers. Wildlife attacks induce livestock losses. The overall livestock sensitivity score being more pronounced in Kolom Punjee (0.48) and Lobonkhal (0.37).

A pronounced dependence on pineapple agroforestry systems for livelihoods was observed in the villages Saisel Punjee (0.85) and Kolom Punjee (0.80), while it was relatively lower in Hmarkhawlein (0.67) (Table 3).

Overall, the environmental, socio-demographic, economic, technological, and institutional factors influenced the extent of climate sensitivity among pineapple agroforestry farmers. These factors can contribute to psychological distress during times of crop failure, ultimately making farmers more vulnerable to climate crisis (Fig. 4).

3.5 Assessment of adaptive capacity among pineapple agroforestry farmers

In this study, Biete Punjee (0.49) and Saisel Punjee (0.64) had relatively lower scores for household infrastructure, indicating limited access to basic amenities. Furthermore, the overall social network scores were most pronounced in Hmarkhawlein (0.44) and least pronounced in Lobonkhal (0.23). According to the respondents, they have strong societal rules and familial responsibilities that provide support during crises affecting families. In focus group discussions, respondents stated that improvements in mobile networks, internet connectivity, and government-led weather alert systems in mobile applications have enabled farmers to access climate-related information more efficiently.

Crop maintenance and support systems were prominent across the villages of the region. The aggregated score was greater in the villages Saisel Punjee (0.82) and Kolom Punjee (0.82) (Table 3), attributed to the soil erodibility control, minimum tillage, residue management, disease and pest management and altering the crop density in the farmland (Fig. 5). According to the respondents, these practices have evolved through trial and error and are adapted to local environmental conditions.

Farmers further explained that they primarily select plots dominated by “Muli” (*Melocanna baccifera*) bamboo for high productivity. According to the farmers, cultivation typically begins with the slashing and burning of fallow vegetation. In general, the slashed materials and felled trees are retained on the plots to dry for at least 2–3 weeks before burning. Large, mature trees are purposely retained during slashing to maintain optimal shade for understory crops and to help control soil erosion. Debris remaining after burning is left on the plots to augment soil nutrient content. Pineapple cultivation does not involve tillage or irrigation facilities during the farm preparation stage. According to the farmers, the process of establishing pineapple agroforestry systems is

Table 3 Estimated values of normalized indicators and components for sensitivity and adaptive capacity across the villages of pineapple farmers of the study region (component values are highlighted in bold), higher value indicates higher sensitivity, adaptive capacity and socio-ecological vulnerability

Component	Villages of pineapple farmers				
	Biete Punjee	Hmarkhawlein	Kolom Punjee	Lobonkhal	Saisel Punjee
Unavailability of farmland	**0.52**	**0.45**	**0.47**	**0.51**	**0.37**
Lower land holding	0.86	0.71	0.79	0.86	0.56
Percentage of unsuitable land	0.17	0.20	0.15	0.17	0.18
Impact of extreme events on crop productivity	**0.41**	**0.55**	**0.44**	**0.56**	**0.52**
Impact of changes in temperature on crop productivity	0.33	0.42	0.38	0.50	0.45
Impact of erratic rainfall on crop productivity	0.55	0.71	0.46	0.58	0.58
Impact of water stress condition on crop productivity	0.33	0.53	0.49	0.58	0.52
Farm sensitivity	**0.35**	**0.43**	**0.37**	**0.49**	**0.38**
Impact of soil fertility on crop productivity	0.61	0.60	0.50	0.66	0.55
Impact of soil erosion on crop productivity	0.22	0.35	0.21	0.53	0.27
Impact of changes in tree diversity on crop productivity	0.41	0.45	0.58	0.54	0.45
Impact of wildlife depredation on crop productivity	0.15	0.31	0.19	0.21	0.23
Water Unavailability	**0.59**	**0.60**	**0.61**	**0.67**	**0.56**
Unavailability of water in farmland	0.65	0.72	0.67	0.71	0.58
Unirrigated area of farmland	0.96	0.95	0.92	0.91	0.91
Distance fetching water	0.17	0.13	0.23	0.37	0.18
Natural capital	**0.51**	**0.42**	**0.44**	**0.52**	**0.61**
Fodder collection from farmland	0.30	0.40	0.31	0.31	0.45
Fuelwood collection from farmland	0.96	0.63	0.77	0.86	1.00
Timber collection from farmland	0.26	0.23	0.23	0.40	0.36
Livestock sensitivity	**0.35**	**0.33**	**0.48**	**0.37**	**0.31**
Impact of changes in temperature on livestock productivity	0.37	0.46	0.65	0.47	0.55
Impact of heavy rainfall on livestock productivity	0.20	0.34	0.23	0.27	0.14
Impact of water stress condition on livestock productivity	0.59	0.34	0.69	0.60	0.36
Impact of soil fertility on livestock productivity	0.28	0.33	0.49	0.23	0.18
Impact of disease on livestock productivity	0.55	0.46	0.64	0.39	0.61
Impact of pest on livestock productivity	0.39	0.25	0.62	0.50	0.32
Impact of wildlife depredation on livestock productivity	0.24	0.34	0.38	0.30	0.18
Impact of weed and invasive plants' infestation on livestock productivity	0.15	0.16	0.12	0.19	0.14
Livelihood	**0.77**	**0.67**	**0.80**	**0.76**	**0.85**
Contribution of agroforestry on total household income	0.59	0.53	0.69	0.69	0.82
Family members in cultivation	0.91	0.69	0.85	0.87	0.82
Time devoted to cultivation	0.81	0.79	0.87	0.71	0.91
Sensitivity	***0.50***	***0.49***	***0.52***	***0.55***	***0.51***
Entropy weight (W_i)	*0.58*	*0.61*	*0.57*	*0.61*	*0.70*
Weighted Sensitivity (SE_v)	***0.29***	***0.30***	***0.29***	***0.34***	***0.36***
Household infrastructure	**0.49**	**0.81**	**0.67**	**0.74**	**0.64**
House types (Pakka, Semi-pakka, Kaccha)	0.30	0.61	0.35	0.54	0.27

Table 3 (continued)

Component	Villages of pineapple farmers				
	Biete Punjee	Hmarkhawlein	Kolom Punjee	Lobonkhal	Saisel Punjee
Household facilities (Sanitation, Electricity, Concrete Road)	0.67	1.00	1.00	0.94	1.00
Social networking	**0.39**	**0.44**	**0.42**	**0.23**	**0.36**
Assistance during crisis	0.48	0.40	0.54	0.23	0.27
Regular climate related information	0.30	0.48	0.31	0.23	0.45
Access and suitability of farmland	**0.61**	**0.58**	**0.59**	**0.64**	**0.64**
Access and communication to farmland	0.65	0.60	0.65	0.63	0.73
Access to agricultural input	0.65	0.60	0.65	0.63	0.73
Percentage of suitable land area	0.52	0.55	0.46	0.66	0.45
Adjustment in cultivation schedule	**0.62**	**0.64**	**0.56**	**0.58**	**0.52**
Changes in plantation	0.62	0.64	0.56	0.58	0.52
Changes in harvesting	0.62	0.64	0.56	0.58	0.52
Crop maintenance and support	**0.76**	**0.79**	**0.82**	**0.69**	**0.82**
Soil erosion control through traditional knowledge	0.87	0.80	0.85	0.69	0.91
Minimum tillage	1.00	1.00	1.00	1.00	1.00
Residue management	1.00	1.00	1.00	0.91	1.00
Management of disease/weed/invasive plants through traditional knowledge	1.00	1.00	1.00	1.00	1.00
Ash management	0.39	0.28	0.38	0.37	0.36
Shifting to productive zones	0.26	0.55	0.77	0.23	0.73
Alter crop density	0.83	0.90	0.77	0.60	0.73
Livestock maintenance and support	**0.67**	**0.69**	**0.56**	**0.44**	**0.61**
Alter livestock density	0.83	0.90	0.77	0.57	0.91
Adjust in livestock rearing schedule	0.78	0.85	0.77	0.57	0.82
Changes in livestock feed	0.39	0.33	0.15	0.17	0.09
Home garden	**0.17**	**0.13**	**0.16**	**0.14**	**0.33**
Area under home garden	0.13	0.12	0.12	0.13	0.30
Benefit from home garden	0.21	0.13	0.21	0.14	0.35
Availability of household assets (Cycle, Motor Cycle, Car, Tractor, Cell phone, Handcart, T.V, L.P.G)	**0.40**	**0.61**	**0.40**	**0.46**	**0.49**
Decision making	**0.76**	**0.73**	**0.75**	**0.71**	**0.70**
Experience in agroforestry by family head	0.52	0.51	0.55	0.46	0.48
Family educational level	0.99	0.95	0.95	0.96	0.91
Adaptive capacity	***0.54***	***0.60***	***0.55***	***0.51***	***0.57***
Entropy weight (W_j)	*0.42*	*0.39*	*0.43*	*0.39*	*0.30*
Weighted Adaptive capacity (AC_v)	***0.23***	***0.23***	***0.24***	***0.20***	***0.17***
Socio-ecological vulnerability (SEVI)	**0.27**	**0.28**	**0.27**	**0.32**	**0.35**

labour-intensive, and family members are actively involved in various farm activities. Farmers further stated that they hire additional labour at a cost of US$4 to US$5 per person per day.

Annual crops (legumes, cereals, rhizomatous crops, spices, etc.) are cultivated along with the fallow trees, particularly in May to June. According to the farmers, they harvest mature annual crops simultaneously and leave residue materials on the plots to enrich the soil with nutrients for the early stages of pineapple growth. After 3–4 months, planting of pineapple suckers begins, usually in September-November, within rows at 0.7–0.8 m spacing, holds approximately 1560–2041 individual plants in a 0.1 ha. Despite the challenges posed by “top rot” and “root rot” diseases and insect attacks, the severity of

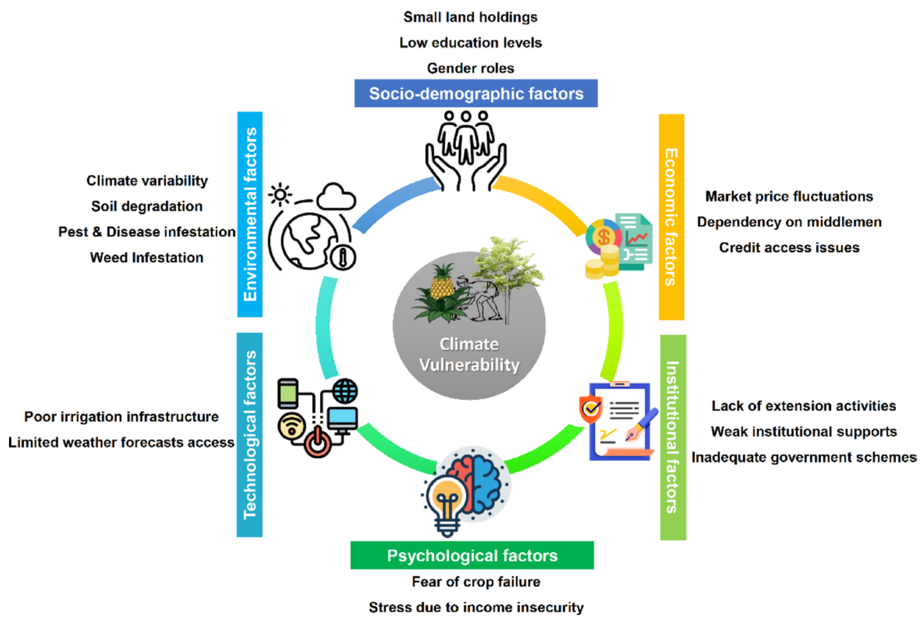

Fig. 4 Key environmental, socio-demographic, economic, institutional, technological, and psychological factors contributing to the climate vulnerability of pineapple agroforestry farmers in the Indian sub-Himalayas

these diseases is relatively low. Farmers prevent the spread of disease by selecting disease-free, healthy suckers for planting, manually removing pests, and uprooting infected plants. An increase in the number of pineapple plants on the planting sites over time boots productivity, resulting in 5200–5400 individual plants in a 0.1 ha at 15 years of stand age. Depending on size, pineapples can fetch US$0.11 to US$0.42 each in local markets.

According to the farmers, pineapple cultivation in the study region is carried out without the use of chemical fertilisers or manure inputs. Farmers typically clear weeds and invasive plants twice a year, particularly during the initial 2–3 years of growth. According to the farmers, adequate shade is vital for optimal pineapple growth and quality. Therefore, straight-trunked, open-canopy tree species are often favoured for providing shade. *Albizia* species are specifically preferred during the early stages of pineapple agroforestry systems. Additionally, *Musa* species and *Areca catechu* are commonly grown along the boundaries of the farmlands.

According to the farmers, the stand is approximately 8–10 years old, and the shade trees, specifically *Albizia* species, are gradually removed by ring-barking and replaced with cash crops like *Parkia timoriana*, *Areca catechu*, *Aquilaria malaccensis*, and *Hevea brasiliensis. Areca catechu* is in high demand in the region, selling for US$1.26 to US$1.89 per kg. *Aquilaria malaccensis* is highly valued for its oleoresin, and individual trees can be sold for up to US$1785 based on quality. While, a mature *Parkia timoriana* tree can produce approximately 10,000–15,000 pods, yielding an annual income of US$89 to US$180 per tree. If further tree removal is required, additional trees are also ring-barked or girdled to avoid damage to understory crops, ensuring optimal shade, suppressing the growth of weeds and invasive plants, and contributing nutrients to the soil. In some cases, farmers prefer to plant fruit trees such as *Mangifera indica* and *Litchi chinensis* for household consumption, with a small portion sold in the local markets. The

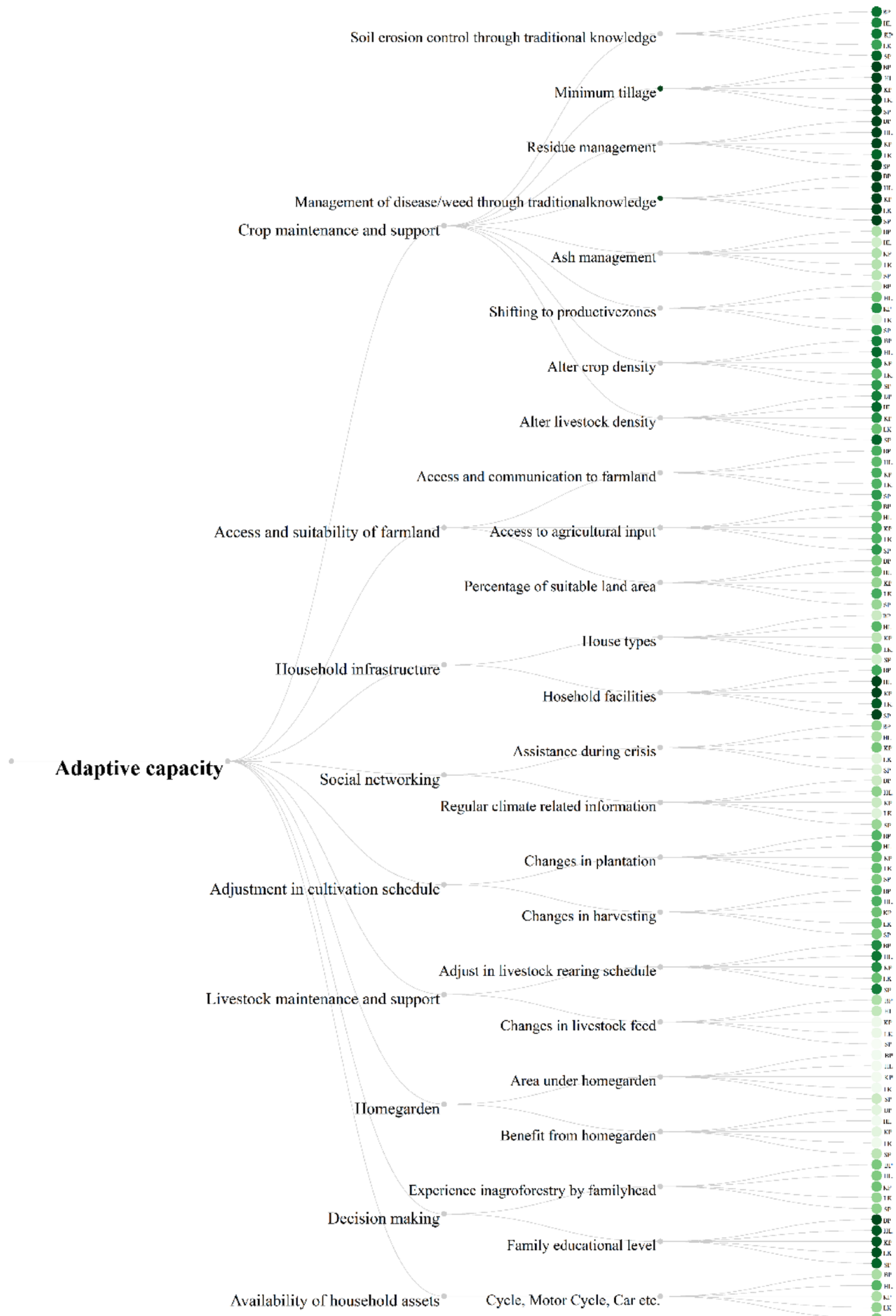

Fig. 5 Magnitude of various components of adaptive capacity among pineapple agroforestry farmers in the Indian sub-Himalayas; dark green shaded circles represent relatively higher values (BP- Biete Punjee, HL- Hmarkhawlein, KL- Kolom Punjee, LK- Lobonkhal, SP- Saisel Punjee)

farmers further stated that shifting to productive zones due to soil health issues is determined by the availability of land under cultivation among the households.

Furthermore, the integration of livestock, fisheries, cash crops, and high-value fruit trees into homegardens was prominent across the surveyed villages, particularly evident in Saisel Punjee (0.33) and Biete Punjee (0.17). Furthermore, farmers stated that adjusting livestock density, rearing schedules, and feeding practices are important strategies

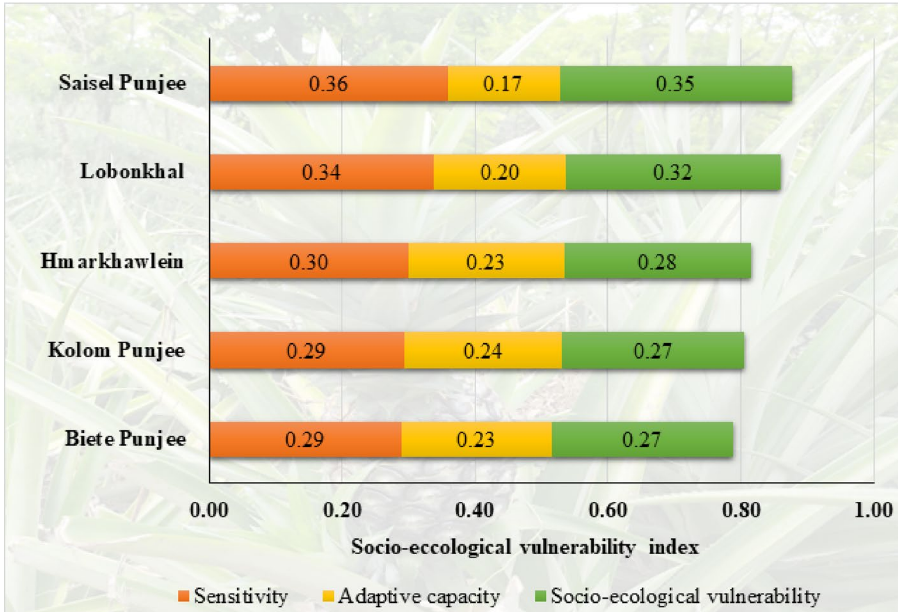

Fig. 6 Magnitude of sensitivity, adaptive capacity and socio-ecological vulnerability of pineapple agroforestry farmers in the Indian sub-Himalayas

to cope with resource variability. Greater livestock management and support practices were recorded in Hmarkhawlein (0.69) and Biete Punjee (0.67) (Table 3).

The availability of assets (Car, Cell phone, Cycle, Handcart, LPG, Motorcycle, Tractor, and TV) in households was higher in Hmarkhawlein (0.61). In contrast, household asset availability was lower in Biete Punjee (0.40) and Kolom Punjee (0.40).

Moreover, the decision-making abilities of families are influenced by educational level and cultivation experience, which differ across villages. Notably, the lower decision-making abilities were evident in Saisel Punjee (0.70) and Lobonkhal (0.71) (Table 3). According to the farmers, experience-based knowledge and acquiring new information are important for improving adaptive capacity.

3.6 Assessment socio-ecological vulnerability index

The socio-ecological vulnerability of pineapple agroforestry farmers was measured using the final weighted sensitivity and adaptive capacity values across the villages. Increased climate sensitivity was notable in Saisel Punjee (0.36) and Lobonkhal (0.34). At the same time, Biete Punjee (0.29) and Kolom Punjee (0.29) showed a lower susceptibility to climate change, as depicted in Fig. 6. The adaptive capacity of farmers was more evident in Kolom Punjee (0.24) and Hmarkhawlein (0.23). In contrast, Saisel Punjee (0.17) showed lower adaptability to climate change (Fig. 6). Saisel Punjee (0.35) and Lobonkhal (0.32) demonstrated higher socio-ecological vulnerability scores. In contrast, Biete Punjee (0.27) and Kolom Punjee (0.27) demonstrated a relatively lower level of vulnerability (Fig. 6). Higher socio-ecological vulnerability scores indicate greater susceptibility to climate change, which may disrupt social, economic, and ecological systems.

4 Discussion

The impact of climate change is greatly influenced by access to resources and livelihood opportunities [60]. In the surveyed villages, most farmers lived in Semi-pakka houses with basic facilities such as sanitation, electricity, and road networks. This indicates a noticeable improvement in community living standards. The development of housing infrastructure is recognised as an important factor in poverty reduction and in enhancing the resilience of communities prone to climate-induced hazards [61]. However, the presence of poor housing infrastructure in some villages, particularly in Saisel Punjee, may increase vulnerability and reflects a high reliance on natural materials for rebuilding houses, thereby imposing additional pressure [62]. Furthermore, the high dependency of households on ring wells, springs, and mud wells for drinking water further highlights the vulnerability of these communities to erratic rainfall [20].

The majority of family members attained formal education up to the matriculation level and relied on agriculture as the main source of livelihood. In particular, Saisel Punjee demonstrated a higher illiteracy rate and greater dependence on agricultural activities. The demographic structure, characterised by a predominance of the adult population, indicates the availability of labour for agricultural activities and enables participation in non-agricultural activities that contribute to income diversification. Raising awareness and improving the educational status of villages with lower literacy levels are therefore essential for strengthening capacity to address both climatic and non-climatic stressors and to explore opportunities for diversifying household incomes [63]. Villages with limited livelihood opportunities are more susceptible to climate variability [64], underscoring the need for livelihood development initiatives to improve living standards. Agricultural income of over US$120 per month indicates socio-economic benefits and reliance on pineapple cultivation for livelihoods. Furthermore, livestock rearing was prevalent across the villages and provides an additional source of income, helping to buffer the impacts of crop failure due to extreme events and market fluctuations [65].

This study highlighted that pineapple agroforestry farmers in the Indian sub-Himalayas are exposed to temperature fluctuations, erratic rainfall, and more frequent extreme climate events, particularly evident in Kolom Punjee, Biete Punjee, and Lobonkhal. These situations can be further intensified by long-term changes in temperature and rainfall regimes [66]. The decline in the annual mean maximum temperature in the study region suggests lower daytime temperatures, possibly due to increased cloud cover and higher daytime evaporation [67, 68]. In contrast, the increasing trend in annual mean minimum temperature may negatively impact crop phenological cycles and overall growth [69].

Pineapple farmers face additional risks from the significant increase in annual rainfall (26.7 mm per year), which indicates high intensity rainfall with potential impacts such as crop damage and landslides in the study region [70]. The trends in climatic data are consistent with a pattern of declining maximum temperatures, rising minimum temperatures, and increasing rainfall observed in Son Beel of the Indian sub-Himalayan region, indicating severe damage to crops and fisheries [70]. Similarly, pineapple farmers in Ghana have been experiencing changes in temperature and rainfall regimes, with associated impacts on productivity [71].

In addition, Saisel Punjee and Lobonkhal Punjee are exposed to high-intensity rainfall and frequent water stress, combined with increased weed and invasive plant growth.

Agricultural systems in Northeast India are facing substantial challenges due to the proliferation of invasive species, including *Ageratina adenophora, Ageratum houstonianum, Chromolaena odorata*, and *Mikania micrantha*, which have widespread impacts on agricultural productivity [72]. These climatic and ecological pressures can potentially threaten the stability of crop productivity [73].

Changes in temperature and rainfall can reduce the quality of pineapples, ultimately affecting economic returns from farmland [71]. Furthermore, extreme climate events negatively affect pineapple export networks, thereby disrupting the pineapple trade [22]. Similar effects of unfavourable climatic conditions on export networks may also observed among pineapple agroforestry farmers of the study region [74]. Furthermore, farmers with small landholdings often lack the capacity to adopt productivity-enhancing measures, as observed in Biete Punjee and Lobonkhal, increasing their socio-ecological vulnerability to climate change.

The sensitivity level may be influenced by low soil fertility, and farmland dominated by moderately fertile soils are associated with lower crop yields [75]. The presence of "red soil" and "sandy soil" in farmlands makes them particularly susceptible to drought and erosion [76]. Villages Hmarkhawlein and Lobonkhal have experienced frequent water stress, making it difficult for farmers to achieve sufficient crop productivity.

Moreover, crop losses caused by wildlife differ among villages, with higher encounters reported in Hmarkhawlein and Saisel Punjee. These encounters are largely determined by the local abundance of wildlife, lack of food resources in forests, and distance to forest areas [77]. Extreme climate events further amplify these interactions and can lead to economic instability and heightened climate sensitivity [78].

The pineapple agroforestry farmers in the study region rely on seasonal rainfall for farming. Water availability in farmland can be severely impacted by rising temperatures and erratic rainfall patterns [79]. Hmarkhawlein and Lobonkhal showed greater water stress, which can lower soil moisture content in agricultural land and eventually disrupt crop productivity [80]. The lack of irrigation facilities in the region exposes agricultural production to severe changes in temperature and rainfall, posing a substantial risk to the food and livelihood security of local communities [12].

Villages Saisel Punjee, Lobonkhal and Biete Punjee rely on natural resources for their daily energy needs and livelihoods. However, high dependence on natural capital can cause deforestation, which threatens ecosystem services and increasing their vulnerability to climate change [28].

Livestock productivity is affected by disease and pest attacks, as well as wildlife interactions, resulting in considerable losses, particularly in Kolom Punjee and Lobonkhal [44]. Furthermore, changes in rainfall and temperature may directly affect livestock or indirectly increase disease and pest prevalence, thereby reducing overall productivity and heightening vulnerability [44].

The household income of Saisel Punjee and Kolom Punjee heavily depends on pineapple cultivation. However, this high reliance on pineapple cultivation also increases the risk of socio-economic disruption [28]. The potential failure of specific crops makes these households more vulnerable to climate impacts [20]. The overall sensitivity levels were greater in Saisel Punjee and Lobonkhal, indicating increased vulnerability under future climatic crisis.

Pineapple agroforestry systems strengthen farmers' social, financial, and natural capital, which are essential for building resilience against climate impacts [81]. Better housing infrastructure with basic amenities, along with transportation facilities through road connectivity, and households' assets such as tractors, motorcycles, and mobile phones reflect improved living standards and facilitate market access and ease of trade [61, 62], thereby enhancing farmers' resilience to climate stress, as evident in Hmarkhawlein.

Furthermore, tribal communities, characterised by strong societal responsibilities and familial networks, provide support during crop failures and family crises, thereby enhancing both specific and general resilience [82] and contributing to lower vulnerability. Access to climate-related information also plays an important role in raising awareness and preparedness for extreme climate events [83]. Strong social networks were particularly evident in Hmarkhawlein and Kolom Punjee. Traditional norms promote social bonding and facilitate knowledge transfer regarding climate-resilient practices, as evident among the Hmar community [84].

Additionally, access to farmlands, favourable market conditions, and better connectivity are crucial for the successful sale of agricultural produce, which is vital for improving the climate resilience of marginalised farming communities [85]. Land availability and suitability for cultivation are also important factors for achieving food security and enhancing adaptive capacity [86], as evident in Saisel Punjee, where greater land availability and suitability for pineapple cultivation were observed. Furthermore, adjustments in cultivation schedules help minimise adverse effects on crop productivity [87] and serve as an adaptive response to extreme climate events.

Furthermore, climate variability and non-climatic challenges profoundly influence farmers' decisions to implement resilient adaptive strategies to achieve substantial yields [24]. Crop management and support practices, intertwined with traditional knowledge, were observed across the villages, with greater prevalence in Saisel and Kolom Punjee, which helped to secure farm productivity and reduce the impacts of climate variability. Farmers highlighted that they primarily opt for "Muli" bamboo (*Melocanna baccifera*) dominated lands for higher productivity due to its extensive rhizome network, which makes it particularly effective in colonising degraded areas such as fallow lands of shifting agriculture or other human-induced disturbances [88].

Slash-and-burn practices remain an important, labour-intensive land-preparation process in pineapple agroforestry systems [13]. Traditional ecological knowledge of fire is used to create desired ecosystem effects; however, prolonged and repeated burning results in greater exposure of the topsoil and accelerates soil erosion [89]. As a preventive measure, farmers selectively preserve mature native trees to support understory crops by providing shade and reducing soil erodibility [13]. Residual plant material from burning is retained on the soil surface to enrich soil fertility [13]. Tree intercropping with short-term annual crops during the cropping phase provides diversified food sources and contributes to enhancing soil organic carbon stocks [90]. The retention of crop residues and their use as mulch further enrich soil nutrients during the early stages of pineapple growth [13].

Furthermore, pineapple is planted using minimum tillage and without fertiliser inputs, indicating that the system is a low-cost, nature-based approach to mitigating agricultural land degradation [91]. Farmers also reported that weeding materials are reused as mulch, which enhances infiltration, maintains soil moisture, and reduces evaporation

[92]. Additionally, *Areca catechu* and *Musa* species are planted along the borders of agricultural sites, helping to control soil erosion while also serving as shelterbelts, natural fences, and windbreaks [93]. These strategies are vital for reducing soil erosion, maintaining soil temperature, improving soil structure, enhancing infiltration, and regulating soil moisture [68]. Collectively, these practices support healthy pineapple growth and help maintain productivity under water stress and high rainfall conditions.

Albizia procera trees dominate the early stages of pineapple establishment and contribute to improved soil fertility through nitrogen fixation and weed suppression [13]. Over time, farmers manage the density and canopy of *Albizia procera* to ensure adequate sunlight, as excessive shade or insufficient light can affect pineapple growth and fruit quality [94]. This demonstrates understanding of farmers' perspectives on resource competition and shade management, which are crucial for increasing the production of suckers and slips [13].

Farmers also manage tree density through ring-barking, creating standing deadwood that gradually decomposes and contributes organic matter to the soil [13]. Local ecological knowledge and farming experience guide the prioritisation and replacement of *Albizia procera* with economically valuable species [14]. Approximately 20 multipurpose tree species have been identified in pineapple agroforestry systems of Assam, serving functions such as income generation, fuelwood, and timber [13]. The integration of pineapple with economically valuable tree species such as *Hevea brasiliensis* has been identified as an effective strategy for poverty alleviation and livelihood security among smallholder farmers [31].

Tree components in agroforestry systems enhance soil fertility through biomass decomposition and nutrient cycling, increasing the availability of soil organic carbon, nitrogen, and phosphorus [29]. Studies have reported total vegetation carbon storage ranging from 28.23 to 71.80 Mg ha^{-1} [14] and soil organic carbon stocks of 177 Mg C ha^{-1} in > 15-year-old pineapple agroforestry systems, which is comparable to adjacent natural forests (182.7 Mg C ha^{-1}) [29]. This demonstrates that tree integration and soil management practices in pineapple agroforestry systems not only support year-round production and enhance farm diversity but also improve soil fertility and plant nutrition, highlighting their role as a nature-based solution (NbS) for sustainable land management [29]. Additionally, alternating crop density and shifting cropland to productive zones serve as key resilient strategies for farmers in adverse conditions such as water stress and nutrient depletion [20].

Furthermore, livestock management and support strategies were prominent in Hmarkhawlein and Biete Punjee, involving adjustments in rearing schedules, animal density, and feeding methods help maintain livestock productivity and support household income [95]. These practices also help farmers address potential challenges associated with disease proliferation, which may be further intensified by climate change [95]. Such management strategies further reflect the awareness and experience in minimising livestock losses caused by ecological and climatic challenges [96].

Furthermore, the management of homegardens is closely linked with cultural traditions and practices, particularly evident in Saisel Punjee [48]. The cultivation of crops and vegetables for household consumption, along with the integration of cash crops such as *Areca catechu*, *Aquilaria malaccensis*, and various fruit trees, as well as livestock rearing within homegardens, can effectively enhance food security and increase household income [97]. Such diversified homegarden systems are considered critical adaptive responses to the consequences of climate change [98].

Additionally, farmers' decision-making abilities are closely linked to farm experience and formal education levels, which are essential for enhancing human capital and supporting climate change adaptation [98]. Decision-making abilities were more prominent in Biete Punjee and Kolom Punjee and comparatively lower in Saisel Punjee. These decision-making abilities influence land-use conversion, resource management, responses to changes in farm productivity and health, market dynamics, and the adoption of new technologies [46]. Furthermore, enhancing formal education and awareness helps provide multiple livelihood opportunities [63], which are essential for long-term sustenance and climate resilience.

Despite significant challenges posed by climate variability, the transition of shifting agricultural land to pineapple agroforestry, supported by ecological knowledge, helps achieve substantial productivity, economic well-being, and ecological stability. The overall resilient adaptive strategies were greater in Kolom Punjee and Hmarkhawlein, potentially contributing to lowering the climate change vulnerability.

5 Conclusions and recommendations

Pineapple agroforestry farmers in the study region are facing significant challenges from climate variability, including temperature fluctuations, erratic rainfall, and more frequent extreme weather events. These issues, compounded by rising precipitation and temperature trends, contribute to increased vulnerability of the farmers. Unpredictable weather patterns may reduce economic returns by lowering pineapple production. Reliance on seasonal rainfall and the lack of irrigation infrastructure further expose agricultural production to climate risks. Additionally, infestations of weeds and invasive plants pose a critical challenge to farm productivity, requiring labour and time investment. Furthermore, households and villages that depend heavily on pineapple cultivation for their livelihoods face increased vulnerability to climate change-induced disruptions, as declining productivity can directly affect household expenses. Notable climate sensitivity was observed in the villages of Saisel Punjee and Lobonkhal, reflecting greater socio-ecological vulnerability.

However, villages implementing resilient farm management strategies, such as erosion control, reduced tillage, proper residue management, pest and disease management, and crop density adjustments, were found to have reduced climate vulnerability. Additionally, the presence of numerous multipurpose trees within these systems provides economic benefits to households, enhances ecosystem services, and contributes to the conservation of tree diversity. Adaptive strategies were comparatively more pronounced in villages such as Kolom Punjee and Hmarkhawlein, resulting in lower climate change vulnerability. Conversely, villages lacking strong social networks, adequate infrastructure, and diversified income sources demonstrated lower adaptive capacity.

Overall, the findings indicate that climate vulnerability varies across villages and is influenced by both environmental and socio-economic factors. Villages with weak social networks, poor infrastructure, and limited income diversification could be supported through improved market access and expanded economic opportunities. Farmers also require scientific guidance and practical support to address weed and invasive plants management. Promotion of pineapple-based agroforestry through extension activities and policy support can enhance climate resilience while improving rural livelihoods. Furthermore, there is considerable potential to develop small-scale pineapple-based industries, such as pineapple juice processing and incense sticks, to improve rural livelihoods.

Supplementary Information

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Supplementary Material 1.

Author contributions

All authors contributed equally to this manuscript.

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Data availability

Data will be made available on request.

Declarations

Ethics approval and consent to participate

The Institutional Ethics Committee of Assam University, Silchar approved this research vide (Ref. No. IEC/AUS/2026/AJN/01). The study was conducted in accordance with the ethical principles of the Declaration of Helsinki and the ethical guidelines prescribed by the Institutional Ethics Committee of Assam University for research involving human participants. Prior permission from the Village Head was obtained, and informed consent to participate in the study was obtained from all participants before conducting the household survey. Participants were informed about the purpose of the study, and their participation was entirely voluntary. No personally identifiable information was recorded, and confidentiality of the data was strictly maintained.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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