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GIS-based Land Suitability Assessment of Large Cardamom Cultivation in Bhutan

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Abstract

Large cardamoms, which were first introduced in the early 70s, have become major cash crops for farmers in the southern Dzongkhags of Bhutan. However, over the years, increased pests and diseases, including climate change impacts such as erratic weather patterns leading to changes in the ecology of cardamoms and making existing cultivable lands less productive, have been a challenge for growers. Moreover, the decline in production in recent years has raised concerns about the sustainability of spice crops in the region. Nevertheless, no major intervention measures have been undertaken to address these issues in the country. Therefore, this study aims to identify suitable areas for large cardamom cultivation in Bhutan via geographic information systems (GIS) and the analytical hierarchy process (AHP) in Bhutan. To address these issues, this study integrates ten agroclimatic factors: elevation, slope, aspect, rainfall, soil type, soil pH, annual mean temperature, land surface temperature, proximity to rivers, and land use factor, to evaluate the spatial suitability for cardamom cultivation. The four-stage AHP methodology, consisting of problem structuring, pairwise comparison, priority derivation and consistency checks and synthesis, was employed in the analysis. The results revealed that elevation was the most influential factor, with a weight of 0.27, whereas land use and distance from the river were the least influential factors, with a weight of 0.037. Furthermore, the findings also revealed that approximately 3,186.14 km^2 of land is highly suitable for cardamom cultivation in Bhutan, of which only 47.29 km^2 (approximately 2%) is currently cultivated, indicating the potential of increasing cardamom cultivation. The findings of this study closely align with the Department of Agriculture (DOA) data, indicating the consistency of the analysis. Thus, the findings present the spatial framework for policymakers, agriculture planners, local leaders, and farmers to capitalise on the opportunity to expand and enhance the production of cardamom, contributing to the agricultural economy in the country.

Keywords— Land suitability, mapping, large cardamom, geographic information systems, analytical hierarchy process.

1 Introduction

2 Introduction

Large cardamom (*Amomum subulatum*), commonly known as “Barlang” in Bhutan, “Bada elachi” in India, and “Alainchi” in Nepal, is a highly valued and widely traded spice worldwide [1, 5, 3]. The crop is believed to have originated in Sikkim, where wild varieties and diverse cultivated forms have existed since ancient times. Initially cultivated in the sub-Himalayan regions of India, its cultivation later expanded to Nepal and Bhutan [4].

India remains the largest producer of large cardamom, particularly in Sikkim, producing approximately 3500–4000 MT of dried cardamom annually. Nepal and Bhutan contribute approximately 1500 MT annually to global production [5]. India is also the largest consumer market, utilizing nearly 7000 MT/year, followed by Bangladesh [5]. In Bhutan, large cardamom cultivation is an important component of rural livelihoods, particularly in southern and subtropical regions. The cultivation area declined from approximately 6968 ha (69.68 km^2) in 1994 [3] to approximately 4700 ha (47 km^2) in 2021 [6].

Bhutan’s diverse topography, climatic zones, and rich biodiversity provide favourable conditions for cardamom cultivation. The crop is generally cultivated between elevations of 700–2000 m above sea level (asl), under humid climatic conditions with optimum temperatures ranging from 4°C to 20°C and annual rainfall between 2000 and 2500 mm [1, 5]. However, in recent years, all major cardamom-producing countries have experienced declining production. Major contributing factors include land degradation, climate change-induced ecological shifts, changing cultivation patterns, poor management practices, pests, and diseases [7, 9].

According to the Agriculture Survey Report published by the National Statistics Bureau of Bhutan [6], approximately 1609 MT of cardamom was harvested in 2021, representing a decline of 566 MT compared with 2020. Similarly, the harvested area decreased from 8658.25 ha (86.58 km^2) in 2018 to 4693.94 ha (46.94 km^2) in 2021. Although increasing market prices have recently renewed interest among Bhutanese farmers, recurring diseases and climate variability continue to threaten production sustainability [10].

Understanding the influence of local environmental conditions on cardamom cultivation is essential for evaluating current distribution patterns and identifying potential areas suitable for future expansion. Despite the economic importance of large cardamom as a cash crop in Bhutan, production has declined considerably over recent decades. However, limited scientific research has examined the effects of climate change and spatial environmental variability on cardamom cultivation in Bhutan. Furthermore, the suitability of alternative cultivation areas affected by declining productivity due to pests, diseases, and climatic changes has not been systematically assessed through land suitability mapping.

Previous studies on large cardamom in Bhutan have primarily focused on commodity chain analysis, stand composition, growth dynamics along elevation gradients, and the influence of rainfall on production [11, 12, 13, 2]. Therefore, a comprehensive spatial assessment integrating environmental and land-use factors is required to support sustainable cardamom cultivation.

This study aims to identify suitable areas for large cardamom cultivation in Bhutan by integrating multiple environmental and land-use parameters influencing crop growth. The findings will support farmers and policymakers by providing improved planning and management options for increasing cultivation efficiency and production. Furthermore, mapping potential shifts in climatic suitability will help identify alternative cultivation zones where favourable conditions exist, reducing dependency on traditionally cultivated areas.

Several studies worldwide have explored cardamom cultivation mapping using satellite remote sensing techniques. However, these investigations have generally been restricted to local and regional scales. The use of multi-temporal satellite imagery with coarse spatial resolution has also limited accurate identification of understorey crops. Recent studies have explored advanced approaches, including unmanned aerial vehicles (UAVs), LiDAR and hyperspectral data integration, Moderate Resolution Imaging Spectroradiometer (MODIS) data combined with maximum entropy (MaxEnt) modelling, and object-based image analysis (OBIA) using multispectral and hyperspectral imagery [16, 17, 18, 19, 20, 21].

However, these advanced approaches remain challenging to implement in developing countries such as Bhutan due to high operational costs and limited data accessibility. Alternatively, Geographic Information System (GIS)-based land suitability analysis integrated with the Analytic Hierarchy Process (AHP) provides a cost-effective approach for evaluating suitable cultivation areas [22, 26]. GIS-based approaches enable the identification and integration of multiple environmental variables influencing crop suitability [31, 34].

Therefore, land suitability assessment through GIS and AHP can support sustainable cardamom cultivation planning in Bhutan by identifying alternative production areas, improving yield potential, reducing crop failure risks, conserving resources, supporting sustainable agricultural practices, and maintaining long-term farmer livelihoods. Additionally, the results will provide baseline information for policymakers to develop effective crop management strategies and enhance agricultural productivity.

3 Materials and Methods

The study area, Bhutan, is a landlocked country in South Asia within the eastern Himalayas, located between latitudes 26.2°N–28.3°N and longitudes 88.7°E–92.1°E. According to the Population and Housing Census of Bhutan 2017 (PHCB 2017), approximately 62.2% of the population is engaged in agriculture, out of a total population of just over 700,000. Bhutan has a total area of 38,394 km^2, of which only 2.93% is under cultivation, while 70.46% is covered by forests [27]. The country exhibits diverse agroecological conditions, encompassing at least six agroecological zones: wet subtropical, humid subtropical, dry subtropical, warm temperate, cool temperate, and alpine, with elevations ranging from approximately 100 m to 7,500 m above sea level [27][28]. The majority of cardamom-cultivating Dzongkhags are located within the humid subtropical to lower temperate agroecological zones.

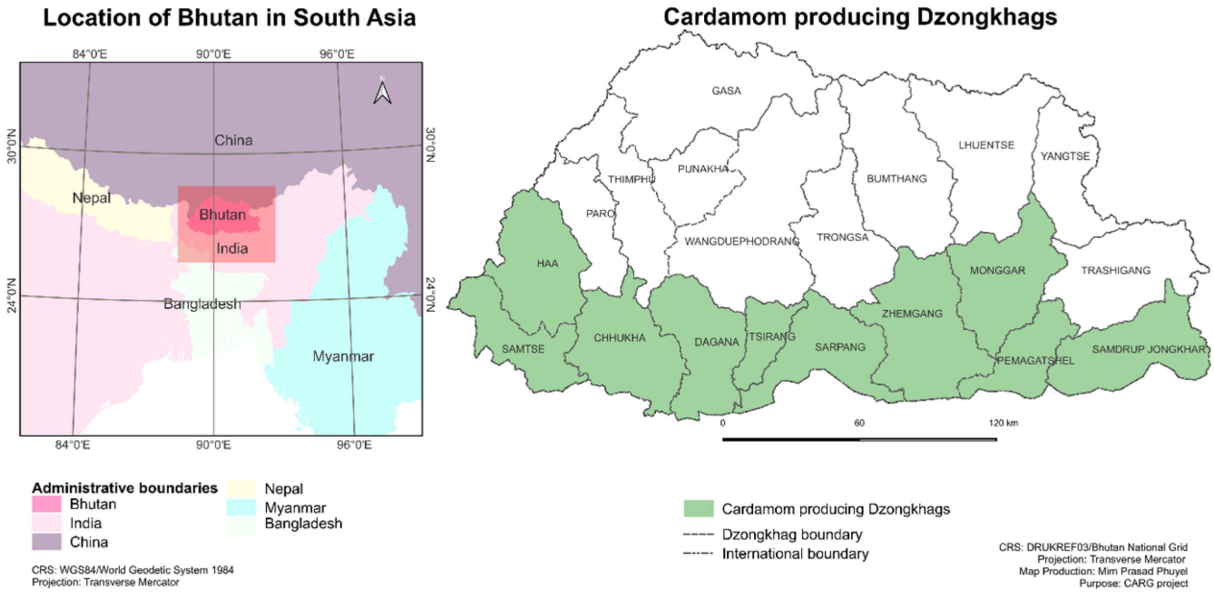

Figure 1: Study area highlighting the major cardamom-producing Dzongkhags.

3.1 Data collection

The study involves the use of different secondary data procured from diverse sources. The topographical data (elevation, slope, and aspect) were extracted via the Shuttle Radar Topography Mission (SRTM), a global high-resolution (30 m) digital elevation model (DEM), and proximity to rivers was computed by integrating the river data of Bhutan with the delineated streams from the SRTM DEM sourced from the USGS (https://www.usgs.gov/). Soil information (soil type and soil pH) was obtained from the National Soil Service Center (NSSC), Bhutan. The rainfall data were collected from the Food and Agriculture Organisation (FAO), and the land surface temperature (LST) data were obtained from MODIS version MOD11A2 V6.1, which was accessed through the Google Earth Engine (GEE). The mean annual temperature data from the National Center for Hydrology and Meteorology (NCHM) were also used to integrate the meteorological variables to determine their influence on sustaining the growth of cardamoms. The land use/land cover (LULC) map is sourced from the National Spatial Data Infrastructure (NSDI) portal (https://nsdi.systems.gov.bt/map), which is maintained by the National Land Commission Secretariat (NLCS), to further validate the suitability of cardamom.

Table 1: Data used and their sources

Data type	**Source**	**Remarks**
DEM (slope, elevation, aspect)	USGS Earth Explorer, Shuttle Radar Topography Mission (`https://www.usgs.gov/`)	30 m
Soil data (soil type, pH)	National Soil Service Center (NSSC)	Vector
Rainfall	Food and Agriculture Organisation (FAO)	30 m
LST	Moderate Resolution Imaging Spectroradiometer (MODIS)	30 m
LULC	[29]	Vector

3.2 Method

The GIS-based multicriteria evaluation approach is used to identify potential areas for cardamom cultivation in Bhutan. In this method, suitability criteria are selected on the basis of the agronomic needs of cardamom cultivation and expert feedback. The AHP was used to derive the weights for each criterion on the basis of pairwise comparisons. Furthermore, a consistency ratio (CR) is used as a threshold ($CR < 0.1$) to ensure acceptable consistency. Figure 2 highlights the systematic workflow of the entire study.

The AHP is a multicriteria decision-making (MCDM) technique that helps decision-makers solve complex problems by breaking them into a hierarchical structure of goals, criteria, sub-criteria, and alternatives proposed by Thomas L. Saaty in the 1970s [30]–[32]. Saaty proposed a four-stage methodology consisting of problem structuring, pairwise comparison, priority derivation and consistency checks and synthesis. First, the goal of the decision is defined, and a hierarchy with the goal at the top is created, followed by criteria, sub-criteria, and alternatives at the lower levels [31]. In the second stage, criteria and alternatives are compared two at a time via Saaty's 1–9 scale (see Table 2) measurements to express relative importance or preference, creating a pairwise comparison matrix.

Table 2: **9-point scale measurement used in AHP pairwise comparison [32].**

Intensity of importance	**Definition**	**Explanation**
1	Equal importance of i and j	Two activities contribute equally to the objective
3	Weak importance of i over j	Two activities contribute equally to the objective
5	Strong importance of i over j	Experience and judgment strongly favour one activity over another
7	Demonstrated importance of i over j	An activity is strongly favoured and its dominance is demonstrated in practice
9	Absolute importance of i over j	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of the above nonzero	If activity i has one of the above nonzero numbers assigned to it compared with activity j, then j has the reciprocal value compared with i	

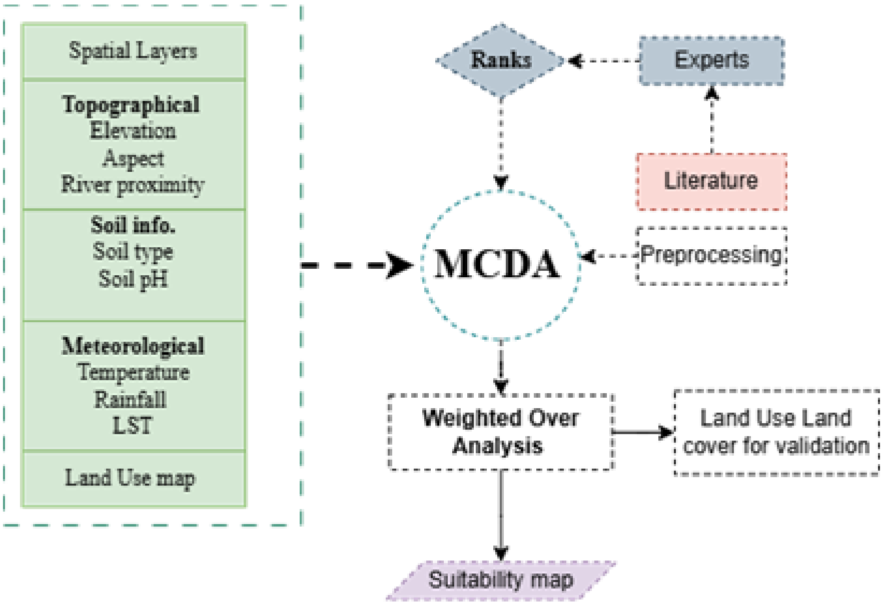

Figure 2: A schematic diagram showing the algorithms for land suitability mapping via a GIS approach

Table 3: Factor classes with their sub-criteria, suitability zones and ratings.

Factor	Class	Suitability	Rating
Elevation (m)	1,000–1,200	Very high	5
	800–1,000	High	4
	600–800	Moderate	3
	< 600	Low	2
	$> 1,200$	Very low	1
Slope (%)	< 10	Very high	5
	10–20	High	4
	20–30	Moderate	3
	30–40	Low	2
	> 40	Very low	1
Aspect	North (330°–30°)	Very high	5
	NE (30°–60°), NW (300°–330°)	High	4
	East (60°–120°), West (240°–300°)	Moderate	3
	SE (120°–150°), SW (210°–240°)	Low	2
	South (150°–210°)	Very low	1
Proximity to river (km)	< 1	Very high	5
	1–2	High	4
	2–5	Moderate	3
	5–10	Low	2
	> 10	Very low	1
Temperature (°C)	> 25	Very high	1
	22–25	High	2
	18–22	Moderate	3
	15–18	Low	4
	< 15	Very low	5
Precipitation (mm)	> 300	Very high	1
	200–300	High	2
	120–200	Moderate	3
	50–120	Low	4
	< 50	Very low	5
LST (°C)	18–22	Very high	1
	22–25	High	2
	15–18	Moderate	3
	25–28	Low	4
	< 15 or > 28	Very low	5
Soil pH	5.6–6.5 (Slightly acidic)	Very high	1
	6.6–7.5 (Neutral)	High	2
	4.6–5.5 (Very acidic)	Moderate	3
	7.6–7.8 (Alkaline)	Low	4
	3.8–4.5 (Extremely acidic)	Very low	5
Soil Type	Eutric Cambisols	Very high	1
	Dystric Cambisols	High	2
	Anthraquic Cambisols, Haplic Lixisols	Moderate	3
	Skeletic Cambisols, Haplic Acrisols	Low	4
	Haplic Alisols	Very low	5
LULC	Forests	Very high	1
	Agricultural Land	High	2
	Shrubs, Meadows	Moderate	3
	Alpine Scrubs, Moraines	Low	4
	Built-up, Non-built-up, Sandy Banks, Water Bodies, Snow/Glacier, Rocky Outcrops, Landslides	Very low	5

After the pairwise comparison, a mathematical method (eigenvalue approach) proposed by Saaty is used to calculate weights or priority vectors, w = (w1, w2, w3,... wn), that represent the relative importance of each criterion and alternative, followed by normalisation of weights given by the following equations:

$$Aw = \lambda_{\max} w, \qquad \lambda_{\max} \geq n \tag{1}$$

$$\lambda_{\max} = \frac{\sum_{j=1}^{n} a_{ij} w_j}{w_i} \tag{2}$$

$$A = \{a_{ij}\}, \qquad a_{ij} = \frac{1}{a_{ji}} \tag{3}$$

where:
A represents the pairwise comparison matrix,
w represents the normalized weight vector,
$\lambda_{\max}$ is the maximum eigenvalue of matrix
A, and a_{ij} represents the numerical comparison value between criteria i and j.

Next, the result of the AHP is validated via the CR, which is calculated via Equation (5), using the consistency index (CI) computed via Equation (4). Finally, weights across levels of the hierarchy are combined or aggregated to determine the best alternative.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

where CI is the consistency index, n is the number of elements being compared, and $\lambda_{\max}$ is the largest or principal eigenvalue of the eigenvalue matrix.

$$CR = \frac{CI}{RI} \tag{5}$$

where the RI (random index) is the average of the resulting consistency index depending on the eigenvalue matrix. To evaluate cardamom cultivation land suitability mapping, the ten most influential criteria or factors or elements were considered, including elevation, slope, aspect, proximity to rivers, soil type and soil pH, mean annual temperature, LST, annual mean rainfall, and land use factors. These elements were specifically selected based on a relevant literature review. To maintain consistency, all spatial layers were resampled to a 30-meter resolution and projected to the Drukref03/Bhutan National Grid coordinate reference system. The spatial layers were then classified into five suitability classes: very low, low, moderate, high and very high suitability levels (see Table 3).

4 Results and Discussion

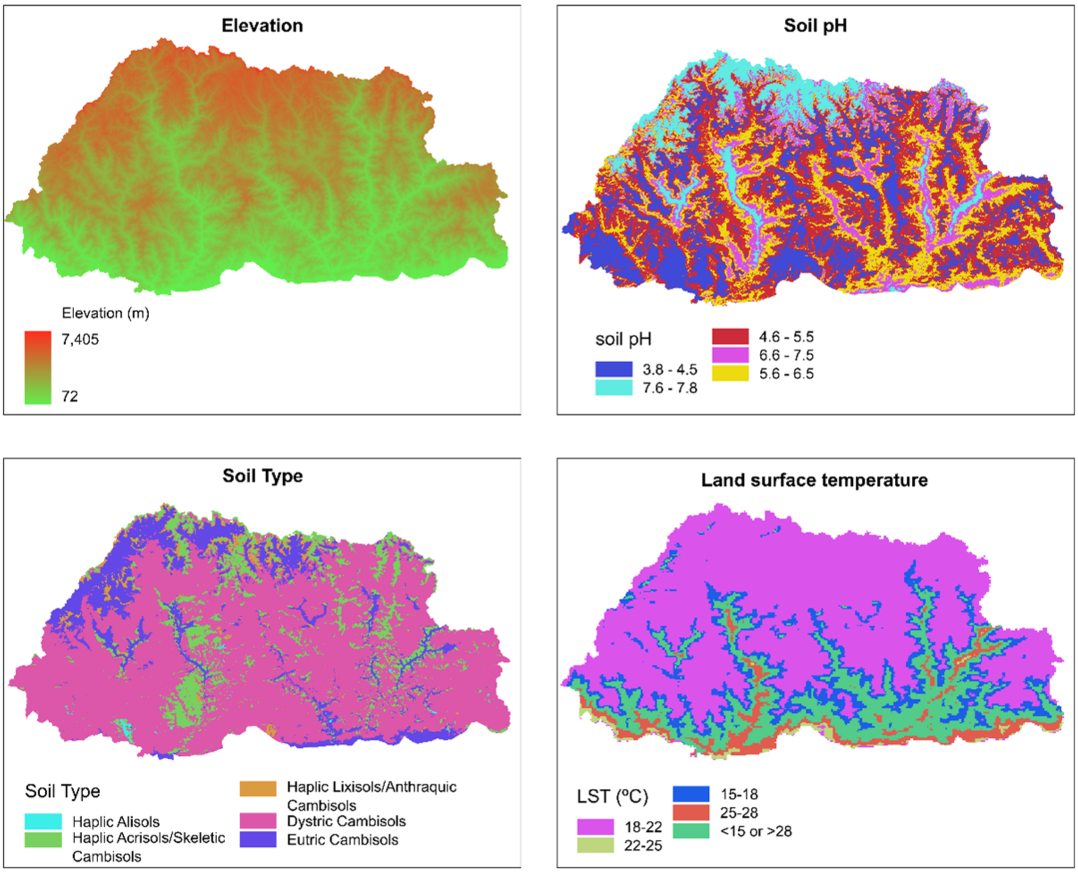

Figure 3: Figure showing the criteria distribution maps of elevation, soil type, soil pH, and LST.

The main aim of this study was to identify suitable land for cardamom cultivation in Bhutan to increase production via the multicriteria evaluation method. The AHP was employed to determine weights for different criteria on the basis of their relative importance provided by the experts and the literature. The relative importance of each factor or criterion for the suitability of cardamom cultivation is highlighted in Table 3. The spatial distribution maps of the agroclimatic factors used in this study are shown in Figures 3 and 4.

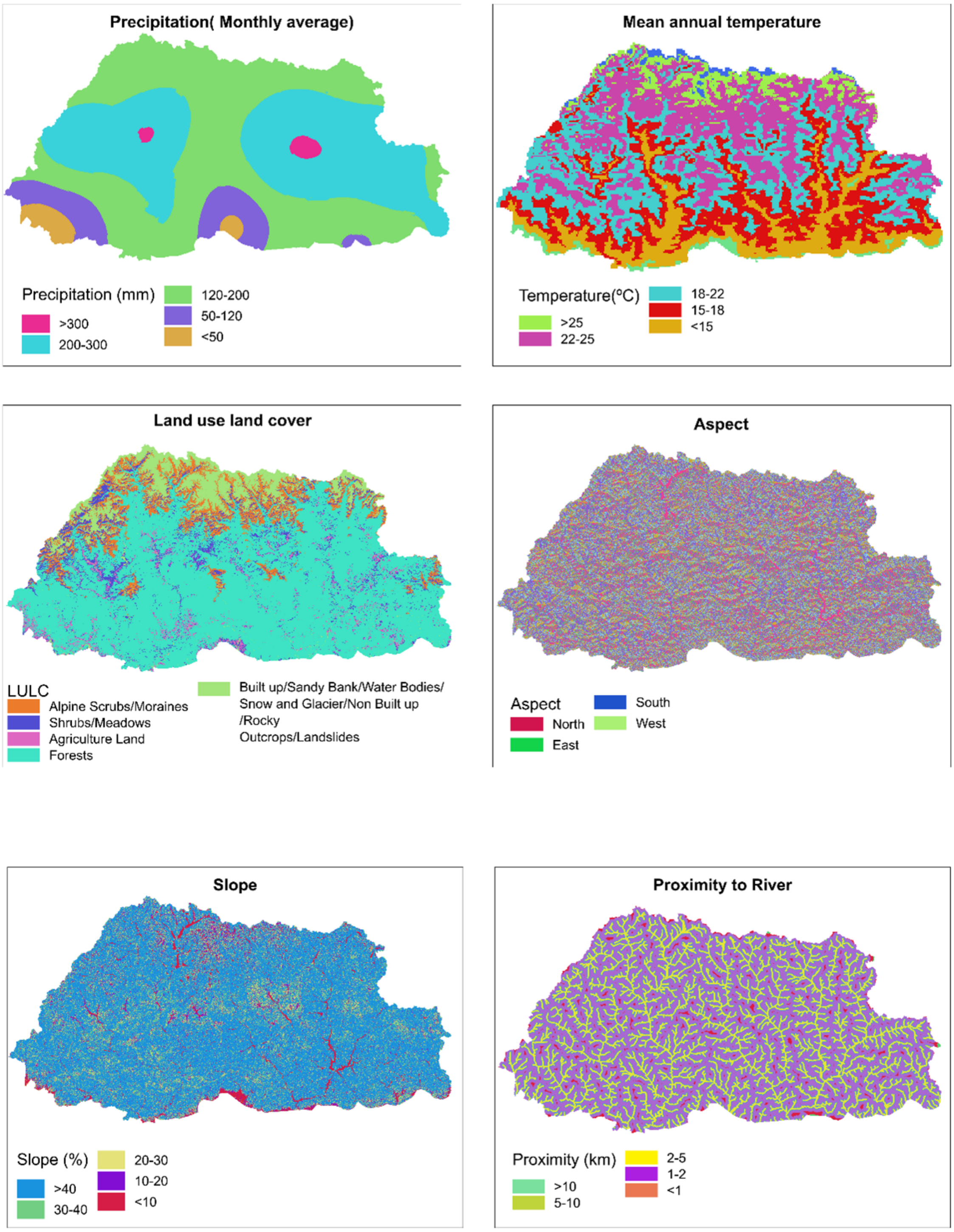

Figure 4: Figure showing the criteria distribution maps of precipitation, LULC, slope, mean annual temperature, aspect, and proximity to rivers

The ten most influential criteria used in this analysis comprised four topographic factors (elevation, slope, aspect, and proximity to river), two soil factors (soil type and soil pH), three climatic factors (mean annual temperature, land surface temperature (LST), and annual mean rainfall), and one land use/land cover (LULC) factor. The analysis identified elevation as the most influential criterion affecting cardamom land suitability because of its strong influence on temperature and rainfall conditions. Elevations between 1000 and 1200 m were classified as *very highly suitable*, 800–1000 m as *highly suitable*, and 600–800 m as *moderately suitable* (Table 3). Accordingly, elevation received the highest normalized weight (0.265) among all criteria (Tables 3 and 4). This result indicates that elevations between 800 and 1200 m above mean sea level provide the most favourable climatic conditions for cardamom cultivation, whereas lower elevations are generally too warm and higher elevations are susceptible to frost damage.

Slope was identified as another important factor, with gentle to moderate slopes (10–30%) providing adequate drainage required for healthy crop growth, whereas steeper slopes are more prone to soil erosion and flatter areas are susceptible to waterlogging [33]. Similarly, aspect influences the local microclimate, where north- and east-facing slopes retain more moisture and maintain relatively cooler conditions, making them more suitable for cardamom cultivation than south- and west-facing slopes, which are generally warmer and drier [34]. Slope and aspect each received a normalized weight of 0.104, reflecting their importance in controlling drainage, erosion, and moisture availability.

Soil characteristics also play a critical role in determining land suitability. Soil type and soil pH each received a normalized weight of 0.104 (Tables 3 and 4), indicating their importance in maintaining suitable soil fertility, nutrient availability, and acidity conditions that support healthy cardamom growth and development [34, 35]. In contrast, land use/land cover (LULC) and proximity to river received the lowest normalized weights (0.037 each), suggesting that although these factors influence cultivation, they are less decisive than topographic, soil, and climatic variables in determining overall land suitability [36].

Overall, the weighting pattern obtained in this study is consistent with findings reported in previous land suitability assessments for cardamom cultivation conducted in Nepal and India, where elevation, slope, soil characteristics, and climatic variables were likewise identified as the dominant determinants of suitable cultivation areas [37, 38].

Table 4: Normalised matrix of each factor and their relative importance.

Factor	**Elevation**	**Slope**	**Aspect**	**Distance**	**Temperature**	**Rainfall**	**LST**	**Soil Type**	**Soil pH**	**Land Use**	**Average Weight**
Elevation	0.278	0.30	0.30	0.192	0.30	0.19	0.30	0.30	0.30	0.19	**0.265**
Slope	0.093	0.10	0.10	0.115	0.10	0.12	0.10	0.10	0.10	0.12	**0.104**
Aspect	0.093	0.10	0.10	0.115	0.10	0.12	0.10	0.10	0.10	0.12	**0.104**
Distance from River	0.056	0.03	0.03	0.038	0.03	0.04	0.03	0.03	0.03	0.04	**0.037**
Temperature	0.093	0.10	0.10	0.115	0.10	0.12	0.10	0.10	0.10	0.12	**0.104**
Rainfall	0.056	0.03	0.03	0.038	0.03	0.04	0.03	0.03	0.03	0.04	**0.037**
LST	0.093	0.10	0.10	0.115	0.10	0.12	0.10	0.10	0.10	0.12	**0.104**
Soil Type	0.093	0.10	0.10	0.115	0.10	0.12	0.10	0.10	0.10	0.12	**0.104**
Soil pH	0.093	0.10	0.10	0.115	0.10	0.12	0.10	0.10	0.10	0.12	**0.104**
Land Use	0.056	0.03	0.03	0.038	0.03	0.04	0.03	0.03	0.03	0.04	**0.037**
Sum	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

According to the final land suitability map (Figure 5), approximately 3,143.20 km^2 of the study area was classified as *highly suitable*, while 17.79 km^2 was identified as *very highly suitable* for cardamom cultivation in Bhutan. The *Agriculture Survey Report* (2021) indicated that the actual area under cardamom cultivation is only 47.29 km^2, representing a small fraction of the land identified as suitable for cultivation [6, 38]. These findings reveal substantial untapped potential for expanding cardamom cultivation across the country. The large disparity between the existing cultivation area and the potentially suitable land highlights significant opportunities to increase production and strengthen Bhutan's cardamom sector.

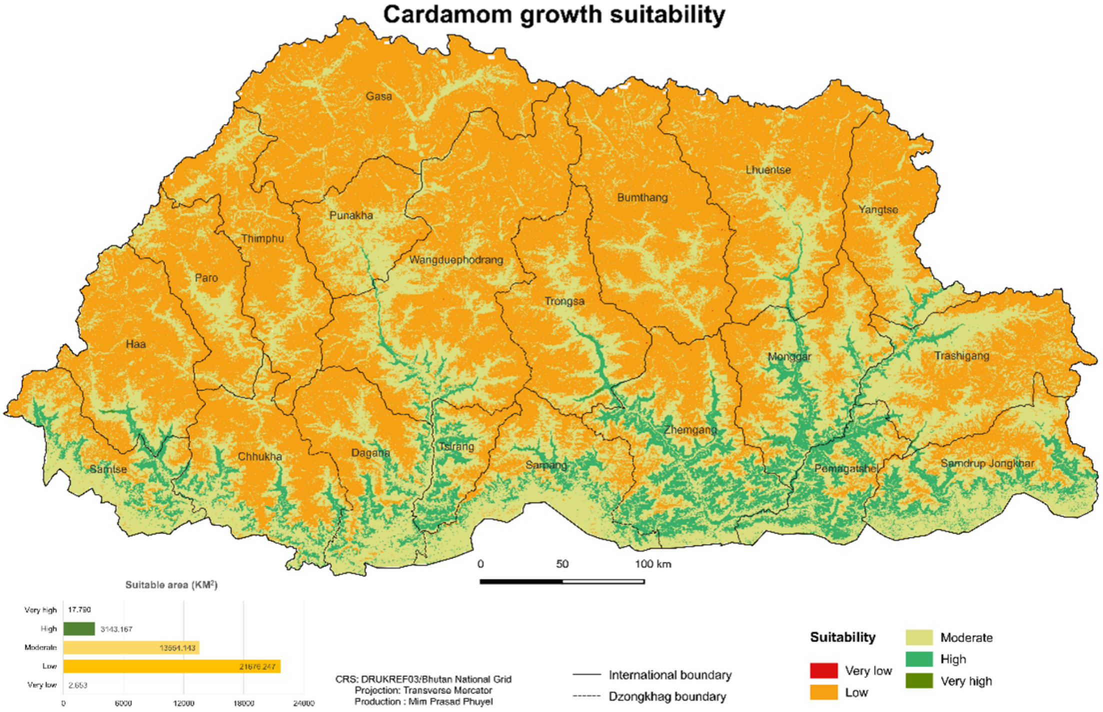

Figure 5: Land suitability map for cardamom cultivation in Bhutan

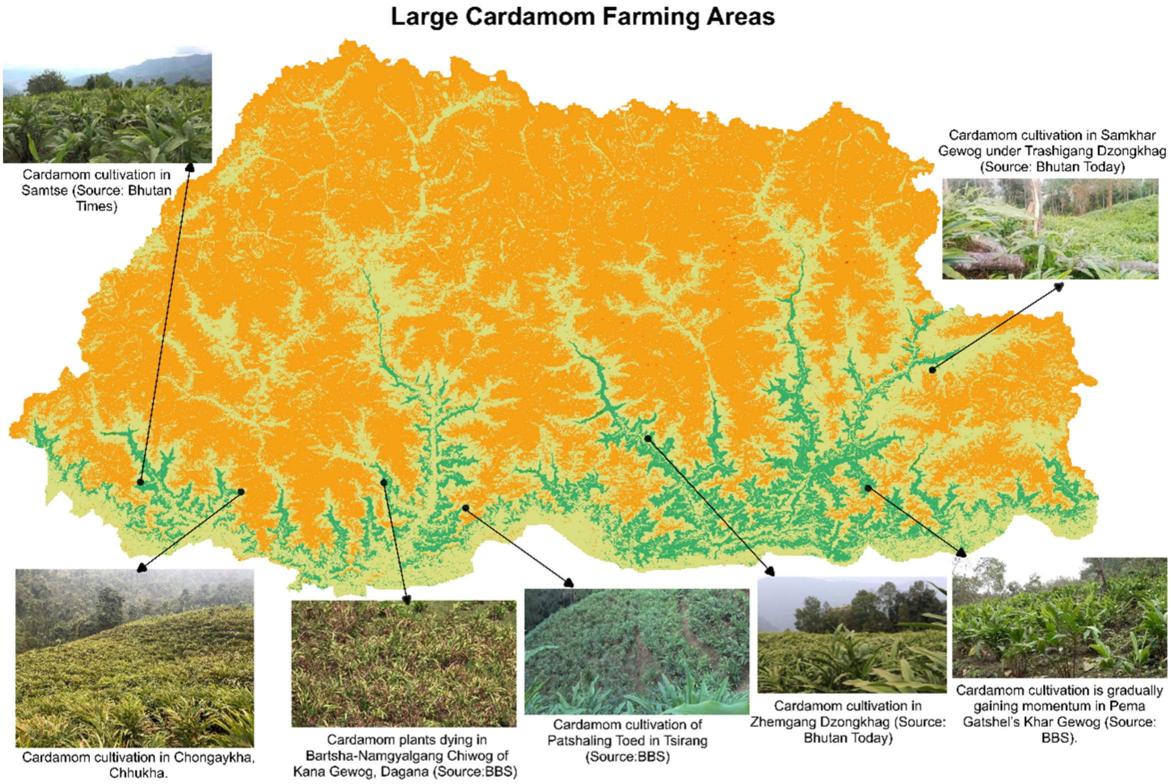

Figure 6: Some of the common cardamom growing areas superimposed on the land suitability map.

The results emphasize the need for greater attention from policymakers, local authorities, agricultural extension services, and farmers to align future agricultural development with the identified suitability zones. Expanding cardamom cultivation into highly suitable areas could improve rural livelihoods, promote sustainable land use, and contribute significantly to Bhutan's agricultural economy.

To validate the land suitability assessment (LSA), ground-based evidence was collected through Global Positioning System (GPS)-referenced photographs from selected large cardamom farming sites across Bhutan. These field observations were compared with the suitability map to assess the reliability of the model predictions (Figure 6).

5 Conclusion

This study uses GIS and AHP-based land suitability analysis for cardamom cultivation in Bhutan. In this context, four topographical factors, two soil suitability factors, three meteorological factors, and one land use factor were used in the analysis. This finding reveals that a significant percentage of suitable areas remain uncultivated. Approximately 3,143 km^2 is classified as potentially suitable; however, only 47.29 km^2 is currently cultivated, which is only about 2% of the total suitable area. The results were cross verified with data from the Department of Agriculture, which revealed a strong correlation that supported the reliability of the analysis. This study also identified the factors with the greatest contribution, such as elevation, slope, soil type and pH, to the viability of cardamom growth. While the study identified the suitable area purely based on environmental and climatic factors, it did not account for constraints such as biological corridors and protected areas. Future researchers may integrate these additional factors to more accurately determine the suitable area for sustainable cardamom cultivation. These findings underscore the potential for expanding cardamom cultivation and call for strategic measures to optimise land use and enhance cardamom productivity in Bhutan. Finally, the use of AHP and GIS is a useful method for examining how climate change affects agriculture using agroecological parameters. These data can offer insightful information for agricultural planners and farmers about how crops adjust to changing environmental factors and can help inform strategies for improving agricultural resilience in the face of climate change.

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