

Climate Resilience of Large Cardamom Cultivars in Sikkim Himalaya: Insights from Participatory MCDM and Indigenous Knowledge of Lepcha Community

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Research Article

Keywords: Sikkim Himalaya, Large Cardamom, Climate Resilience, Lepcha Community, Dual Vulnerability

Posted Date: August 13th, 2025

DOI: <https://doi.org/10.21203/rs.3.rs-7262051/v1>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Agroforestry Systems on November 24th, 2025. See the published version at <https://doi.org/10.1007/s10457-025-01393-4>.

Abstract

Large cardamom (*Amomum subulatum* Roxb.) plays an important role in supporting both the rural livelihoods and ecological balance in the Eastern Himalaya, especially in Sikkim. However, its long-term survival is increasingly at risk due to changing climate patterns, the increase of pests and diseases outbreaks. This study evaluates the climate resilience of six large cardamom cultivars Seremna, Dzongu Golsey, Sawney, Ramsey, Ramla, and Varlangey using a combined approach of Indigenous Knowledge Systems and the Multi Criteria Decision Making (MCDM) method called TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). Data were gathered through Participatory Rural Appraisal (PRA) tools, surveys, and expert consultations with Lepcha farmers from the Dzongu region. Five key criteria were prioritized: productivity, resistance to pests and diseases, lifespan, adaptability to climate, and environmental tolerance. These criteria were weighted and analyzed using TOPSIS to calculate each cultivar's resilience score. The results show that Seremna is the most climate-resilient cultivar, with a Closeness Coefficient (CCi) of 0.94, performing best across all resilience measures. Dzongu Golsey and Sawney ranked in the middle, while Ramla and Varlangey showed lower resilience. This study highlights the value of community led assessments in identifying climate resilient crops and demonstrates the usefulness of participatory MCDM methods in agroecological planning. By combining traditional ecological knowledge with structured analysis, it presents a flexible and context aware model for promoting climate smart agriculture. The findings also draw attention to a dual vulnerability in the Sikkim Himalaya: the climate sensitivity of large cardamom cultivars and the marginalization of the Lepcha community.

1. Introduction

In the Eastern Himalaya, especially in Sikkim, large cardamom (*Amomum subulatum* Roxb.) plays an important role in both supporting rural livelihood and maintaining environmental health. It has historically made up more than 80% of India's total production (Avasthe et al. 2011; Bhutia et al. 2024; Bisht 2011). Grown for generations under forest canopies in traditional agroforestry systems in rural areas, this crop is key to the rural economy and helps maintain ecological balance by preventing soil erosion, regulating local climates, and preserving biodiversity (Sharma et al. 2009; Avasthe et al. 2011; Bist and Bhatt 2021; G. Sharma 2024; Lepcha et al. 2023; Sharma et al. 2007; Muthuri et al. 2023; Rolo et al. 2023).

The Lepchas, known as the original inhabitants of Sikkim, were the first to harvest large cardamom from natural forests (Varadarasan and Biswas 2002; Lepcha et al. 2023). For the Lepcha community, large cardamom farming is more than just a way to make a living; it is a deeply rooted cultural practice that reflects their connection to the land (Varadarasan and Biswas 2002; Rao et al. 2016). Their traditional ecological knowledge, passed down through generations, shows a practical understanding of local soils, weather patterns, plant health, and pest behavior (Gudade et al. 2012; Chhetri et al. 2023). Because of this, their knowledge is essential for understanding how people adapt to the environment in the Sikkim Himalaya.

In recent years, Large cardamom farming has become very vulnerable to climate change (Maharjan et al. 2019; Wangchuk et al. 2023; Swar et al. 2023). Farmers across the region have noticed unpredictable rainfalls, longer dry periods, unexpected frost, and warmer winters, all of which harm crop yields, quality and lifespan (Feroze et al. 2022; Abdullah and Parvin 2024). These climate problems are made worse by the spread of diseases like chirkey and foorkey, as well as pest outbreaks such as white grubs and stem borers (Deka et al. 2016; Mandal et al. 2012; Raj 2013; Gurung et al. 2025; Raj et al. 2021).

In addition to these environmental challenges, there is a demographic concern: the Lepcha community, which started large cardamom cultivation in the past, is now facing population decline over the decades. Our analysis shows that over the past 120 years (1891–2011), the Lepchas have had the lowest population growth among the major Scheduled Tribes in Sikkim. With a Compound Annual Growth Rate (CAGR) of just 5.37%, they fall far behind other tribal groups like the Bhutia, Tamang, and Limboo. This pattern points to a deeper demographic vulnerability, which is especially worrying for a Lepcha community that is not only native to the region but also key to its cultural and agricultural identity.

These factors highlight two main challenges: the growing climate sensitivity of traditional large cardamom cultivars and the social marginalization of the Lepcha community. This makes it clear that there is an urgent need to find climate resilient large cardamom cultivars and to record and include the community's views to help develop farming methods that can adapt to changing conditions.

In this context, it is essential to identify cultivars that can withstand both biotic and abiotic stresses to ensure the sustainability of large cardamom cultivation and the livelihoods it supports (Roy et al. 2021; Kesineni et al. 2023; Bela 2023). Although several cultivars like Seremna, Dzongu Golsey, Sawney, Ramsey, Ramla, and Varlangey are currently grown across Sikkim's diverse agroecological zones (Nair 2020; Lepcha et al. 2023), there has been lack of systematic evaluation of their performance under climate stress. Most research so far has focused on productivity, disease control, and post-harvest management, with limited attention to how these cultivars respond to climate variability (Maharjan et al. 2019; Rijal 2014).

Another important gap is the lack of integration of indigenous knowledge into formal scientific assessments. Although Lepcha farmers have valuable practical insights, they are often overlooked in top down research approaches that do not take local ecological and cultural contexts into account. This disconnects makes adaptation strategies less relevant and harder to accept. Moreover, structured evaluation tools like Multi Criteria Decision Making (MCDM) frameworks are rarely used in this field. Techniques such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) have shown their usefulness in agricultural decision making and resource prioritization (Heidarisoltanabadi et al. 2023), but their use in assessing large cardamom cultivars, especially through community led, participatory methods, is still limited.

This study aims to bridge research and methodological gaps by combining scientific evaluation with indigenous ecological knowledge from the Lepcha community to assess the climate resilience of six large cardamom cultivars. Specifically, it seeks to: (i) identify climate resilience criteria as defined by the community, (ii) carry out participatory scoring of cultivar performance, and (iii) use the TOPSIS method to rank the cultivars based on overall scores. By integrating these approaches, the research helps create knowledge that blends traditional wisdom with analytical tools, strengthening the adaptive capacity of Himalayan farming systems.

2. Materials and Methods

2.1 Study Area

Dzongu, located in the Mangan district, Sikkim, India is a remote area with great ecological and cultural value (Fig. 1). It lies between the Teesta River and the Khangchendzonga mountain range and has been set aside as a Lepcha Reserved Area to protect the ancestral land, culture, and identity of the Lepcha people. Strict permit rules and limits on non-resident settlement help keep traditional Lepcha lifestyles and sustainable practices alive, which are deeply connected to their spiritual and ecological beliefs. The Lepchas, considered the original inhabitants of Sikkim, share a sacred bond with Mount Khangchendzonga, seen as their guardian deity (Pradhan and Badola, 2008; Lepcha et al. 2017). Dzongu is also part of the Khangchendzonga Biosphere Reserve (KBR), known for its diverse ecosystems ranging from subtropical to alpine and recognized by UNESCO in 2016 as a World Heritage Site for its unique natural and cultural importance.

Dzongu is an important cultural and ecological area for the Lepcha people, but this study looks beyond that local setting to examine the population trends of the Lepcha community across the whole state of Sikkim. This wider view is needed to understand how their population has changed over time. The Compound Annual Growth Rate (CAGR) of the Lepcha population was calculated using both historical and recent census data to reveal long term patterns. The first detailed population census of Sikkim, carried out in 1891 by the British Political Officer (Risley 1993), serves as a historical starting point, while data from the 2011 Census of India helps show more recent trends. Additionally, the study compares the Lepcha population trends with those of other major Scheduled Tribes in Sikkim, such as the Bhutia, Tamang, and Limboo (Subba) communities, to place the Lepchas' demographic changes in the broader context of the state's tribal groups.

For calculation of total annual growth rate, we use the following formula

$$\text{CAGR} = \left(\frac{P_1}{P_2} \right)^{1/n} - 1$$

Where,

CAGR = Compound Annual Growth Rate of the Population

P_1 = Initial population

P_2 = Final population

n = Number of years

An analysis of long-term population data from 1891 to 2011 reveals notable disparities in the demographic growth of Sikkim’s four tribal communities Lepcha, Bhutia, Tamang, and Limboo (Subba). Using the Compound Annual Growth Rate (CAGR) as a key metric, the data indicate that the Lepcha community experienced the slowest population growth over the 120 year period. In 1891, the Lepchas were the most populous among these groups, numbering 5,762, compared to 4,804 Bhutia, 2,867 Tamang, and 3,356 Limboo (Subba). However, by 2011, their population had increased to 42,909, while the Bhutia rose to 69,598, Tamang to 37,696, and Limboo to 53,703. The corresponding CAGRs further highlight these differences: Lepcha-5.37%, Bhutia-11.24%, Tamang-10.12%, and Limboo (Subba)-12.50%.

Table 1
Sikkim tribal community population records for the 1891 and 2011

Tribal Community in Sikkim	Population in 1891	Population in 2011	CAGR (%)
1. Lepcha	5,762	42,909	5.37%
2. Bhutia	4,804	69,598	11.24%
3. Tamang	2,867	37,696	10.12%
4. Limboo (Subba)	3,356	53,703	12.50%

This data reveals a striking reversal in relative population status, the Lepchas, once the most numerous, are now the least populous among these four tribal communities in Sikkim. Their CAGR of just 5.37%, less than half of that of the Bhutia and Limboo communities, points toward a demographic stagnation or vulnerability. Several factors may contribute to this slow growth, including restricted settlement policies in areas like Dzongu (a Lepcha Reserved Area), lower fertility rates, out-migration of youth for education or employment, and socio-economic isolation. Despite their deep cultural and spiritual ties to Sikkim as the region's original inhabitants, the Lepchas now appear numerically and demographically at risk when compared to other Scheduled Tribes of Sikkim.

2.2 Selection of Cultivars and Evaluation Criteria

Using Participatory Rural Appraisals (PRA), six commonly grown large cardamom cultivars were identified and selected: Seremna, Dzongu Golsey, Ramsey, Varlangey, Ramla, and Sawney. Each cultivar was evaluated based on five key criteria developed through community consultations. These criteria are: 1) Productivity: the relative yield of each cultivar; 2) Disease and Pest Resistance: the ability to resist major threats like Chirke, Foorkey, stem borers, and fungal rot; 3) Lifespan: the average productive years of the plant before it starts to decline; 4) Climate Adaptability: how well the cultivar adapts to changes in rainfall, temperature, and soil moisture; and 5) Environmental Tolerance: tolerance to stresses such as wind, cold spells, and partial shade. These factors capture both agricultural performance and ecological resilience, making them ideal for evaluating climate-resilient cultivars.

These five criteria were then rank through consultation using pair-wise ranking one of the Participatory Rural Appraisal (PRA), as a result the climate adaptability rank 1st followed by Productivity, Environmental Tolerance, Disease and Pest Resistant and Life Span (Table 1). After ranking the criteria, weights were assigned based on the ranking of the criteria using following formula.

2.2.1 Calculation of Values (Weight) for each criterion by using the standard formula:

$$W_i = \frac{(n - r_i + 1)}{(n + 1)} \times 2$$

Where,

n = total number of criteria

r_i = rank of the particular criteria

Table 2
Pair-wise Ranking of Criteria for Identification of Climate Resilience Large Cardamom cultivars.

Criteria	<i>Life Span</i>	<i>Disease and Pest Resistant</i>	<i>Productivity</i>	<i>Environment Tolerance</i>	<i>Climate Adaptability</i>	Ranking	Weight
Life Span	X	<i>Disease and Pest Resistant</i>	<i>Productivity</i>	<i>Environment Tolerance</i>	<i>Climate Adaptability</i>	5th	0.0667
Disease and Pest Resistant		X	<i>Productivity</i>	<i>Environment Tolerance</i>	<i>Climate Adaptability</i>	4th	0.1333
Productivity			X	<i>Productivity</i>	<i>Climate Adaptability</i>	2nd	0.2667
Environment Tolerance				X	<i>Climate Adaptability</i>	3rd	0.2000
Climate Adaptability					X	1st	0.3333

2.3 Data Collection and Scoring Procedure

Field data were collected through structured interviews and scoring exercises with 100 large cardamom farmers, representing all major cardamom growing villages within Dzongu. Respondents were asked to rate each cultivar on a 1–6 scale for each of the five criteria. The average score for each cultivar per criterion was used to populate the decision matrix. This participatory scoring process ensured that local ecological knowledge was embedded within the data structure.

2.4 Analytical Framework: TOPSIS Method

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), developed by Hwang and Yoon (1981), is a widely used Multi Criteria Decision Making (MCDM) method (Zyoud and Fuchs-Hanusch 2017; Behzadian et al. 2012; Madanchian and Taherdoost 2023). It ranks a set of alternatives based on their relative closeness to the ideal solution (Li et al. 2024). The fundamental premise of TOPSIS is that the chosen alternative should have the shortest geometric distance from the Positive Ideal Solution (PIS) and the farthest distance from the Negative Ideal Solution (NIS) (Behzadian et al. 2012).

2.4.1 Construct the Decision Matrix

Let the decision matrix $\backslash \text{varvec} D$ represent $\backslash \text{varvec} m$ alternatives (six cultivars) evaluated against $\backslash \text{varvec} n$ criteria (five):

$$\backslash \text{varvec} D = \left[\backslash \text{varvec} x_{\backslash \text{varvec} i \backslash \text{varvec} j} \right] \backslash \text{varvec} m \times \backslash \text{varvec} n$$

Where,

$\backslash \text{varvec} x_{\backslash \text{varvec} i \backslash \text{varvec} j}$ is the performance score of the i^{th} alternative under the j^{th} criterion,

$\backslash \text{varvec} i = 1, 2, \dots, 6; j = 1, 2, \dots, 5.$

2.4.2 Normalize the Decision Matrix

The normalization process removes scale differences among criteria by transforming all values to a dimensionless scale:

$$\backslash \text{varvec} r_{\backslash \text{varvec} i \backslash \text{varvec} j} = \frac{\backslash \text{varvec} x_{\backslash \text{varvec} i \backslash \text{varvec} j}}{\sqrt{\sum_{\backslash \text{varvec} i=1}^{\backslash \text{varvec} m} \backslash \text{varvec} x_{\backslash \text{varvec} i \backslash \text{varvec} j}^2}}$$

Where,

$\backslash \text{varvec} r_{\backslash \text{varvec} i \backslash \text{varvec} j}$ is the normalized value of x_{ij} ,

$\backslash \text{varvec} m$ is the number of alternatives (cultivars).

2.4.3 Construct the Weighted Normalized Matrix

Weights w_j are assigned to each criterion based on its importance. The normalized matrix is multiplied by the weights:

$$\backslash \text{varvec} v_{\backslash \text{varvec} i \backslash \text{varvec} j} = \backslash \text{varvec} w_{\backslash \text{varvec} j} \times \backslash \text{varvec} r_{\backslash \text{varvec} i \backslash \text{varvec} j}$$

Where,

$\backslash \text{varvec} v_{\backslash \text{varvec} i \backslash \text{varvec} j}$ is the weighted normalized value,

$\backslash \text{varvec} w_{\backslash \text{varvec} j}$ is the weight of the j^{th} criterion (where $\sum \backslash \text{varvec} w_{\backslash \text{varvec} j} = 1$).

4. Determine the Positive Ideal and Negative Ideal Solutions

The Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) are determined as:

$$\backslash \text{varvec} A^+ = \left\{ \backslash \text{varvec} v_1^+, \backslash \text{varvec} v_2^+, \dots, \backslash \text{varvec} v_{\backslash \text{varvec} n}^+ \right\} = \left\{ \max_{\backslash \text{varvec} i} \left(\backslash \text{varvec} v_{\backslash \text{varvec} i \backslash \text{varvec} j} \right) \right\}$$

$$\backslash \text{varvec} A^- = \left\{ \backslash \text{varvec} v_1^-, \backslash \text{varvec} v_2^-, \dots, \backslash \text{varvec} v_{\backslash \text{varvec} n}^- \right\} = \left\{ \min_{\backslash \text{varvec} i} \left(\backslash \text{varvec} v_{\backslash \text{varvec} i \backslash \text{varvec} j} \right) \right\}$$

Where,

$\backslash \text{varvec} v_1^+$ and $\backslash \text{varvec} v_1^-$ are the best and worst values of each criterion.

2.4.4 Calculate the Separation Measures

The distance of each alternative from the ideal and negative-ideal solutions is calculated using Euclidean distance:

Separation from PIS:

$$\sqrt[n]{\text{varvec}S_{\text{varvec}i}^+} = \sqrt[n]{\sum_{\text{varvec}j=1}^n (\sqrt[n]{\text{varvec}v_{\text{varvec}i}\text{varvec}j} - \sqrt[n]{\text{varvec}v_{\text{varvec}j}})}$$

Separation from NIS:

$$\sqrt[n]{\text{varvec}S_{\text{varvec}i}^-} = \sqrt[n]{\sum_{\text{varvec}j=1}^n (\sqrt[n]{\text{varvec}v_{\text{varvec}i}\text{varvec}j} - \sqrt[n]{\text{varvec}v_{\text{varvec}j}})}$$

2.5 Calculate the Closeness Coefficient

The closeness of each alternative to the ideal solution is calculated as:

$$\sqrt[n]{\text{varvec}C_{\text{varvec}i}^{\text{varvec}*}} = \frac{\sqrt[n]{\text{varvec}S_{\text{varvec}i}^-}}{\sqrt[n]{\text{varvec}S_{\text{varvec}i}^+} + \sqrt[n]{\text{varvec}S_{\text{varvec}i}^-}}$$

Where, Higher $\sqrt[n]{\text{varvec}C_{\text{varvec}i}^{\text{varvec}*}}$ values indicate greater similarity to the ideal solution. Ranking of alternatives are ranked in descending order based on $\sqrt[n]{\text{varvec}C_{\text{varvec}i}^{\text{varvec}*}}$. The alternative with the highest $\sqrt[n]{\text{varvec}C_{\text{varvec}i}^{\text{varvec}*}}$ is considered the most preferred.

3. Results

The assessment of climate resilient large cardamom (*Amomum subulatum* Roxb.) cultivars was carried out using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a Multi Criteria Decision Making (MCDM) method that ranks options based on how close they are to an ideal solution and how far from the worst case scenario. Five key criteria were identified through community consultations: productivity, disease and pest resistance, lifespan, climate adaptability, and environmental tolerance. These criteria were prioritized and ranked using pair-wise comparison, a Participatory Rural Appraisal (PRA) tool, and assigned weights for further analysis. In the first stage, a normalized decision matrix was created to standardize the data and allow comparison across criteria. This involved converting raw scores into values between 0 and 1. Among the cultivars, Seremna achieved the highest normalized values for productivity (0.54), climate adaptability (0.60), and environmental tolerance (0.58), showing strong performance in key resilience traits (Table 2). Sawney showed strengths in lifespan (0.48) and disease and pest resistance (0.47), while cultivars like Ramla and Varlangey had consistently lower normalized scores, reflecting community concerns about their resilience under stress.

Table 3
Normalized decision matrix

Large Cardamom cultivars/Criteria	Productivity	Disease and Pest Resistant	Lifespan	Climate Adaptability	Environmental Tolerance
1. Seremna	0.54	0.43	0.39	0.60	0.58
2. Dzongu Golsey	0.49	0.32	0.47	0.37	0.40
3. Ramsey	0.30	0.34	0.37	0.41	0.40
4. Varlangey	0.34	0.45	0.35	0.32	0.33
5. Ramla	0.35	0.41	0.37	0.29	0.29
6. Sawney	0.39	0.47	0.48	0.38	0.39

Next, weights were assigned to each criterion based on what the community prioritized. These weights were applied to the normalized matrix to create the weighted normalized decision matrix. Once again, Seremna showed the highest weighted scores in climate adaptability (0.20) and environmental tolerance (0.12), highlighting its importance to farmers dealing with

climate uncertainty (Table 3). Cultivars like Dzongu Golsey and Sawney performed fairly evenly, while Ramsey and Ramla fell behind in most areas.

Table 4
Weighted normalized decision matrix

Large cardamom Cultivars/Criteria	Productivity	Disease and Pest Resistant	Lifespan	Climate Adaptability	Environmental Tolerance
1. Seremna	0.14	0.06	0.03	0.20	0.12
2. Dzongu Golsey	0.13	0.04	0.03	0.12	0.08
3. Ramsey	0.08	0.05	0.02	0.14	0.08
4. Varlangey	0.09	0.06	0.02	0.11	0.07
5. Ramla	0.09	0.06	0.02	0.10	0.06
6. Sawney	0.10	0.06	0.03	0.13	0.08

The third phase involved identifying the positive ideal solution (V^+) and the negative ideal solution (V^-). The V^+ vector [0.14, 0.06, 0.03, 0.20, 0.12] represents the best possible scores across all criteria, while the V^- vector [0.08, 0.04, 0.02, 0.10, 0.06] represents the lowest performance values. Using these points, the Euclidean distance from both the ideal and anti-ideal solutions was calculated for each cultivar.

In the fourth stage, separation measures (D^+ and D^-) were calculated to show how close each cultivar is to the ideal and how far it is from the worst-case scenario. A lower D^+ means the cultivar is closer to the ideal, while a higher D^- means it is farther from the worst profile. Seremna stood out with the lowest D^+ (0.01) and the highest D^- (0.13), showing it closely matches the best resilience profile. On the other hand, Ramla had the highest D^+ (0.13) and the lowest D^- (0.02), indicating it performed the weakest overall (Table 4).

Table 5
Separation from positive ideal and negative ideal solutions, closeness to ideal solution and ranking

Large Cardamom Cultivars	D+	D-	CCi	Ranking
1. Seremna	0.01	0.13	0.94	1
2. Dzongu Golsey	0.09	0.06	0.40	2
3. Sawney	0.09	0.05	0.34	3
4. Ramsey	0.10	0.04	0.30	4
5. Varlangey	0.12	0.02	0.16	5
6. Ramla	0.13	0.02	0.11	6

The closeness coefficient (CCi) for each cultivar was calculated, with values ranging from 0 to 1, where a higher score means better alignment with the ideal solution. Seremna scored 0.94, confirming its strong position as the most climate resilient cultivar according to the farming community. Following Seremna, Dzongu Golsey (CCi = 0.40) and Sawney (CCi = 0.34) showed moderate resilience. Ramsey, Varlangey, and Ramla had lower resilience, with CCi values of 0.30, 0.16, and 0.11, respectively. The wide range of CCi values (0.11 to 0.94) highlights the significant differences in how these cultivars are viewed in terms of resilience. Notably, Seremna’s score was more than twice that of the second ranked cultivar, showing a clear preference and consistent performance across key attributes. Based on these results, the cultivars can be divided into three groups: high resilience (Seremna), moderate resilience (Dzongu Golsey and Sawney), and low resilience (Ramsey, Varlangey, and Ramla). In summary, using the TOPSIS method with community-informed data confirmed Seremna as the

best choice for climate resilient large cardamom farming. This ranking not only reflects quantitative performance but also incorporates the practical knowledge of farmers who manage these cultivars under real environmental conditions. The findings show how participatory evaluation, combined with strong decision-making tools like TOPSIS, can provide useful and scientifically sound insights for sustainable agricultural planning in climate-sensitive Himalayan areas.

4. Discussions

This study combined farmers' knowledge with the TOPSIS method to identify climate resilient cultivars of large cardamom. Using community input alongside a structured decision making tool provided clear and reliable results. The findings reveal that Seremna is the most preferred cultivar, as it performed best across key factors such as productivity, climate adaptability, and environmental tolerance. Its high closeness coefficient ($CC_i = 0.94$) and very small distance from the ideal value ($D^+ = 0.01$) indicate it is the most suitable variety for current climate challenges. These results are further supported by Sankar et al. (2024), who reported that Seremna has the highest yield and significantly contributes to increasing farmers' income.

The community's focus on climate adaptability and environmental tolerance shows their awareness of issues like unpredictable rainfall, temperature changes, and shifting seasons, all of which directly impact large cardamom farming. This awareness aligns with previous studies that recommend including farmers' perspectives in climate change planning, as it makes the outcomes more practical and useful (Wangchuk et al. 2023; Maharjan et al. 2019; Posibia et al. 2022; Swar et al. 2023; Vineeta et al. 2023). Other cultivars, such as Dzongu Golsey and Sawney, with CC_i scores of 0.40 and 0.34 respectively, also showed moderate resilience. These cultivars might be suitable for areas with less severe climate stress or when used alongside others to spread the risk.

In comparison, cultivars like Ramla and Varlangey ranked lower. Their greater distance from the ideal and closer values to the worst case profile suggests they are less suitable for farming under changing climate conditions. However, not all strengths of a cultivar are fully reflected in this type of evaluation. For example, Lepcha et al. (2023) found that Varlangey grows better at higher elevations (above 1515 meters) compared to mid-elevations (975–1515 meters). This means some cultivars may perform better in specific locations, even if their overall scores are low. Similar cases have been reported in other traditional farming systems, where certain varieties are maintained because they thrive under particular local conditions (Vineeta et al. 2023; Sharma et al. 2009).

This research highlights both the vulnerability of the crop and the social challenges faced by the Lepcha community, who were the first to cultivate large cardamom (Lepcha et al. 2023; Abdullah and Parvin 2024). The Lepcha community is becoming increasingly marginalized. Their population growth rate has been the lowest among Sikkim's tribal groups for over 120 years, showing signs of demographic fragility. Since they rely heavily on large cardamom cultivation for their livelihood and cultural identity, climate related crop failures threaten not only their economic security but also their traditional knowledge, food security, and cultural heritage. This combined vulnerability of the crop and the community highlights the urgent need to develop climate resilient crops and to include the perspectives of the Lepcha people in policy and practice.

The TOPSIS model used in this study effectively combined farmers' experience with measurable data. It helps compare different options by showing how close each one is to the best and worst outcomes (Behzadian et al. 2012). This provides a more comprehensive result than simple ranking methods. Using decision making tools like TOPSIS, along with a participatory approach, improves both the accuracy of the results and their acceptance. In Himalayan regions such as the Eastern Himalayas, where farmers face many challenges and limited support, these tools assist in selecting the right cultivars (Figueira et al. 2005; Malczewski 2006). The range of CC_i values from 0.11 to 0.94 indicates that the evaluation criteria effectively distinguished strong cultivars from weaker ones. However, future studies could include additional factors, such as a cultivar's vulnerability to pests under changing weather conditions, how well cardamom stores after harvest, or its marketability. These extra criteria would make the assessment more thorough.

This study highlights the importance of recognizing and promoting local cultivars like Seremna, which are not only productive but also better adapted to changing climate conditions. As weather patterns increasingly impact farming in the Sikkim Himalayas, blending farmers' knowledge with structured approaches like TOPSIS can support better farming decisions that are practical and reliable for local communities. Tackling the twin challenges of vulnerable crops and vulnerable communities will be essential for building climate-resilient agricultural systems in the Himalayas.

5. Conclusions

This study assessed the climate resilience of large cardamom (*Amomum subulatum* Roxb.) cultivars using a multi criteria approach based on the knowledge and perceptions of the Lepcha farming community. The results clearly show that selecting the right cultivar is crucial for sustainable agriculture, especially as climate related stresses become more frequent. Among the six cultivars evaluated, Seremna stood out as the most resilient, consistently performing well across key factors: productivity, lifespan, climate adaptability, disease and pest resistance, and environmental tolerance. Dzongu Golsey and Sawney showed moderate resilience, making them suitable for areas with medium risk. These cultivars could be good options for farmers in regions where full resilience is not essential but stability remains important.

In contrast, cultivars like Ramla, Varlangey, and Ramsey scored lower in both performance and farmer preference. These cultivars may be more vulnerable to climate challenges and disease outbreaks. Their continued use may require careful monitoring or may be better suited to specific conditions where certain traits still provide benefits. The findings highlight the valuable knowledge indigenous farmers have about crop performance and resilience. This local understanding should be more widely used when planning agricultural development and deciding which cultivars to promote. The results also support the broader goal of encouraging climate resilient crops in Himalayan regions, where protecting livelihoods and biodiversity is vital.

Looking ahead, it is important to focus on preserving and spreading high performing cultivars like Seremna. This can be achieved by strengthening community seed systems, encouraging local propagation, and supporting climate resilient value chains. Future research should include field trials in stress prone conditions to better understand how different cultivars perform and adapt. Combining community-based assessments with formal agronomic studies will help develop more reliable and location-specific strategies for adapting Himalayan agriculture to a changing climate.

This study highlights the urgent need to address two key vulnerabilities in the Sikkim Himalaya: the risk that traditional large cardamom cultivars face from changing climate conditions, and the demographic challenges of the Lepcha community, who first started cultivating this crop. As the original practitioners of large cardamom under agroforestry systems, the Lepchas are experiencing population stagnation. Protecting the climate resilience of large cardamom farming is closely tied to preserving the Lepcha people's cultural identity and economic well-being. Future strategies for adaptation must consider both environmental and social factors, incorporating indigenous knowledge into policies and protecting the bio-cultural heritage of these vulnerable Himalayan communities.

Declarations

6. Acknowledgements

The author gratefully acknowledges the support and encouragement of the Director, GBPNiHE, Almora for facilitating this research. This study was carried out as part of the DST STI-Hub project (no. *DST/SEED/TSP/STI/2022/818(G)/I*) supported by the **DST, Govt. of India**. Sincere thanks are extended to the entire MLAS, Dzongu and GBPNiHE project team for their support during the field support for assistance in data collection during survey. Finally, heartfelt gratitude is extended to the people of **Dzongu** for their time, cooperation, and for generously sharing their experiences and traditional knowledge, which formed the foundation of this research.

Author contribution:

JL: Conceptualization, Methodology, Data collection, Data analysis, original draft writing

KSG: Conceptualization, Methodology, Data analysis, original draft writing,

NSK: Methodology, Data collection, original draft writing

DB: Data collection, Data analysis, original draft writing

RJ: Methodology, investigation, Review

SR: Methodology, investigation, Review

Funding Declaration: This research was supported by the DST-STI Hub Project. No funds were received for open access/article publication.

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Figures

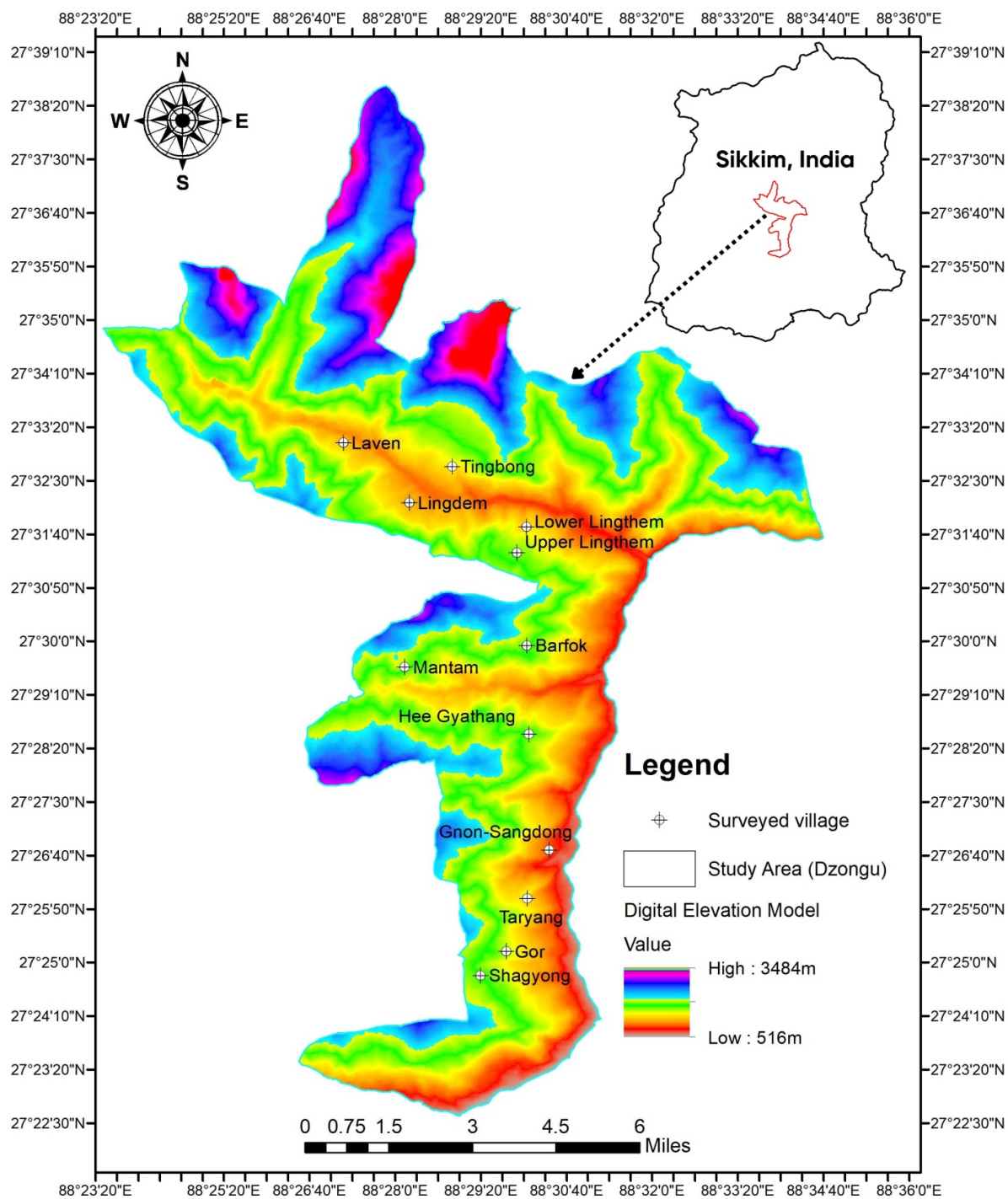


Figure 1

Map of Dzongu and surveyed villages (Developed using ArcMap software)