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Article

Climate Change and Farming in Sikkim: A Study on Selected Crops

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Abstract: Climate change is a global phenomenon with far-reaching implications for ecosystems and human well-being. It poses a particularly severe threat to agriculture, which is both highly climate-sensitive and a major contributor to greenhouse gas emissions. The impacts of climate change are not evenly distributed and tend to disproportionately affect ecologically fragile and socio-economically vulnerable regions. This study investigates the impact of climate change on the cultivation of large cardamom (*Amomum subulatum*), maize (*Zea mays*), and ginger (*Zingiber officinale*)—three high-value crops vital to Sikkim's agrarian economy and identifies the adaptation strategies by farmers. Primary data were collected in 2023 from 200 farmers by using a structured schedule across lowland, mid-hill, and high-altitude agro-climatic zones. Stratified random sampling was used to ensure crop and zone representation. Quantitative analysis involved descriptive statistics, chi-square tests for pest and disease incidence, and logistic regression to determine factors influencing adaptation behavior. The results indicate significant yield declines, increased pest and disease outbreaks, and farmers' growing reliance on practices like water conservation, planting date adjustment, and crop diversification. Farm size, education, and access to extension services were significant predictors of adaptation. The study emphasizes the need for policies to enhance the adaptive capacity of smallholder farmers in climate-vulnerable regions like Sikkim.

Keywords: adaptation strategies; agro-climatic zones; climate change; crop diversification

JEL Classification: Q54; Q16; Q12

1. Introduction

Climate change is a global phenomenon with far-reaching implications for ecosystems, economies, and human well-being. It poses a particularly severe threat to agriculture, which is both highly climate-sensitive and a major contributor to greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC, 2014) estimates that agriculture accounts for approximately 19–29 per cent of global anthropogenic greenhouse gas emissions, primarily due to methane from livestock, nitrous oxide from fertilizers, and land-use change. While agriculture contributes to climate change, it is also one of the most vulnerable sectors to its impacts. Changes in temperature, precipitation patterns, and the frequency of extreme weather events can severely affect crop yields, livestock productivity, and food system stability.

This vulnerability is especially critical for developing countries with agrarian economies, where agriculture forms the basis of livelihoods, employment, and food security. Subsistence farming systems, which dominate in many of these regions, rely heavily on climatic stability and lack the infrastructural and technological buffers that industrial agricultural systems often enjoy. As of 2020, approximately 690 million people—8.9 per cent of the global population—were undernourished, and this number is expected to rise without urgent reforms to the global food system (FAO, 2020a; FAO, 2020b). To feed a projected global population of 9 billion by 2050, agricultural output must increase by at least 70 per cent, despite the simultaneous threat of decreasing productivity due to climate-induced stressors (Fischer et al., 2005; Wheeler & Von Braun, 2013). Without timely intervention, climate change could significantly reduce crop productivity and increase global food insecurity. Economic forecasts suggest a minimum global welfare loss of USD 268 billion and GDP losses of over USD 265 billion due to the agricultural effects of climate change by 2050 (Calzadilla et al., 2013).

The impacts of climate change are not evenly distributed and tend to disproportionately affect ecologically fragile and socio-economically vulnerable regions. One such region is the Indian Himalayan state of Sikkim. Located in the Eastern Himalayas, Sikkim is characterized by steep terrain, rich biodiversity, and diverse agro-climatic zones that support the cultivation of a variety of high-value crops. Agriculture forms the backbone of the state's economy, supporting nearly 65 per cent of the population through direct or indirect engagement in farming activities (Sharma et al., 2020). Crops such as large cardamom (*Amomum subulatum*), maize (*Zea mays*), and ginger (*Zingiber officinale*) are not only important for food and income but are also deeply embedded in the cultural and ecological fabric of the region.

However, the agricultural systems in Sikkim are becoming increasingly strained under the pressure of climate variability. Rising temperatures, unpredictable rainfall patterns, and an increase in the frequency of extreme weather events—such as landslides, floods, and prolonged dry spells—are severely affecting crop production and soil health (Das & Bhowmick, 2018). Over the past three decades, average temperatures in the Eastern Himalayan region have shown a marked upward trend, accompanied by erratic monsoon behavior and shifting rainfall patterns (Tambe et al., 2012). These climatic changes have disrupted traditional farming calendars, delayed sowing and harvesting times, and increased the uncertainty faced by farmers who rely heavily on monsoon rains.

Large cardamom, one of the most important cash crops in Sikkim, has witnessed a steady decline in productivity due to climate-induced stressors. The crop is particularly sensitive to temperature and moisture changes, and has suffered from increased outbreaks of fungal diseases like blight and wilt under warmer and wetter conditions (Singh et al., 2015). Similarly, maize and ginger have been affected by irregular rainfall, reduced soil fertility, and rising incidences of pests and diseases. The fall armyworm (*Spodoptera frugiperda*), a pest historically confined to tropical regions, has expanded its range due to rising temperatures, causing widespread damage to maize fields (Shrestha et al., 2020). Ginger, too, has been impacted by bacterial wilt (*Ralstonia solanacearum*), which thrives under high soil moisture and humidity, conditions that are becoming more frequent in the region (Pradhan et al., 2018).

These agronomic challenges are compounded by socio-economic vulnerabilities. The majority of Sikkim's farmers are smallholders who operate on marginal landholdings and rely heavily on rainfed agriculture. Many lack the financial capacity, access to irrigation, or technological resources necessary to adapt to shifting climatic patterns (Gurung et al., 2019). As a result, some farmers are abandoning traditional crops in favor of less climate-sensitive alternatives or are leaving agriculture altogether in search of alternative livelihoods. This transition not only undermines household food and income security but also threatens the long-term sustainability of the region's agricultural heritage. Furthermore, the erratic nature of the monsoon and the increasing frequency of landslides—exacerbated by both climate change and deforestation—pose additional risks to agricultural infrastructure and accessibility (Chakraborty & Joshi, 2021; Mandal & Dutta, 2020).

While the impacts of climate change on agriculture have been widely acknowledged in academic and policy literature, much of the existing research in India has focused on large-scale farming systems and staple crops like rice and wheat. There is a noticeable lack of region-specific studies that examine the localized effects of climate change on high-altitude cropping systems, such as those found in Sikkim (Pant et al., 2019). Moreover, little attention has been paid to the socio-economic consequences of climate variability on smallholder farmers in this context, or to the indigenous knowledge and adaptive strategies that might inform sustainable responses. This research gap is especially concerning given Sikkim's pioneering status as India's first fully organic state and its dependence on environmentally sustainable farming practices.

Addressing this gap is essential for informing regional policy, guiding climate-resilient agricultural development, and supporting the livelihoods of vulnerable farming communities. Without detailed, crop-specific, and location-specific data, policy interventions may fail to address the real needs and capacities of local farmers. Understanding the complex interplay between climatic variables, ecological processes, and socio-economic conditions is therefore critical to building resilient agricultural systems in the Himalayan region.

The theory of **production under uncertainty** provides a lens to examine how changing climatic variables such as rainfall and temperature influence agricultural output, while **expected utility theory** helps explain farmers' adaptation behavior in response to perceived risks and shocks (Dercon, 2002). Additionally, climate change in agriculture is conceptualized as a **negative externality**, where unaccounted environmental costs—such as emissions and biodiversity loss—result in suboptimal social outcomes (Stern, 2007). The study also incorporates a **production approach**, in which climate variables are modeled alongside socio-economic inputs like land, education, and institutional access to assess their effects on crop productivity (Mendelsohn et al., 1994). Furthermore, **adaptive efficiency** (North, 1990) frames the role of institutions—such as extension services, credit access, and climate training—in facilitating or constraining effective adaptation.

Against this backdrop, the present study aims to investigate the impact of climate change on the cultivation of large cardamom, maize, and ginger in Sikkim. It focuses on three key dimensions: long-term climatic trends (temperature and rainfall variability), pest and disease dynamics, and farmers' perceptions and coping strategies. The central objective is to assess the extent and nature of climate-induced vulnerabilities in these crops and to identify practical, region-specific adaptation strategies.

2. Methodology

This study employed a quantitative research design to examine the impact of climate change on the cultivation of large cardamom, maize, and ginger in Sikkim. The data was conducted in 2023 across three elevation-based agro-climatic zones in Sikkim: the lowland zone (300–1000 meters), the mid-hill zone (1000–2000 meters), and the high-altitude zone (2000–3000 meters). These zones were selected to reflect the region's ecological diversity and varying degrees of climatic exposure. The choice of Sikkim as the study site was based on its ecological sensitivity, agricultural dependence, and distinctive position as India's first fully organic state. The region's agricultural systems face increasing vulnerability due to irregular monsoons, temperature fluctuations, pest outbreaks, and other climate-induced challenges.

A stratified random sampling technique was used to select respondents. This method ensured proportional representation of farmers cultivating cardamom, maize, and ginger across the three elevation zones. A total of 200 farmers were surveyed using structured questionnaires. The survey captured detailed information on demographic and socio-economic characteristics, observed changes in temperature and rainfall, pest and disease incidence, and the adoption of various adaptation strategies. Both closed-ended and Likert-scale questions were included to facilitate consistent and analyzable responses. Before data collection, a pilot study with 15 farmers was conducted to ensure clarity and reliability of the questionnaire. Necessary modifications were made based on the pilot study, and Cronbach's alpha was calculated to assess internal consistency. The overall Cronbach's alpha value for the pilot-tested questionnaire was 0.81, indicating a high level of internal consistency and reliability. Face-to-face interviews were conducted with farmers to ensure accuracy in responses. Diagnostic tests, including Variance Inflation Factor (VIF) for multicollinearity, the Breusch-Pagan test for heteroskedasticity, and the Shapiro-Wilk test for normality of residuals, were conducted to validate regression assumptions and confirm the statistical reliability of the results. **Variance Inflation Factor (VIF)** values were all below 2, indicating no serious multicollinearity. The **Breusch-Pagan test** yielded a *p*-value (0.26) greater than 0.05, suggesting homoscedasticity. The **Shapiro-Wilk test** for normality of residuals was also not significant ($p > 0.05$), indicating that the residuals followed a normal distribution.

The collected data were analyzed using a combination of descriptive and inferential statistical techniques. Descriptive statistics such as means, standard deviations, and frequencies were used to summarize the socio-economic profile of respondents and their perceptions of climate change. To identify factors influencing the adoption of at least one climate change adaptation measure, a **logistic regression model** was used. Independent variables included farm size, education level, annual income, perceived changes in temperature, access to extension services, and participation in climate-related training programs.

Cross-tabulation analysis was carried out to explore the variation in pest and disease incidence across agro-climatic zones. To test whether these variations were statistically significant, a chi-square test of independence was applied.

This research involved minimal risk and consisted solely of interviews with adult farmers regarding their agricultural practices and perceptions of climate change. While formal IRB approval was not required as per institutional norms for non-invasive, non-clinical research, ethical standards were strictly followed. Participants were informed about the research objectives, and their participation was entirely voluntary. Informed consent was obtained, and confidentiality was ensured by anonymizing all personal identifiers.

3. Results

The results address socio-economic characteristics, climate change perceptions, crop-specific impacts, adaptation practices, yield changes, access to services, and pest and disease variation—fulfilling all research objectives and reflecting the analytical methods used.

Table 1 presents the socio-economic characteristics of the 200 surveyed farmers across Sikkim. The average age of respondents was 47.6 years with a standard deviation of 12.4, indicating that most farmers were middle-aged, with variation across younger and older age groups. The mean farming experience was 19.2 years (SD = 8.7), showing that respondents had long-term engagement in agriculture. The average farm size was 1.8 acres with a standard deviation of 0.6 acres, reflecting a predominance of smallholder farmers. Literacy among respondents was relatively high, with a mean rate of 81 per cent and a standard deviation of 7.5 per cent, suggesting some variation in educational attainment. Annual household income averaged ₹1,42,000 with a standard deviation of ₹38,000, indicating variation in income levels within the sample. The mean household size was 5.3 members (SD = 1.9), showing moderate variation in family structure. Access to extension services was reported by 62 per cent of respondents, with a standard deviation of 13.4 per cent. Access to formal credit was reported by 46 per cent of farmers (SD = 11.2 per cent). These reflect variability in the availability and use of institutional services across the sample.

Table 1. Socio-Economic Profile of the Respondents

Variable	Mean	Standard Deviation
Age (years)	47.6	12.4
Farming Experience (years)	19.2	8.7
Farm Size (acres)	1.8	0.6
Literacy Rate (%)	81	7.5
Annual Income (₹)	1,42,000	38,000
Household Size	5.3	1.9
Access to Extension Services (%)	62	13.4
Access to Credit (%)	46	11.2

Source: Author's Calculation

Table 2 presents farmers' perceptions of various climate change impacts. A majority of respondents (85 per cent) reported erratic rainfall patterns as a major issue. Rising temperatures were noted by 78 per cent of farmers, followed by increased pests and diseases (72 per cent). Reduced crop yields were identified by 68 per cent of respondents as a noticeable consequence of climate variability. Increased soil erosion was reported by 64 per cent, while 61 per cent observed a delayed onset of the monsoon season. Additionally, 58 per cent of respondents reported experiencing prolonged dry spells in recent years. These results indicate that farmers are aware of multiple climatic disruptions affecting their agricultural practices.

Table 2. Perceptions of Climate Change Impacts

Perception Indicator	Percentage (%)
Erratic Rainfall Patterns	85
Rising Temperatures	78
Increased Pests and Diseases	72
Reduced Crop Yields	68
Increased Soil Erosion	64
Delayed Monsoon Onset	61
Prolonged Dry Spells	58

Source: Author's Calculation

Table 3 shows the average percentage of yield decline as reported by farmers for the three major crops studied. Cardamom exhibited the highest average yield decline at 41 per cent, with fungal wilt and heat stress identified as the primary contributing factors. Maize showed an average yield decline of 35 per cent. The main threats reported were fall armyworm infestations and irregular rainfall patterns. Ginger had an average reported yield decline of 38 per cent, attributed mainly to bacterial wilt and waterlogging conditions. These findings reflect crop-specific vulnerabilities as perceived by farmers across different agro-climatic zones in Sikkim.

***Table* 3.** Yield Declines and Major Threats by Crop

Crop	Avg. Yield Decline (%)	Major Issues
Cardamom	41	Fungal Wilt, Heat Stress
Maize	35	Fall Armyworm, Irregular Rainfall
Ginger	38	Bacterial Wilt, Waterlogging

Source: Author's Calculation.

Table 4 panel (a) shows the distribution of pest incidence across the lowland, mid-hill, and high-altitude agro-climatic zones of Sikkim. In the lowland zone (300–1000 meters), fall armyworm was the most commonly reported pest, affecting 50 out of 70 farmers. The mid-hill zone (1000–2000 meters) was predominantly affected by white grubs, reported by 44 of 65 farmers. In the high-altitude zone (2000–3000 meters), aphids were the most frequently observed pest, with 36 out of 65 farmers indicating infestation. The results of the chi-square test ($\chi^2 = 13.47$, degrees of freedom = 4, $p < 0.01$) indicate a statistically significant association between agro-climatic zone and the type of pest reported. This suggests that pest incidence varies considerably with elevation and related climatic conditions, emphasizing the need for zone-specific pest management strategies.

Table 4 panel (b) shows the incidence of crop diseases across the three elevation zones in Sikkim. In the lowland zone, bacterial wilt was the most commonly reported disease, with 42 of 70 farmers affected. In the mid-hill zone, 40 out of 65 farmers reported leaf blight as the primary disease. In the high-altitude zone, fungal wilt was most prevalent, with 42 out of 65 farmers affected. The chi-square test for disease incidence across zones produced a value of 14.12 (degrees of freedom = 4, $p < 0.01$), indicating a statistically significant variation in disease patterns by elevation. These findings highlight that different agro-climatic zones experience distinct disease pressures, likely influenced by temperature, humidity, and crop distribution, thereby calling for tailored disease control interventions.

Table 4. Pest and Disease Incidence Across Agro-Climatic Zones.

Panel (a): Pest Incidence Across Agro-Climatic Zones				
Pest Type	**Lowland (n = 70)**	**Mid-Hill (n = 65)**	**High Altitude (n = 65)**	**Total**
Fall Armyworm	50	4	0	54
White Grubs	5	44	2	51
Aphids	0	2	36	38
Total Farmers	55	50	38	143
Source: Author's Calculation; *Chi-square* (χ^2) *= 13.47, df = 4, p * < 0.01*				
Panel (b): Disease Incidence Across Agro-Climatic Zones				
Disease Type	**Lowland (*n* = 70)**	**Mid-Hill (*n* = 65)**	**High Altitude (*n* = 65)**	**Total**
Bacterial Wilt	42	8	1	51
Leaf Blight	6	40	2	48
Fungal Wilt	2	5	42	49
Total Farmers	50	53	45	148
Source: Author's Calculation; *Chi-square* (χ^2) *= 14.12, df = 4, p < 0.01*				

Table 5 presents the adoption rates of various climate change adaptation strategies reported by farmers. Water conservation techniques were the most widely adopted strategy, with 72 per cent of respondents indicating their use. Changing planting dates was reported by 65 per cent of farmers as a way to cope with shifting rainfall patterns and seasonal variability. Organic pest control methods were adopted by 63 per cent of respondents, while 60 per cent reported practicing crop diversification. The adoption of climate-resilient crop varieties was reported by 58 per cent of farmers. Additionally, 39 per cent of farmers had participated in climate-related training programs. These results indicate that a range of adaptive practices are being implemented at varying levels across the farming population.

Table 5. Adaptation Strategies Used by Farmers.

Adaptation Strategy	**Adoption (%)**
Water Conservation Techniques	72
Changing Planting Dates	65
Organic Pest Control	63
Crop Diversification	60
Climate-Resilient Varieties	58
Accessed Climate Training	39

Source: Author's Calculation

Table 6 presents the results of the binary logistic regression analysis conducted to identify the factors influencing farmers' adoption of climate change adaptation strategies. The dependent variable was defined as the adoption of at least one adaptation measure (1 = yes, 0 = no). Farm size was found to have a positive and statistically significant effect on adaptation decisions (coefficient = 0.45, $p = 0.02$), indicating that larger landholders were more likely to adopt adaptation measures. Education level also showed a significant positive relationship (coefficient = 0.67, $p = 0.01$), suggesting that more educated farmers were more likely to engage in adaptation. Perceived temperature rise was positively associated with adaptation behavior (coefficient = 0.52, $p = 0.03$), indicating that farmers who observed temperature changes were more inclined to adopt strategies. Access to extension services (coefficient = 0.58, $p = 0.04$) and participation in climate training (coefficient = 0.69, $p = 0.01$) were both significant predictors, emphasizing the role of institutional support. Income level had a positive but statistically non-significant association with adaptation (coefficient = 0.33, $p = 0.07$).

Table 6. Logistic Regression – Determinants of Adaptation.

Variable	Coefficient	Std. Error	*p*-Value
Farm Size	0.45	0.12	0.02 *
Education Level	0.67	0.15	0.01 *
Perceived Temperature Rise	0.52	0.13	0.03 *
Income Level	0.33	0.11	0.07
Access to Extension	0.58	0.14	0.04 *
Climate Training Participation	0.69	0.17	0.01 *

Source: Author's Calculation; * Significant at $p < 0.05$

Table 7 presents data on farmers' access to key institutional support services. A total of 62 per cent of respondents reported regular access to government extension services. Access to formal credit was available to 46 per cent of the surveyed farmers. Participation in climate-related training programs was reported by 39 per cent of the sample. These figures suggest variability in institutional outreach and support services among farming communities in Sikkim.

Table 7. Access to Institutional Support.

Support Service	Access Reported (%)
Government Extension Services	62
Formal Credit Access	46
Climate Training Participation	39

Source: Author's Calculation

4. Discussion

The findings of this study highlight the increasing vulnerability of Sikkim's agricultural systems to climate change, especially in the cultivation of large cardamom (*Amomum subulatum*), maize (*Zea mays*), and ginger (*Zingiber officinale*). These crops are critical to Sikkim's economy and food systems, and their productivity has been increasingly impacted by changing climatic conditions such as erratic rainfall, rising temperatures, and emerging pest and disease threats. This discussion interprets the findings in the context of existing literature and situates the results within broader regional and scientific discourses on climate change and high-altitude agriculture. One of the most prominent themes emerging from the study is the shift in climatic conditions, particularly rainfall irregularities and rising temperatures. Farmers reported unpredictability in monsoon onset, delayed rains, and extended dry spells. Such changes have disrupted traditional sowing and harvesting schedules and undermined local climate knowledge that previously guided agricultural decisions. These observations align with previous studies indicating a rise in average temperatures and changing precipitation patterns across the Eastern Himalayas (Tambe et al., 2012). Sharma et al. (2020) also documented similar climate-induced disruptions in planting schedules and seasonal planning among farmers in Sikkim's organic farming systems.

For cardamom, a perennial crop that thrives in cool, moist environments under forest cover, increasing temperatures and humidity have contributed to a higher incidence of fungal diseases such as blight and wilt. Singh et al. (2015) found that the productivity of cardamom in Sikkim has been declining due to increased vulnerability to Fusarium oxysporum and Phytophthora species, both of which are favored by warmer and wetter conditions. Farmers in this study also observed declining cardamom yields and attributed them to such conditions, reinforcing the link between climatic shifts and disease susceptibility. Maize cultivation has faced challenges due to erratic rainfall and new pest outbreaks, particularly the fall armyworm (*Spodoptera frugiperda*). This invasive pest, previously uncommon in the Himalayan region, has recently expanded its range due to warming temperatures and changing agro-ecological conditions (Shrestha et al., 2020). The pest's destructive feeding habits have caused visible damage to maize crops, leading to yield losses and higher labor costs for pest management. The findings echo Rana et al. (2021), who reported similar trends in neighboring hill states.

Ginger farmers have reported an increase in bacterial wilt (*Ralstonia solanacearum*) and root rot, especially during periods of heavy rainfall. Pradhan et al. (2018) established that the pathogen thrives in saturated soils and warmer temperatures, conditions which have become more frequent in recent years. As a result, ginger productivity has become highly variable, with some farmers reporting significant losses depending on the timing and intensity of rainfall. Beyond crop-specific impacts, the study reveals broader socio-economic implications of climate variability. Most farmers in Sikkim are smallholders operating on limited landholdings, and many rely on traditional farming methods with minimal irrigation infrastructure. As noted by Gurung et al. (2019), smallholder farmers in the Eastern Himalayas are particularly vulnerable to climate-induced shocks due to financial constraints, limited institutional support, and heavy dependence on monsoon rains. These vulnerabilities were evident in this study, where farmers expressed concerns over declining yields, rising input costs, and increasing uncertainty in crop outcomes.

Despite these challenges, farmers have shown adaptability by implementing a range of coping strategies. Adjusting planting dates, particularly to accommodate delayed monsoons, was a frequently adopted measure. Similar adaptation strategies were documented by Sharma et al. (2020), who found that farmers in Sikkim were increasingly relying on seasonal forecasts and local knowledge to reschedule planting windows. Another key strategy was the adoption of climate-resilient crop varieties. Das and Bhowmick (2018) emphasized the growing interest among farmers in disease-resistant and drought-tolerant varieties, though the availability and affordability of such seeds remain barriers. Water conservation practices such as rainwater harvesting, mulching, and construction of small-scale irrigation systems were also noted. These methods help improve soil moisture retention and buffer against rainfall irregularities. Rai et al. (2017) highlighted similar practices in their study on soil degradation and climate resilience in the region. In line with Sikkim's organic farming policy, many farmers also relied on organic pest control methods, including biopesticides and crop rotation. However, Mandal and Dutta (2020) argue that the effectiveness of such techniques is often limited by lack of training and support, a concern echoed by farmers in this study.

Crop diversification emerged as a pragmatic risk-reduction strategy, allowing farmers to distribute risk across multiple crops and reduce dependency on a single commodity. This aligns with findings by Pant et al. (2019), who reported that diversification helps build economic resilience and improves food security in high-altitude farming systems. Institutional support remains a critical determinant of adaptation success. Farmers reported inconsistent access to extension services, limited training on climate-resilient practices, and restricted access to formal credit. These constraints have also been highlighted in previous literature (Gurung et al., 2019; Lama et al., 2022). Although state policies in Sikkim have promoted organic and sustainable agriculture, the effectiveness of these programs in reaching vulnerable farmers remains uneven. Farmers are already experiencing a shift in climate patterns that has affected the productivity of major crops and exacerbated pest and disease pressures. While many have adopted adaptation strategies, their effectiveness is shaped by access to knowledge, financial resources, and institutional support. Strengthening these areas through targeted interventions can significantly enhance the resilience of Sikkim's agricultural systems in the face of ongoing climate change.

5. Conclusion

This study highlights the complex and growing impacts of climate change on the cultivation of cardamom, maize, and ginger in Sikkim—three crops that are vital to the region's agrarian economy, ecological balance, and cultural identity. Farmers across different agro-climatic zones are experiencing disruptions due to shifting temperature regimes, erratic rainfall, and increased pest and disease prevalence. These environmental stressors have led to significant yield variability, economic uncertainty, and challenges in maintaining traditional agricultural practices. Despite these challenges, farmers have responded with considerable resilience, employing a variety of adaptive strategies. These include adjusting planting dates to accommodate shifting seasons, adopting climate-resilient crop varieties, conserving water through local techniques, practicing organic pest control, and diversifying crops to spread production risks. These actions reflect a growing awareness of climate risks and a willingness to adapt, even within the limitations of smallholder farming systems. However, the effectiveness and sustainability of these strategies are highly dependent on supportive institutional frameworks. Limited access to extension services, formal credit, and targeted training continues to constrain farmers' adaptive capacity. Addressing these systemic barriers is essential to build long-term resilience and protect food and livelihood security in the face of continued climate variability.

6. Recommendations

To enhance the climate resilience of Sikkim's agricultural sector, a comprehensive and context-specific policy approach is imperative. One of the foremost priorities is to improve and decentralize agricultural extension services by strengthening village-level centers and equipping them with climate adaptation training modules tailored to local needs. Policymakers should also invest in climate-resilient infrastructure, including small-scale irrigation systems, rainwater harvesting units, and pest surveillance networks, particularly in vulnerable agro-climatic zones. Expanding crop insurance schemes that are specifically designed for high-altitude and smallholder farming systems can help mitigate risks arising from erratic rainfall and pest outbreaks. In addition, the availability and dissemination of climate-resilient seed varieties—especially those resistant to fungal and bacterial infections—should be scaled up through public-private partnerships and local seed banks. Given Sikkim's status as an organic farming state, targeted subsidies and training for organic adaptation techniques—such as biopesticide use, composting, and intercropping—would support environmentally sustainable responses to climate stress. Lastly, encouraging the integration of indigenous knowledge systems with modern scientific practices through participatory policy frameworks can ensure that adaptation strategies are not only effective but also socially and culturally grounded. These policy interventions, if effectively implemented, can significantly strengthen the adaptive capacity of Sikkim's farming communities and safeguard the sustainability of its unique agro-ecological systems.

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