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Land suitability analysis for sustainable cultivation of apple (*Malus domestica*) using integrated geospatial and multi-criteria modelling in Southwestern Ethiopia

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Abstract
Apple cultivation represents a sustainable livelihood strategy that enhances farmers' income while contributing to environmental conservation. Apple production is highly constrained by winter chilling requirements, which are strongly influenced by altitude and local climate. This study assessed the spatial distribution of land suitability for apple cultivation in the study area using geospatial modeling techniques. Climatic, topographic, and environmental variables were integrated using GIS-based multi-criteria analysis to identify suitable zones for apple production. The results obtained from the evaluation of the suitability of the land for growing apple (Malus domestica) showed large variability in space. While 1.6% (112.5 km^2) and 35.2% (2423.8 km^2) were recorded as highly and moderately suitable areas respectively, 57.3% (3954.4 km^2) ranked as marginally suitable. The remaining 5.9% (404.9 km^2) is unsuitable because of factors consisting of high temperature, low chill intensity in winter, and soil characteristics. The highly suitable regions were largely dominated by Dabo Hana, Diga, and Bedele Zuriya in the mid and northwestern parts of the region, and the marginally suitable and unsuitable regions were largely dominated by Boricha and Gechi in the southern and Eastern districts, respectively. This indicates that apple production potential in the region is still limited and dependent on management interventions. Furthermore, the dominance of marginal suitability in the region shows that if apple production is extended without consideration of suitability, it may result in less productivity and climate risk. Thus, it is recommended to focus on apple production in highly suitable, moderately suitable, and marginal areas of the region, adopting climate-smart approaches like supplemental irrigation, fertilizer application, and the introduction of new apple varieties of low chill and heat française.

Keywords Apple cultivation, Chilling hours, District, GIS, Remote sensing, Suitability classes

1 Introduction

Globally, apple (Malus domestica) is one of the most widely cultivated and economically important fruit crops, having originated from Central Asia where it was first domesticated [45]. Its popularity can be attributed to its nutritional value, extended shelf life, and robust market demand [10, 26]. The production of apples plays a crucial role in enhancing livelihoods, particularly for small-scale farmers, through income generation and job creation [4, 35]. Additionally, apple orchards contribute positively to environmental sustainability, offering benefits such as soil enrichment, biodiversity conservation, and water management [3, 8, 37]. Recognizing the multifaceted advantages of apple production is essential as it aligns with sustainable agricultural practices that prioritize economic viability and environmental stewardship [6, 21, 46]. In addition to enhancing environmental sustainability, apple play a key role in improving socioeconomic well-being of smallholders farmers [3, 14].

In Ethiopia, apple cultivation was introduced in the 1950s by British Protestant missionaries in the southwestern highlands and later expanded by other agricultural initiatives [23, 47]. Despite this historical introduction, the apple subsector in Ethiopia remains underdeveloped, with limited production areas and low productivity levels [2, 7, 9, 48]. Small-scale farmers face numerous challenges, including inadequate access to superior apple varieties, vulnerability to pests and diseases, lack of water resources, and insufficient irrigation infrastructure. These challenges hinder the potential for apple farming to contribute effectively to local economies and food security.

A critical aspect of addressing these challenges lies in land suitability assessments, which help identify regions capable of efficiently producing crops while minimizing environmental degradation. Recent advancements in geospatial technologies and multi-criteria decision analysis (GIS-MCDA) have enabled systematic and spatially explicit assessments of crop suitability. Studies on maize and wheat production have successfully applied GIS-MCDA approaches to identify optimal cultivation areas, demonstrating the effectiveness of integrated analyses of topography, soil types, climate, and hydrological data [44, 51]. However, there is a limited study focused on apple cultivation in Ethiopia, despite the increasing economic significance and nutritional benefits of Apple.

The current study addresses this significant knowledge gap by employing an integrated geospatial and multi-criteria approach to evaluate land suitability for apple production in the southwestern Ethiopia. The study assesses various factors influencing apple growth, including topographic features, soil types, climatic conditions, water availability, and infrastructure development. By deriving a composite suitability index through the integration of these variables, the study aims to pinpoint areas with the highest potential for successful apple cultivation. The results of this study provide valuable insights for smallholder farmers, agricultural investors, and policymakers, enabling them to make informed decisions regarding site selection for apple production. By identifying optimal locations for cultivation, this study aims to maximize yields while minimizing production costs and associated environmental impacts. Additionally, this work contributes to the broader scientific community by establishing a replicable GIS-MCDA framework for apple land suitability assessments that can be applied to other crops in Ethiopia and beyond.

Furthermore, this study not only fills a knowledge gap concerning apple production in southwestern Ethiopia but also offers recommendations that aim to enhance economic benefits and improve land use sustainability. By supporting local livelihoods and promoting environmental conservation, the present study underscores the vital role of sustainable agricultural practices in fostering economic growth and food security in the region.

2 Methodology

2.1 Description of the study area

This study was conducted in southwestern Ethiopia (Fig. 1). The study area is situated to the west of Addis Ababa and to the south and east of Nekemte city, with an altitude ranging from 1121 to 2604 m a.s.l. In terms of geographical location, the study area extends from 8° 8′ 00″ N to 9° 12′ 00″ N and from 35° 44′ 00″ E and 37° 40′ 00″ E, with an approximate area of 6895.6 km^2. The major soil texture classes in the study area include sandy clay, clay loam, sandy clay loam, loam and loamy sand. The average annual temperature of the area ranges from 18 to 36 °C, and the annual rainfall ranges between 1850 and 2157 mm.

This region is known for its diverse landscape with different land use and land cover (LULC) classes, which encompass cultivated land, forests, grassland, bare land, built-up areas, water bodies, and wetlands. Mixed agriculture is the most dominant and commonly practiced economic activity of the local communities. Maize, sorghum, teff, coffee, nug, and various vegetables are some of the cultivated crop types. Livestock types such as cattle, goats, sheep, chicken, and pack animals are commonly tended by the smallholder farmers of the study districts. This analysis considered various factors such as topographic, edaphic, and climatic parameters influencing apple growth and productivity.

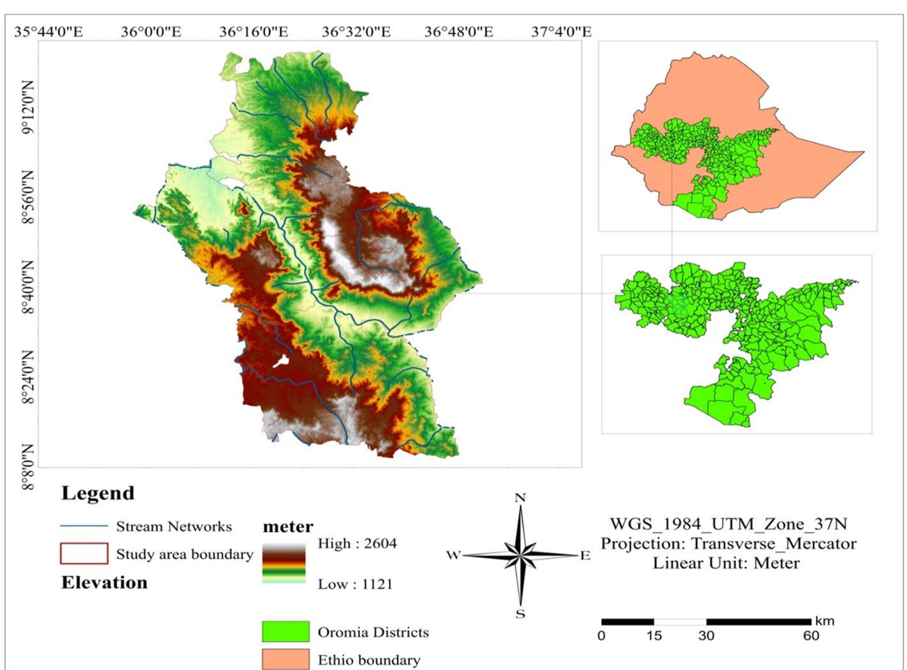

Fig. 1 Locational map of the study area

2.2 Data sources and processing

Topographic, soil, and climatic data were collected from various reliable sources for the suitability analysis of land for apple production (Table 1). Topographic data were obtained from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model with a resolution of 30 m, which was used to generate slope and aspect maps [43]. The slope maps were then reclassified according to FAO guidelines for the land suitability evaluation of permanent agricultural and horticultural crops (FAO, 1976). Soil depth and drainage factors were sourced from the Ethiopian Soil Information System and the ISRIC SoilGrids database, which provides soil property maps at spatial scales of 250–1000 m [18, 24]. Climatic data were collected from CHIRPS rainfall estimates at a resolution of 5 km [20] and from the ERA5-Land reanalysis datasets for mean annual temperature and minimum temperature, both at a spatial resolution of 9 km [33]. Minimum temperature estimates were used to assess the chilling hour requirement of 7.2 °C, indicating the critical area suitability for the winter chilling requirements of the apple crop (Eq. 1).

$$Chilling\ Hours/day = \begin{cases} 24 & if\ T_i \leq 7.2\,°C, \\ 0 & if\ T_i < 7.2\,°C, \end{cases} \quad (1)$$

Chilling hours were classified according to apple cultivar requirements, with high-chill cultivars requiring more than 800 h, medium-chill cultivars requiring 400 to 800 h, and low-chill cultivars requiring less than 400 h.

The presence of the apple crop was sampled using a stratified method based on land strata that are similar in characteristics. 226 points were systematically sampled from the superimposition of topographic, soil, and climate factors. The soil samples were collected from pedons, and climate factors were interpolated to raster maps. Estimation of land suitability for growing apples was carried out based on the standards set by FAO (1976).

2.3 Software packages used

To track environmental changes over the past decades, we performed LULC classification and accuracy assessment using the Earth Resources Data Analysis System (ERDAS) software. Pairwise comparison calculation and weight assignment were made for the

Table 1 Data types, descriptions, spatial resolution, and data sources used in the study

Data type	Description	Spatial resolution (m)	Source
Digital Elevation Model (DEM)	Elevation data used to derive slope and aspect	30	SRTM
Slope	Percentage slope derived from DEM; reclassified using FAO (1976) guidelines	30	Derived from SRTM DEM
Aspect	Cardinal aspect classes (N, NE, E, SE, S, SW, W, NW) derived from DEM	30	Derived from SRTM DEM
Soil depth	Effective rooting depth for apple orchard establishment	250–1000	EthioSIS; ISRIC SoilGrids
Soil drainage	Soil drainage classes indicating aeration and waterlogging risk	250–1000	EthioSIS; ISRIC SoilGrids
Annual Rainfall	Precipitation required for apple water requirements	5000 (~ 0.05°)	CHIRPS
Landsat images	Land use land cover types	30 m	USGS
Minimum temperature	Tmin was used to compute chilling hours (≤ 7.2 °C)	9000 (~ 0.1°)	ERA5-Land

Table 2 Tools and software used

No	Software	Purpose
1	ArcGIS 10.3	Analysis and visualization of spatial Data
2	ERDAS 2015	LULC classification and accuracy assessment
3	Google Earth Pro	Obtaining ground truth data for LULC accuracy assessment
4	IDRISI Selva 17	For pairwise comparison and assigning weights

Table 3 Rating parameters for apple tree cultivation land suitability analysis

S/no	Parameters	Land suitability criteria rating for apple cultivation			
		Highly suitable(S1)	Moderately suitable(S2)	Marginally suitable(S3)	Not suitable (SN)
1	LULC (name)	Grassland	Agricultural land	Forest	Bare land, built up, water body
2	Slope (degree)	0–7	7–15	15–30	> 30
3	Aspects(degree)	359–256	256–168	168–89	< 89
4	Soil drainage	Well	Moderate	Imperfect, somewhat excessive	Excessive
5	Rainfall (mm)	1300–1500	1500–1700	1700–1900	> 1900
6	Chilling hours	1000–1200	800–1000	600–800	400–600
7	Soil depth(cm)	> 100	75–100	50–75	< 50
8	Soil texture (classes)	Clay loam, loam	Loam sandy	Sandy Clay, Sandy Clay Loam,	Sandy loam

variables selected and considered in the study using the IDRISI Selva 17 software. The accuracy of LULC from the satellite imagery was validated using ground truth data, which were obtained through ground verification (Table 2).

2.4 Data analysis

The land suitability classes for apple cultivation were evaluated from an aggregation of some targeted parameters, including slope, LULC, aspects, rainfall, temperature, soil depth, soil drainage and soil texture. The rating values and suitability classes of all selected parameters are elaborated in Table 3.

2.4.1 Land use land cover

Landsat image preprocessing steps applied in this study included image enhancement, layer stacking, false colour combination, and subsetting of the image to the study area. After preprocessing, the Landsat images were subjected to further analysis. Satellite image preprocessing was made for enhancing purposes, which in turn was aimed at increasing the accuracy of the image classification process. Image enhancement was undertaken with the intention to prepare data for subsequent visual interpretation, which support image analysts during the image processing [42].

Image classification is the system of categorizing all readable pixels into specific LULC classes by using image classification techniques on the training areas [16]. Further analysis is guided by the conversion of image data into useful thematic data. The number of training samples taken from all pixels of objects observed in the images normally influences the reliability of the classified image. More accurate image classification was carried out by optimizing results from the training samples in the study area.

To understand the extent of a well-classified land cover map in reality on the ground, we performed LULC map accuracy assessment, which helps the users understand the degree of error across different land cover classes [36]. For this purpose, we utilized both overall accuracy and the Kappa coefficient (K_{hat}). An acceptable LULC classification must have an overall accuracy value of greater than 80% and a Kappa coefficient greater than 0.7. Both overall accuracy and Kappa coefficient (K_{hat}) were calculated using Eqs. 2 and 3, respectively.

$$\text{Overall accuracy} = \frac{\text{Sum of the diagonal elements}}{\text{Total number of accurate sites (pixels)}} * 100 \tag{2}$$

Kappa coefficient (K_{hat}) is used for evaluating the agreement between classified images and reality on the ground (Eq. 3) from the confusion matrix following Roba et al. [38].

$$K_{hat} = \frac{\text{Obs} - \text{exp}}{1 - \text{Exp}} \tag{3}$$

where Obs is the observed correct class. It represents the accuracy reported in the error matrix, and Exp is the expected correct class. It represents correct classification.

2.4.2 Slope

Slope refers to the steepness or flatness of an area, and it obviously results in various degrees of land suitability for apple cultivation. For instance, an area with a steep slope is often exposed to severe soil erosion, reduced soil depth and fertility, which implies a negative influence on apple cultivation. As reported by Admasu et al. [2], an area with a slope angle less than 7° is highly suitable; 7° to 15° (moderately suitable); 15° to 30° (marginally suitable), while greater than 30° is unsuitable for apple cultivation.

2.4.3 Aspect

Aspect describes the direction of slope inclination, and it determines the amount of solar radiation received, temperature, and moisture availability [49]. In other words, aspect is defined as the measure of specific direction towards which the slopes are facing (South, North, East, or West). Thus, aspect influences the amount of sunlight and temperature status, which result in various levels of potential land suitability for apple farming. The result from the study by Fayaz et al. [19] revealed south-facing slopes receive more sunlight and higher temperatures, implying a higher degree of suitability, while lower temperatures for the north-facing slopes tend to result in the receipt of less direct sunshine, implying a lower degree of suitability for apple cultivation.

2.4.4 Soil drainage

Soil drainage refers to the degree to which water vertically moves in the soil profile, i.e., soil movement in a downward or upward direction. Soil drainage is influenced by the degree of exposure to runoff and soil erosion. Well-drained soils are highly suitable, whereas an area with excessive soil drainage is unsuitable for apple cultivation [9].

2.4.5 Soil depth

Soil depth normally refers to the thickness of soil within the soil continuum [52]. Sufficient soil depth allows an adequate root penetration and development, water and nutrient uptake for normal plant growth and yield maximization. This indicates that deeper soils characterized by more water and nutrient-holding capacity are essential for apple growth and fruit production. The study made by Manandhar et al. [30] revealed that an area with soil depth greater than 100 cm is highly suitable, whereas 75 to 100 cm is moderately suitable for apple cultivation. Furthermore, soil depth ranging between 50 and 75 cm is marginally suitable, and areas with soil depth less than 50 cm are unsuitable for apple cultivation.

2.4.6 Soil texture

Apple cultivation may thrive under various soil texture classes namely, clay loam, loam, loam sandy, sandy clay, sandy clay loam, and sandy loam. Variations in soil texture classes may result in various potentials for apple farming. This suggests that apple cultivation requires an appropriate soil texture. In particular, soils of clay loam textures are highly suitable for productive apple cultivation [13].

2.4.7 Chilling hours

The chilling hours for the dormancy period from November to February were calculated by applying a simplified model of chilling hours when temperatures are below 7.2 °C. To apply this model for a region when more specific temperature data are not available, daily minimum values of temperature (Tmin) can be employed as a proxy [25, 29]. This land surface model explicitly sets chilling hours per day depending upon predefined values of Tmin, and total chilling accumulation over a winter season of 120 days can then be calculated for each pixel by summing over four months of daily chilling accumulation values. For all raster calculations, floating-point calculations are employed to account for NoData values appropriately.

The non-indexed areas with chilling temperatures greater than 7.2 °C, is unsuitable for dorm-release conditions for apples, and were excluded. The marginally suitable index included 400–600 h, potentially leading to irregular growth. A moderate index consisted of 601–800 h, moderately suitable for most varieties, while areas recording between 800 and 1000 h were labelled ideal for synchronized flowering and fruiting, 1000 and 1200 h were labelled as having very high suitability. Thus, chilling hours are an integral parameter in determining whether an area is amenable to the growth of an apple plant (Thakur et al., 2024).

2.4.8 Rainfall

Amount and seasonality of rainfall are among the most influential factors to determine suitable areas for apple production. Both above and below the optimum rainfall amounts have adverse impacts on land suitability for apple cultivation. A moderate amount of rainfall is highly recommended for apple plant growth. Total annual rainfall between 1300 and 1500 mm is highly suitable, while greater than 1900 mm is less suitable for apple cultivation [5]. It also categorized a total rainfall between 1500 and 1700 mm as moderately suitable and between 1700 and 1900 mm as marginally suitable for apple cultivation.

2.5 Multi-criteria evaluation (MCE) of land suitability for apple cultivation

A GIS-based MCE model in combination with the Analytical Hierarchy Process (AHP) was used for identifying land suitability classes for apple cultivation. This was performed through integration of the targeted parameters using overlay analysis. This model was selected because of its appropriateness for identifying and weighting the different

Table 4 Relative importance of parameters and their description

Intensity of the importance	Definition	Description
1	Equal importance	Both parameters contribute equally to the impacts on the objects
3	Somewhat more important	The impacts of one parameter slightly favour the other
5	Much more important	The impacts of one parameter strongly favour the other
7	very much important	The impacts of one parameter strongly favour the other, and its impacts are demonstrated in practice
9	Absolutely more important	The evidence favouring one parameter over another is the highest possible validity
2,4,6,8	Intermediate importance	When comparison is required

Table 5 Random index value table

Intensity importance	1	2	3	4	5	6	7	8	9	10
Constant number	0.00	0.00	0.58	0.90	1.12	1	1.32	1.41	1.45	1.49

criteria used for conducting spatial analysis and land suitability mapping. Saaty [39] proposed 1 to 9 scientific ratios of calculated criteria for suitability analysis (Table 4).

Calculated values of the parameters were used for reclassifying and weighing all factors based on the degree of influence and significance levels. The relative relevance of the parameters was determined from the normalized eigenvector factors (Table 5).

The accuracy of pairwise comparison depends on the calculated values of the consistency ratio [17, 32]. The calculated value of CR was less than 10%. Consistency Ratio (CR) was the consistency ratio index (CI) to the random index (Eq. 4).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{4}$$

where CI refers to the consistency index, and RI is the random index as shown in Eq. 5.

$$\mathrm{CI} = \frac{\lambda\,\mathrm{max} - \mathrm{n}}{\mathrm{n} - 1} \tag{5}$$

where λmax refers to the principal eigenvalue of parameters, which is calculated from the multiplication of the reciprocal summation of the parameters' weighted values per column with its estimated priority vectors or Eigen vectors; n refers to the number of targeted parameters for suitability analysis during the study period. Random Index is the constant number given from a random index value table based on the number of the targeted parameters used for suitability analysis (Table 6).

2.6 Weighted overlay analysis

A suitability index was applied to aggregate all the criteria maps after their significance-based prioritization for the evaluation of the potential area for apple tree cultivation. The final suitability indices were then calculated using Eq. 6.

$$\mathrm{SI} = \sum \mathrm{Wi}^{*}\mathrm{Xi} \tag{6}$$

where SI is the suitability index, Wi is the weight of parameter I and Xi is the normalized criterion score of parameter, and the weight was assigned based on their degree of influence [12, 15, 31].

Table 6 Parameters' pairwise comparison matrix

Factors	Slope	LULC	Aspect	Soil drainage	Rain fall	Temperature	Soil depth	Soil texture	Weights
Slope	1	2	2	3	4	4	5	6	0.029
LULC	1/2	1	2	2	3	4	5	6	0.046
Aspect	1/2	1/2	1	2	3	3	4	5	0.060
Soil drainage	1/2	1/2	1/2	1	2	3	4	5	0.087
Rainfall	1/4	1/3	1/3	1/2	1	2	2	3	0.125
Chilling hours	1/4	1/4	1/3	1/3	1/2	1	2	3	0.161
Soil depth									
	1/5	1/5	1/4	1/4	1/2	1/2	1	2	0.212
Soil texture	1/6	1/6	1/5	1/5	1/3	1/3	1/2	1	0.280
Σ =	3.2	4.95	6.61	9.66	14.33	17.83	23.5	31	1

Table 7 LULC Types and corresponding area coverage

LULC types	Area (km^2)	Area (%)
Agricultural land	4668.3	67.70
Bare land	206.8	3.00
Built-up area	34.2	0.50
Forest land	1245.3	18.06
Grassland	738.7	10.71
Water body	2.4	0.03
Total	6895.6	100.00

3 Results and discussions

3.1 Land use and land cover

The LULC classifications in this study showed high reliability across all years, with overall accuracy rates of 92.4% in 2025, indicating strong classification performance. The Kappa coefficients were 0.88, reflecting strong agreement between reference data and classified data. These results demonstrate consistent accuracy in the LULC classification process, providing confidence in the validity of the study's findings on land cover changes over time.

The major LULC types identified include forest land, grassland, bare land, agricultural land, built-up area, and water bodies. The various LULC types have different levels of suitability potential for apple cultivation. The results indicate that 67.7% of the study area was moderately suitable, whereas 18.06% was marginally suitable for apple cultivation. However, about 10.71% of the study area was highly suitable, while the remaining 3.53% was found to be not suitable for apple production (Table 7).

Geographically, the southwestern, central, and a few northeastern parts were highly suitable. In contrast, larger parts were characterized as moderately suitable for apple cultivation. However, the remaining areas, mostly those found in the southwest and southeast parts of the study area, were found to be not suitable for apple farming (Fig. 2a). In line with the findings of this study, Yalew et al. [50] indicated the impact of various LULC types on land suitability for different agricultural practices.

3.2 Slope

The result of the slope suitability assessment reveals that about 66.3% of the study area is highly suitable, whereas 24.3% is moderately suitable for apple cultivation. The remaining

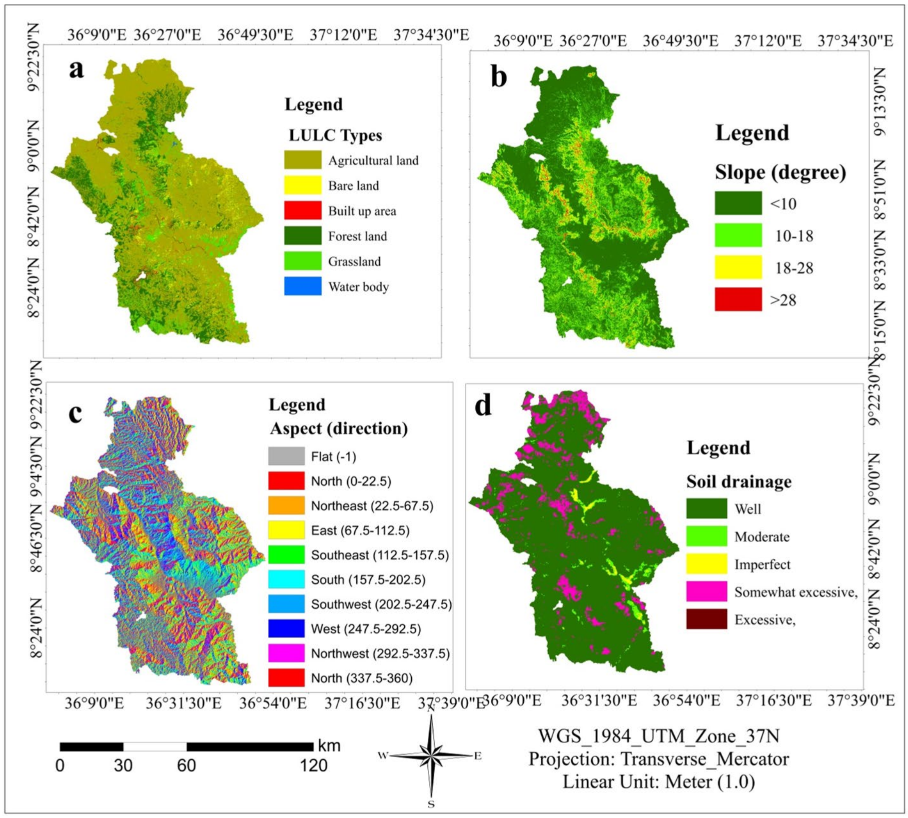

Fig. 2 LULC (**a**), slope (**b**), aspect (**c**) and soil drainage (**d**)

Table 8 Slope classes and area coverage

Slope (degree)	Area (km^2)	Area (%)
< 10	4571.0	66.3
10–18	1675.7	24.3
18–28	547.3	7.9
> 28	101.6	1.5
Total	6895.6	100.0

7.9% and 1.5% of the study area respectively, are marginally suitable and unsuitable for apple farming (Table 8).

Spatially, the southeastern, central and northern parts were found to be highly suitable for apple production. In contrast, some of the southwest and northeast parts were moderately suitable for apple farming. Conversely, a smaller proportion of the area in the central and northern parts was found to be marginally suitable and unsuitable for apple farming (Fig. 2b). A slope-based land suitability study was also conducted in the Sentele Watershed of Hadiya zone, which categorized the study area as 1/4th highly suitable, 1/3rd moderately suitable, 1/4th marginally suitable, and about 1/10th not suitable for apple production [9].

3.3 Aspect

Aspect of the study area was classified as 256–359°, 168–255°, 89–167°, and < 89°, which were highly suitable, moderately suitable, marginally suitable and not suitable, respectively (Fig. 2c). Approximately 27.8% and 24.3% were highly and moderately suitable for

Table 9 Aspect suitability classes and area coverage

Aspect direction (degrees)	Area (km^2)	Area (%)
256–359	1915.9	27.8
168–255	1677.4	24.3
89–167	1454.4	21.1
< 89	1848.0	26.8
Total	6895.6	100

Table 10 Soil drainage classes and area coverage

Soil drainage classes	Area (km^2)	Area (%)
Imperfect	53.7	0.78
Moderate	138.7	2.01
Well	6006.9	87.11
Somewhat excessive	695.1	10.08
Excessive	1.2	0.02
Total	6895.6	100.00

apple farming (Table 9). Aspect, or the direction a slope faces, is important for growing apples because it affects how much heat, moisture, and sunlight trees receive. Growers can affect fruit development, maturity, and production by controlling this factor. A mild slope that faces east or south is beneficial since it reduces the risk of disease and frost damage [40].

3.4 Soil drainage

Land suitability for apple cultivation may be influenced by the volume and speed of water movement across the soil particles. The magnitude of the soil porosity determines the speed at which water moves through the soil profile. Hence, soil with higher porosity is characterized by higher soil drainage capability. The current results indicate that about 87.11% was characterized by good soil drainage capability, which implies a higher degree of suitability for apple cultivation. Additionally, about 10.86% was dominated by imperfect and somewhat excessive soil drainage capability that was marginally suitable for apple cultivation. However, the remaining 2.01% and 0.02% were moderately suitable and unsuitable for apple cultivation, respectively, due to their moderate and excessive soil drainage conditions (Table 10). There are different factors that influence land suitability for apple production. For instance, Admasu et al. [2] found that soil types, drainage, and pH are some the factors that influence land suitability for apple production.

The drainage suitability map indicates that most parts, except for a few portions in the northwest and southwest, are highly suitable. Moderately suitable areas are distributed across the southeast and some areas of the northeastern parts of the study area. However, some of the northwestern and southwestern were marginally suitable and unsuitable for apple production (Fig. 2d). The finding of this study is similar to that of AbdelRahman et al. [1] which reported that nearly 25.82% of the studied area was highly suitable and nearly 34.73% was moderately suitable for mango cultivation based on the soil character assessment in Chamarajanagar district of Karnataka, India.

3.5 Soil depth

Cultivation and productivity of the apple are also influenced by soil depth. Greater soil depth is required for apple cultivation since apples are a tree crop with longer roots. The results of the soil depth analysis reveal that the southeast and western parts are dominated by deeper soils (depths greater than 100 cm), which are highly suitable for apple. Some of the northeast and southwest parts were moderately suitable (Soil depth between 75 and 100 cm). Some of the northern, southwestern and a few of the eastern parts were marginally suitable and unsuitable due to the shallower soil depth (Fig. 3a). The results of this study are consistent with the study conducted in Hadiya Zone of Southern Ethiopia, which also highlighted the significance of soil depth in assessing whether the area of land is suitable for growing apples [9].

3.6 Soil texture

Soil texture can influence land suitability potential. Variation in the soil texture causes corresponding variations in land suitability classes for apple cultivation. Approximately 52.63% was not suitable for apple cultivation, whereas 43.85% was a marginally suitable area. Results show that 3.32% were moderately suitable while 0.16% were highly suitable for apple (Table 11). This finding is in line with the findings by Admasu et al. [2], which assess the impact of soil texture on apple production. In terms of soil texture, some central, northwest, southeast and southwestern parts were unsuitable due to the dominance of the sandy loam soil texture. Marginally suitable areas are distributed in the northern and southern parts, while moderately suitable and highly suitable areas are distributed in the central and eastern parts (Fig. 3b).

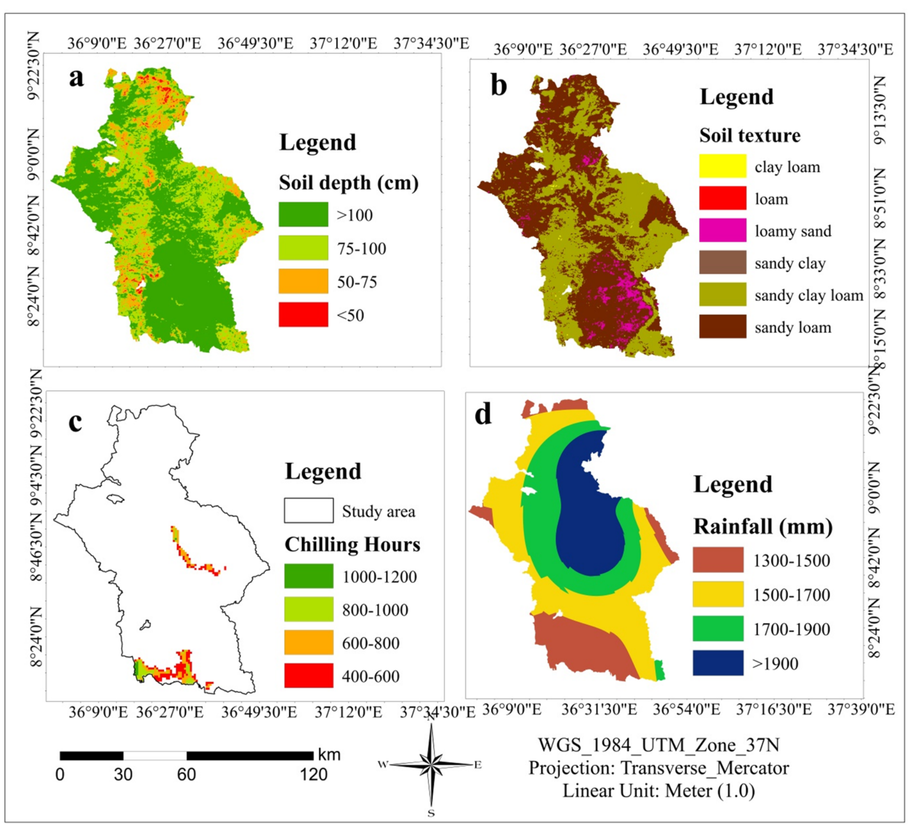

Fig. 3 Soil depth (**a**), Soil texture (**b**), Chilling hours (**c**) and Rainfall (**d**)

Table 11 Soil texture and area coverage

Soil texture	Area (km^2)	Area (%)
Sandy clay	3.2	0.05
Clay loam	5.8	0.08
Sandy clay loam	3020.0	43.80
Loam	5.2	0.08
Sandy loam	3632.5	52.68
Loamy sand	228.9	3.32
Total	6895.6	100

3.7 Chilling hours

Figure 3c illustrates the spatial distribution of areas where minimum temperatures are less than or equal to 7.2 °C, representing the required critical threshold to achieve the chilling necessary for the release of bud dormancy in apple (Malus domestica). It is classified into low (< 480 h, red), moderate (480–720 h, yellow), high (720–960 h, cyan), and very high (960–1200 h, blue) categories.

The high and very high chilling regions are found in the southern and northeastern mountainous regions, suitable for temperate fruit such as apples, although inadequate chilling is found in the central and lowland regions. This data emphasizes the significance of evaluating crop suitability based on regional chilling hours, revealing regions suitable for cultivation that can be used to design orchards and maximize productivity, and propose methods such as dormancy breakers in low-chilling regions [11, 29]. The large number of unsuitable lowland areas identified by this study confirms general fears that future rising temperatures will further degrade chill hour requirements under tropical conditions, as expected for tropical highlands under future projected conditions [29]. The general suitability pattern described above clearly confirms the relevance of microclimates for apple suitability.

3.8 Rainfall

Amount, seasonality and severity of the rainfall are deemed to be among the determining factors of apple cultivation. Sufficient rainfall at the right time is required to produce a sufficient amount of apples at a reasonable cost. The result from rainfall analysis reveals that most of the southern and some northern parts are characterized by sufficient amounts of annual rainfall (1300–1500) and hence are highly suitable for apple cultivation. However, marginally suitable (1700–1900 mm) areas are mainly found in the central parts. The upper regions of eastern parts were not suitable for apple cultivation (Fig. 3d). The result from this study aligns with the study conducted by Beyene et al. [9], who reported the significance of rainfall as one of the determining factors of apple tree production in the Sentele watershed of Hadiya Zone, Southern Ethiopia. The most appropriate areas for apple production based on rainfall amount are situated in the central and northern parts.

4 Land suitability for apple cultivation

Table 12 indicates that only 1.6% or 112.5 km^2 of the area is highly suitable for growing apples, 35.2% or 2,423.8 km^2 is moderately suitable, 57.3% or 3,954.4 km^2 is marginally suitable, and the remaining 5.9%, or 404.9 km^2, is not suitable for growing apples because of limitations such as high temperature, low chill hours, and unfavorable soil. However, the high percentage of the area that is only marginally suitable implies that,

Table 12 Final land suitability classes and corresponding area coverage

Suitable classes	Area (km^2)	Area (%)
Highly suitable	112.5	1.6
Moderately suitable	2423.8	35.2
Marginally suitable	3954.4	57.3
Not suitable	404.9	5.9
Total	6895.6	100

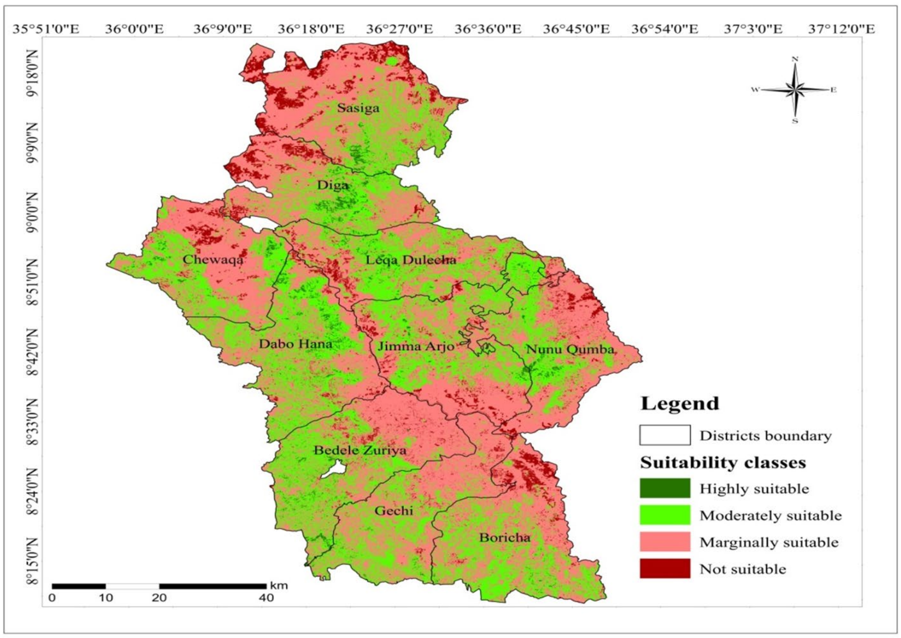

Fig. 4 Land suitability map for Apple cultivation

although the area is potentially suitable for growing apples, proper management practices such as irrigation, soil fertility improvement, and growing low-chill apples would be needed for optimal production. This result supports other studies that identified the vulnerability of the suitability of apples to climatic variability and elevation factors [27, 28], and the importance of spatial assessment in determining the favourable production zones. In general, there is an important lesson to be learned from this study to take into consideration specific location-related factors to maximize the sustainability of apple production.

Figure 4 shows the spatial distribution of land suitability classes for apple (Malus domestica) cultivation in the study area. The classification shows that S1 areas, represented by dark green color, are mainly situated in the central and northwest regions of the study area, specifically in the Lega Dembi, Diga, and Sasiga regions. The area experiences favorable agro-ecological conditions suitable for apple cultivation, such as temperature and chill hour requirements, and topography. This finding is consistent with existing literature that highlights the importance of favourable agro-ecological conditions for apple cultivation, such as optimal temperature ranges and sufficient chill hours [34, 41]. The geographical positioning of these areas suggests that microclimatic factors play a significant role in enhancing their suitability for apple production.

The moderately suitable regions (S2, light green) are found close to the highly suitable regions and can be found in areas such as Limu Arjo and Nunu Qumba, where the regions surround the highly suitable regions in the form of belts. This region is suitable for apple production but may need adaptive management, for example, the application of manure or irrigation. This finding aligns with findings from previous studies indicating that proximity to more favourable climatic conditions often enhances the potential for agricultural productivity [51]. However, while these regions are deemed suitable for apple production, they may require adaptive management strategies, such as manure application or irrigation, to optimize yield potential. Research has shown that such practices can effectively mitigate environmental stressors and improve crop performance [22].

The marginally suitable (S3) regions (orange) are largely confined to the southern and eastern parts of the study area, encompassing parts of Bede Zuria and Boricha. In these regions, inadequate temperature, low chill unit values, and moisture conditions limit apple production. On the contrary, the unsuitable (N) areas (red regions), which are largely found in the extreme southern and eastern parts, especially in the Boricha and the Gechi administrative regions, are known to be the regions where the environmental constraints of increased temperature, insufficient winter chill, and poor soil quality, among others, prevail. The central and northern regions have a high level of suitability, and in comparison, the southern region requires a high level of environmental or management intervention to reach a level of suitability in order to enhance the expansion of apple cultivation in the favourable zones.

4.1 Potential land suitability classes per districts

The spatial distribution of apple suitability classes for each district is shown in Table 13. The results indicate large variability in terms of suitability potential. The districts that cover the highest highly suitable areas are Dabo Hana (21.5 km^2), Diga (20.4 km^2), and Bedele Zuriya (17.3 km^2), which are classified as the highest Apple production potential districts, reflecting favourable agro-climatic and topographic conditions for apple cultivation. The districts with low highly suitable areas are Boricha and Gechi (2.9 and 3.9 km^2, respectively). Most districts are dominated by marginally suitable areas, particularly Sasiga (507.2 km^2) and Jimma Arjo (426.1 km^2). The current findings indicate that the requirement for location-specific adaptation measures, such as irrigation

Table 13 Suitability classes and area coverage for Apple cultivation in km^2 each district

Districts	Highly suitable	Moderately suitable	Marginally suitable	Not suitable	Total
Diga	20.4	189.3	325.4	51.2	586.2
Sasiga	12.3	203.5	507.2	113.4	836.3
Leqa Dulecha	9.4	258.2	316.7	33.1	617.4
Jimma Arjo	7.7	288.9	426.1	35.4	758.1
Nunu Qumba	7.7	179.3	389.1	36.4	612.7
Dabo Hana	21.5	356.1	351.6	17.9	747.1
Gechi	3.9	208.2	407.9	14.0	634.1
Boricha	2.9	258.4	431.6	46.3	739.3
Bedele Zuriya	17.3	279.7	423.8	24.7	745.5
Chewaqa	9.5	202.3	374.9	32.4	619.1
Total	112.5	2423.8	3954.4	404.9	6895.6

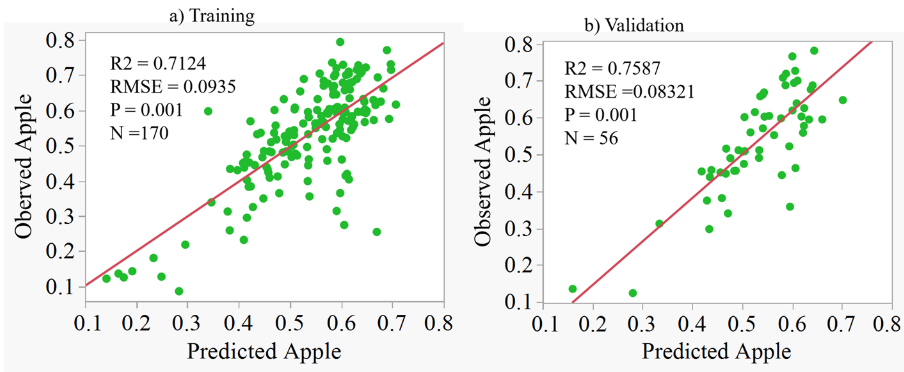

Fig. 5 Relationship between observed and predicted apple suitability for the training (**a**) and validation (**b**) datasets

management and soil and plant breeding modifications, would be necessary for apple management practices.

Similar variability has also been observed for apple suitability based on temperature and altitude variables defined by different authors, such as Luedeling et al. [28] and Kumar et al. [27]. The findings indicate variability and differences based on location and require differences and modifications according to location and context for proper management and intervention measures and strategies to be implemented and adopted. Other studies conducted by Fayaz et al. [19] on land suitability for apple cultivation in the mountainous Kashmir valley of India. A study by Chozom and Nimasow [13] also conducted a suitability analysis for apple cultivation in the West Kameng district of Arunachal Pradesh, India. Additionally, the study conducted in mountainous regions of western Nepal by Manadhar et al. (2014) also indicated similar suitability for apple production.

4.2 Model training and validation

Results indicate that there is a strong agreement between actual and predicted values of apple suitability, with high goodness-of-fit ($R^2 = 0.712$) and low prediction error (RMSE = 0.094) with 170 samples. Similarly, the validation test outcomes indicate strong prediction ability with improved goodness-of-fit ($R^2 = 0.759$) and lower prediction error (RMSE = 0.083) with 56 independent samples. The statistically significant values ($p = 0.001$) within the sets indicate the prediction accuracy and generalization capability within apple suitability prediction (Fig. 5).

5 Conclusions

This research evaluated the land suitability for growing the apple (*Malus domestica*) crop in the southwestern highlands of Ethiopia using geospatial multi-criteria evaluation. Spatial criteria, such as slope, aspect, soil depth, soil type, drainage, rainfall, temperature, and chilling hours (< 7.2 °C), obtained from DEM/Topographic maps, Ethiopian soil Map, meteorological stations, ERA5 climate raster, and GIS, contributed to the land suitability assessment. The outcome was validated for conformation with actual land suitability on the ground, using existing apple plantations for truth-point confirmation. Results from the analysis for land suitability show that the best spots for growing apples are few and not evenly distributed. Although some areas in the center and northwestern regions appear supportive, the large majority of the areas fall in the moderately or marginally suitable classes. This may suggest that apples in the area grow mainly in conditions that are not ideal, or, in other words, that they grow mainly due to limitations in climatic conditions such as high temperatures and low winter chill. Hence, growing apples in the area would be possible but not ideal.

The dominance of marginal suitability values is significant in agricultural planning and climate change adaptation. This shows that unguided development in apple production will result in low productivity as well as climate change vulnerability. Thus, efficient production of apples will rely on location-specific management practices rather than a location-independent guide. Therefore, to improve sustainability and productivity, adaptive approaches like supplementary irrigation, improving soil fertility using organic and inorganic fertilizers, and developing low-chill apple varieties tolerant to heat stress are highly advocated. Although the current study indicates apple land suitability analysis, this study has some limitations regarding its components. For example, socioeconomic factors are not included in this study, and there are limited field tests. Future research could be carried out at the farm level, incorporating socioeconomic factors and additional environmental variables.

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Author contributions
MMG and MBM took part in the design of the study, the gathering of data, Landsat image analysis, and reviewing and editing. HKK, TEE, ZRR, MD, and KTD participated in methodology, data analysis, and interpretation included. DN, FBC, BI, MEF, and DOG participated in conceptualization, methodology, data analysis, and reviewing and editing.

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Declarations

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