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MULTICRITERIA-BASED SITE SUITABILITY ASSESSMENT FOR COFFEE CULTIVATION IN LOW AND MID HILLS OF HIMACHAL PRADESH

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ABSTRACT
Coffee is emerging as a promising diversification crop in the subtropical low and mid-hill zones of Himachal Pradesh. There has been limited systematic assessment of spatial suitability of coffee for sustainable scaling up. The present study included climatic, physiographic and edaphic variables in a GIS based multi-criteria decision analysis (MCDA) framework for delineating potential sites for coffee cultivation in seven districts of Himachal Pradesh (Hamirpur, Bilaspur, Una, Kangra, Mandi, Solan and Sirmaur). Sentinel 2A/B images were used to map land use/land cover (LULC). Terrain parameters (elevation, slope and aspect) were derived from CartoSat-1 DEM. Climate layers (temperature, rainfall) were obtained from IMD and WorldClim data. Soil data (pH, EC, organic carbon and available NPK) were collected from secondary sources and field sampling. Re-grouped criteria based on coffee-specific threshold and weighted through Analytical Hierarchy Process (AHP). The composite suitability maps were generated through weighted overlay of layers using ArcGIS 10.8 with four classes, namely, Highly Suitable (S1), Moderately Suitable (S2), Marginally Suitable (S3), and Not Suitable (N). The findings show that only a small part of the research area located at mid-elevation belts is classified as S1 for Arabica. Large parts of it are marginal (S3) or unsuitable (S4) due to steep slopes, shallow or degraded soils or unfavourable climate conditions. Robusta has a broader climatic range but still is constrained by soil and topographic conditions. Planners and extension agencies can use suitability maps developed as a spatial decision support framework to target coffee expansion in favourable zones in Himachal Pradesh.

KEYWORDS: Coffee; AHP; GIS; land suitability; western Himalayas; Himachal Pradesh

INTRODUCTION
Coffee is an evergreen tree originated in north-central Africa belonging to family Rubiaceae. It is now cultivated in 76 countries and is one of the three most widely drunk drinks in the world. The two main types of coffee are *Coffea arabica* and *Coffea canephora* (robusta). Arabica accounts for about 80 percent of total coffee area and is noted for high cup quality. Robusta is preferred as it grows well in the warm lowlands. It has more caffeine and is more productive Arabica thrives best at altitudes between 600-1400 m amsl, where the altitude has a profound effect on the quality of the beans, often more than genetic variation does (Ge et al. 2023).

Climate, soils, landform, genetics and farming practices affect coffee production (Estrada et al. 2017). Altitude, diurnal temperature variation, distribution of rainfall and shade management are important in relation to growth, time to maturity and duration of bean filling. This is a long term crop with high investment and returns are after a long time. Choosing the wrong site can leave farmers tied into sub-optimal systems for many years. Therefore, inventory and classification of available resources which determine the biophysical potential of land to grow specific crops i.e. land suitability evaluation is a precondition to risk aware planning in coffee based systems .

Conventional land suitability analysis using manual methods and analogue maps are often expensive, time consuming, lack analytical accuracy and may not adequately integrate land use, terrain and environmental aspects. Alternatively, a land suitability analysis based on the use of a GIS multi-criteria decision analysis (MCDA) offers an integrated framework where climatic, edaphic and physiographic parameters can be systematically weighted according to the preferences of decision makers (Rono and Mundia, 2016; Flora, 2025). The Analytical Hierarchy Process (AHP) is a widely used Multi-Criteria Decision Analysis (MCDA) method to evaluate the relative importance of the suitability criteria and to produce composite suitability maps.

Coffee cultivation is restricted to the southern Indian states of Karnataka, Kerala and Tamil Nadu with marginal expansion into non-traditional areas like Andhra Pradesh, Odisha and North-Eastern states of India. The agro-climatic diversity in Himachal Pradesh provides a great opportunity for diversification of crops with high value plantation crops like coffee (Asif and Panakaje, 2022). The Department of Agriculture, Himachal Pradesh carried out a pilot project in 2014 and after field observations and quality assessment, it was found that coffee can be grown in the low and mid-hill areas having similar climatic and topographical conditions as that of Chikkamagaluru region of Karnataka.
The present scenario necessitates a systematic multicriteria site suitability assessment based on GIS for location of sites in Himachal Pradesh where coffee cultivation can be promoted in a sustainable manner and under which management regimes. The present study was carried out to delineate land suitability classes of Arabica and Robusta coffee in selected districts of Himachal Pradesh using AHP-MCDA and to identify major climatic, physiographic and edaphic factors controlling spatial change in coffee suitability. The maps and analysis are meant to give a spatial context for potential coffee expansion, helping planners and farmers to identify areas that are ecologically suitable and economically viable.

MATERIALS AND METHODS

Study Area

The study was conducted in seven districts of Himachal Pradesh namely Una, Hamirpur, Bilaspur, Kangra, Mandi, Solan and Sirmaur representing low and mid-hill coffee growing belt (Figure 1). The districts have varied landscape with predominant tree cover and agricultural land in mid to high hill areas and more barren and built-up areas in lower hills. The altitudinal range is from approximately 400 m to above 2000 m a.m.s.l. with monsoon dominated rainfall regimes and mean annual temperature between 20 °C and 27 °C.

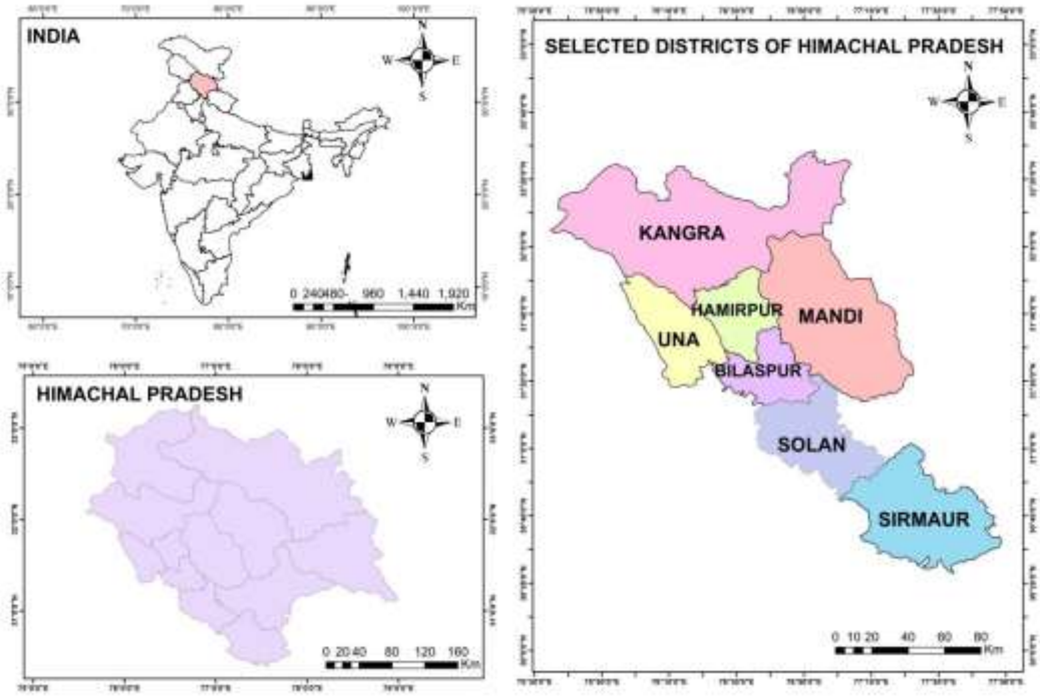

Figure 1: Selected Low and Mid Hill Districts of Himachal Pradesh for Coffee Suitability Analysis

Data collection

The primary data were collected from field surveys and soil samples from low and mid-hill coffee growing sites of Hamirpur, Bilaspur, Una, Kangra and Mandi districts in 2024-2025. GPS coordinates of the plantations and sampling points were recorded using Garmin GPSMAP 64s (WGS84 datum) and integrated in ArcGIS 10.8. The secondary data layers were compiled in the following way:
LULC: Copernicus Sentinel-2A/2B multispectral imagery (10 m) classified into agricultural land, barren land, built-up area, tree cover, sediments and water bodies.
Topography : CartoSat-1 DEM (30 m) and Survey of India toposheets for elevation, slope and aspect.
Climate: IMD and WorldClim gridded rainfall and temperature data interpolated at district scale .
Soils: pH, organic carbon, electrical conductivity and available NPK from field samples for sampled sites and from Soil Survey of India and published literature for unsurveyed areas.
The datasets were projected to UTM Zone 43N (WGS84 datum), georeferenced, mosaiced and resampled as needed before integration into the GIS database.

Criteria selection and reclassification

Parameters used in the assessment of suitability of the site for coffee were classified into three thematic domains:
Climatic: Annual rainfall, mean annual temperature.
Physiographic: altitude, slope, and aspect.

Soil: pH, electrical conductivity (EC), organic carbon (OC) and available NPK.

Suitability classes (e.g. highly suitable, moderately suitable, marginally suitable, unsuitable) were defined for each parameter based on coffee-specific thresholds from national recommendations and international literature (Fekadu and Andarege, 2025; Jutia et al., 2021; Marbun et al. 2020). For example, soils with moderate acidity and higher organic carbon content were rated more suitable for arabica, but steep slopes and shallow soils were rated less suitable due to risk of erosion and root constraints.

Analytic Hierarchy Procedure (AHP) and Weights

The relative importance (weights) of selected criteria were assigned using the Analytical Hierarchy Process . Pairwise comparison matrices (Table 1) were constructed for the climatic, physiographic and soil domains based on expert judgement and literature on the sensitivity of coffee to each of the factors (Fekadu and Andarege, 2025; Rono and Mudia, 2016). Consistency ratios were calculated to check for acceptable levels of coherence in decision making. The weights were normalised and used to reclassify raster layers . Climatic variables were highly weighted followed by slope and soil properties (Table 2).

Table 1:Pairwise comparison matrix used for site suitability analysis for *C. arabica* and *C. canephora*

Parameter	DEM	Slope	Aspect	LULC	pH	EC	OC	N	P	K	Rainfall	Tmax	Tmin
DEM	1.00	1.33	3.00	1.71	2.40	6.00	6.00	6.00	6.00	6.00	0.63	0.71	0.71
Slope	0.75	1.00	2.25	1.29	1.80	4.50	4.50	4.50	4.50	4.50	0.47	0.53	0.53
Aspect	0.33	0.44	1.00	0.57	0.80	2.00	2.00	2.00	2.00	2.00	0.21	0.24	0.24
LULC	0.58	0.78	1.75	1.00	1.40	3.50	3.50	3.50	3.50	3.50	0.37	0.41	0.41
pH	0.42	0.56	1.25	0.71	1.00	2.50	2.50	2.50	2.50	2.50	0.26	0.29	0.29
EC	0.17	0.22	0.50	0.29	0.40	1.00	1.00	1.00	1.00	1.00	0.11	0.12	0.12
OC	0.17	0.22	0.50	0.29	0.40	1.00	1.00	1.00	1.00	1.00	0.11	0.12	0.12
N	0.17	0.22	0.50	0.29	0.40	1.00	1.00	1.00	1.00	1.00	0.11	0.12	0.12
P	0.17	0.22	0.50	0.29	0.40	1.00	1.00	1.00	1.00	1.00	0.11	0.12	0.12
K	0.17	0.22	0.50	0.29	0.40	1.00	1.00	1.00	1.00	1.00	0.11	0.12	0.12
Rainfall	1.58	2.11	4.75	2.71	3.80	9.50	9.50	9.50	9.50	9.50	1.00	1.12	1.12
Tmax	1.42	1.89	4.25	2.43	3.40	8.50	8.50	8.50	8.50	8.50	0.89	1.00	1.00
Tmin	1.42	1.89	4.25	2.43	3.40	8.50	8.50	8.50	8.50	8.50	0.89	1.00	1.00

Table 2: Criteria hierarchy with normalized priority weights for coffee

Parameters	Normalized priority weights
Rainfall	18.56
Tmax	16.49
Tmin	16.49
DEM	12.39
Slope	9.28
LULC	7.22
pH	5.15

Parameters	Normalized priority weights
Aspect	4.12
EC	2.06
OC	2.06
N	2.06
P	2.06
K	2.06

GIS Overlay and Suitability Assessment
Composite suitability indices were derived based on weighted criteria layers using raster overlay analysis in ArcGIS 10.8. The resulting index was re-categorized into four categories:
S1: Highly suitable
S2: Moderately Suitable
S3: Marginally Suitable
S4: Not Suitable
Suitability maps were created independently for Arabica and Robusta based on their species-specific thermal preferences and tolerance ranges (Figure 2). The zonal analysis tools were used to quantify potential coffee growing areas by suitability statistics (area under each class per district).

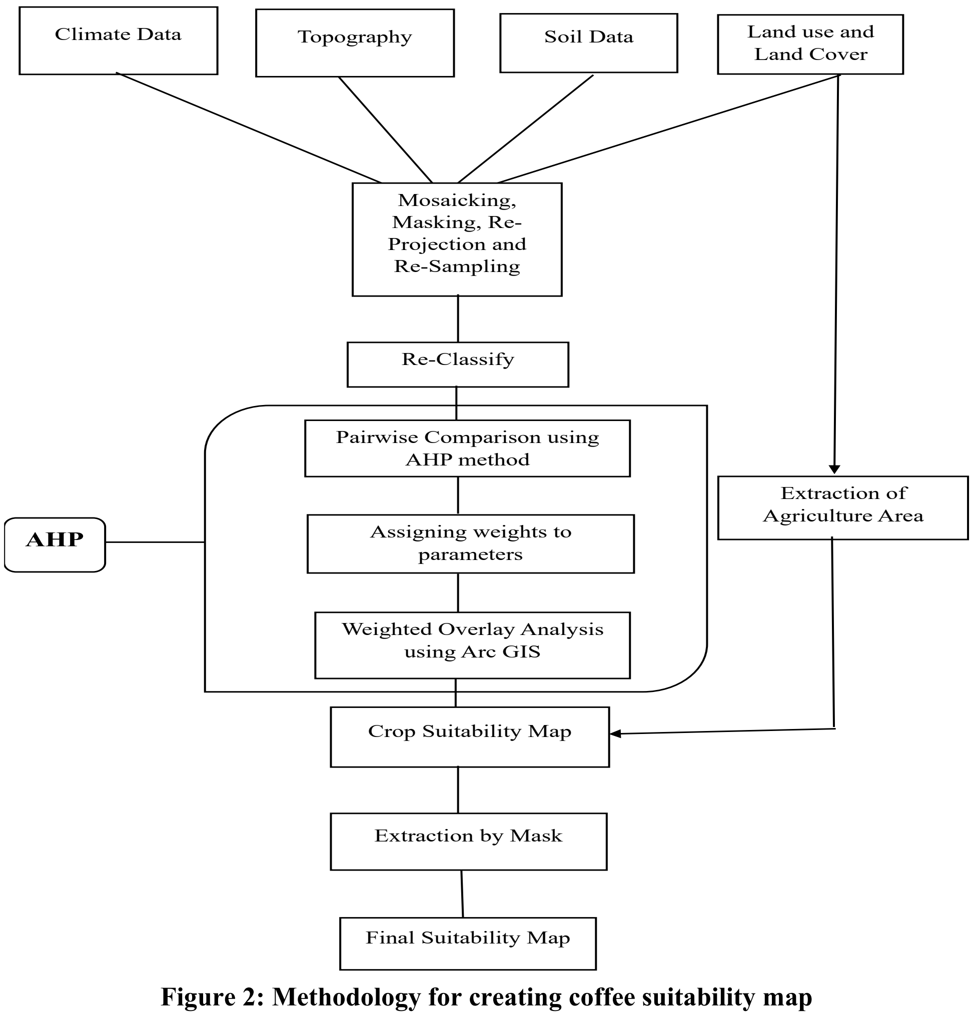

Figure 2: Methodology for creating coffee suitability map

RESULTS
Land use/land cover
Tree cover and agricultural land dominate in mid to high hill districts of Kangra, Mandi, Solan and Sirmaur, forming a strong mosaic of forest-agriculture systems as revealed by LULC analysis. Large extent of vegetation cover was also

shown by Mandi and Sirmaur. These landscapes provide suitable conditions to incorporate shade-grown coffee into existing agroforestry systems.
Lower-hill districts (Una, Hamirpur, Bilaspur) showed higher proportions of barren land and built-up land indicating more land-use pressure and potential for environmental constraints for coffee establishment. All the districts had very low area under water bodies and sediment classes. Thus, their role in suitability assessment was very insignificant.

Climatic envelopes of Arabica and Robusta
The climate analysis revealed that the mid-hill districts generally have adequate annual rainfall and moderate temperature conditions suitable for Arabica, while some warmer pockets in the low-hill area are more suitable for Robusta. Areas with moderate temperatures and well-distributed rainfall were classified as highly to moderately suitable for Arabica, while warmer, more humid zones with relatively stable temperatures were found to be more favourable for Robusta (Fekadu and Andreage, 2025; Jutia et al., 2021).
Arabica was rated less suitable in areas with prolonged frost and very low winter temperatures, consistent with its cold stress sensitivity. Robusta was rated less suitable in areas with prolonged dry periods and moisture stress, consistent with its higher humidity requirement. These climatic envelopes were a key factor in determining the spatial distribution of suitability classes in the whole study area.

3.3 Physiographic features: elevation, slope and aspect
In suitability analysis slope was found to be a major physiographic constraint. Moderate slopes were rated as more suitable, since they promote proper drainage and avoiding water stagnation. On the other hand, steep slopes were related to hazards of soil erosion and management difficulties (Jutia et al., 2021). As a result large areas of steep country were classified as marginal or unsuitable, particularly in parts of the high-hill districts.
Suitability was affected by aspect through its effects on solar radiation and thermal conditions. In the present study, north-east and north-facing slopes were often rated more suitable for Arabica, under Himalayan conditions, with favourable radiation and temperature regimes, whereas warmer slopes were assigned higher suitability scores for Robusta (Fekadu and Andreage, 2025). This differentiation by aspects improved the refinement of suitability among districts with similar ranges of elevation.

3.4 Soil Factors
Highly suitable (S1) for coffee production were classified deep, well drained soils with high organic matter content and a favorable pH (slightly to moderately acidic). Moderately acidic soils with higher organic carbon content improved root penetration, nutrient retention and water-holding capacity, increasing suitability for Arabica (Fekadu and Andreage, 2025). Shallow, compacted or poorly drained soils and soils with extreme pH values lowered suitability ratings.

The current study indicated that Arabica was more successful in fertile, slightly acidic soils with a high level of organic matter, whereas Robusta was more adaptable to a wider range of soil conditions as long as drainage and moisture in the soil were adequate. These soil considerations led to large areas of the study area being classified as moderate (S2) or marginal (S3) instead of highly suitable (S1).

3.5 Spatial distribution of suitability categories
Composite suitability maps showed that only a small proportion of the total area in each district was within the S1 class of Arabica, mostly in mid-elevation belts where climatic, physiographic and edaphic conditions were favourable. Much larger areas were classified as S2 (moderately suitable) indicating that coffee could be grown with appropriate management interventions such as shade regulation, mulching, soil conservation and supplemental irrigation.
The marginally suitable (S3) and unsuitable (S4) areas were mostly characterized by extreme slopes, degraded or shallow soils, or climatic constraints such as frost-prone highlands and very dry low-hill pockets. Such patterns are comparable to the findings of Ethiopia and other coffee regions where moderate suitability classes are dominant and can be improved through particular agronomic and conservation measures (Fekadu and Andreage, 2025; Nzeyimana et al., 2014).

4.2.5.1 Final *Coffea arabica* suitability maps
The final suitability map for *Coffea arabica* were generated by weighted overlay analysis in ArcGIS using the weights derived from AHP for rainfall, maximum and minimum temperature, elevation, slope, aspect, land use/land cover and soil properties. The pixels were classified into four suitability classes, S1 (highly suitable), S2 (moderately suitable), S3 (marginally suitable) and S4 (not suitable) according to the FAO land evaluation framework and the suitability thresholds used in this study, taking into account the combined effect of all thematic layers. The area under different suitability classes for *Coffea arabica* in the study area districts is shown in table 3.

At the scale of the whole study area (18,270.2 km^2), about 22.5% (4,106.4 km2) was delineated as highly suitable (S1) and 34.6% (6,311.6 km2) as moderately suitable (S2) for Arabica coffee. Therefore, about 57% of the low and mid–hill landscape has favourable combinations of climate, terrain, soils and land use for Arabica cultivation. Marginally suitable land (S3) represented about 23.0% (4,203.9 km^2) and 19.8% (3,648.2 km^2) was classified as unsuitable (S4) land, i.e. land where one or more of the factors (very steep slopes, unsuitable aspects, thermally limiting climates or incompatible land use) impose serious constraints.

District wise, Kangra and Mandi together contributed maximum share of high potential land for Arabica. Kangra had 1291.3 km^2 in S1 and 1901.8 km^2 in S2 indicating that more than half of the total area represents a contiguous belt of highly to moderately suitable zones for Arabica coffee. These favourable tracts are primarily associated with mid elevation bands, gentle to moderate slopes, north to east facing aspects, well distributed rainfall and a mosaic of agricultural and tree covered land use. Mandi also emerged as a key Arabica district with 1,003.0 km ^{2} as S1 and 1,537.3 km^2 as S2.

Solan and Sirmaur exhibited moderate but still significant Arabica potential with 413.5 km^2 and 516.5 km^2 in S1 and 651.9 km^2 and 1,061.7 km^2 in S2 respectively. In these districts, zones of high suitability are concentrated in mid-altitude landscapes where moderate slopes, favourable aspects and tree dominated LULC co-exist with the best temperature bands. The marginally suitable area (S3) in Solan (441.6 km^2) and Sirmaur (631.9 km^2) is generally on steeper terrain or pockets with slightly warmer or cooler conditions than optimum, which indicates that coffee could be grown but would require careful soil and water conservation measures and species/variety selection.

More limited but still non-trivial suitability for Arabica was observed in lower-hill districts like Una, Hamirpur and Bilaspur. In Una, 355.4 km^2 were S1 and 338.5 km^2 S2, therefore about half of the area of the district is capable of supporting Arabica with the adoption of adequate management of shade and microclimate. Hamirpur had 384.8 km^2 of highly suitable and 406.7 km^2 of moderately suitable land, while Bilaspur had 141.9 km^2 of S1 and 413.7 km^2 of S2 area. In these lower-hill districts, S1 and S2 zones are often embedded within a matrix of S3 and S4 land where relatively higher temperatures, greater prevalence of barren land and localized slope/aspect limitations reduce suitability. However, the existence of substantial S2 tracts, especially in Bilaspur and Hamirpur, indicates that Arabica can be promoted there under shade-based agroforestry systems and better moisture conservation.

In all districts, marginally suitable areas (S3) are typically characterized by one or more limiting factors, such as steep slopes (≥30%), south-facing aspects, proximity to barren land or temperature regimes at the upper edge of Arabica tolerance. Unsuitable zones (S4) are concentrated in very steep terrain, high altitude cold pockets, excessively warm low valleys, built-up areas and water bodies, especially in Kangra and Mandi where complex topography creates large areas beyond the physiological range of Arabica. The final Arabica suitability map indicates that truly optimal zones are restricted to mid-hill belts in Kangra, Mandi, Solan and Sirmaur, but there are substantial areas of Arabica cultivation potential across all seven districts with site-specific management interventions. The final suitability maps for arabica coffee are shown in figures 3 to 9 for selected districts of study.

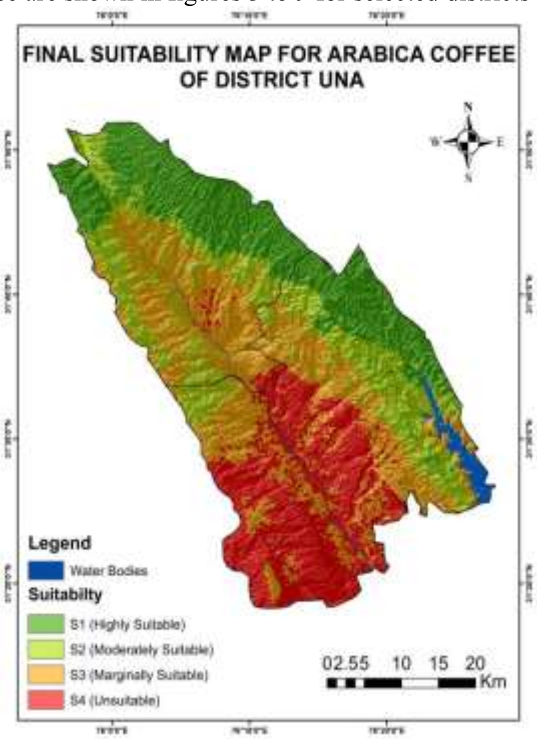

Figure 3: Final Suitability Map for Arabica Coffee in District Una

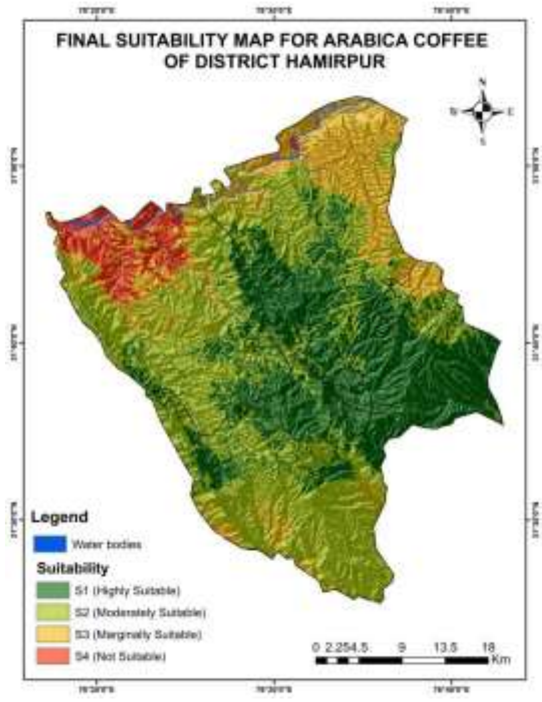

Figure 4: Final Suitability Map for Arabica Coffee in District Hamirpur

Figure 5: Final Suitability Map for Arabica Coffee in District Bilaspur

Figure 6: Final Suitability Map for Arabica Coffee in District Kangra

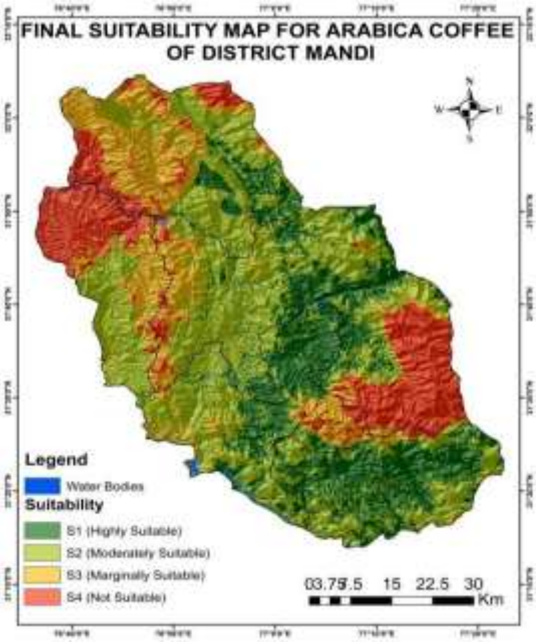

Figure 7: Final Suitability Map for Arabica Coffee in District Mandi

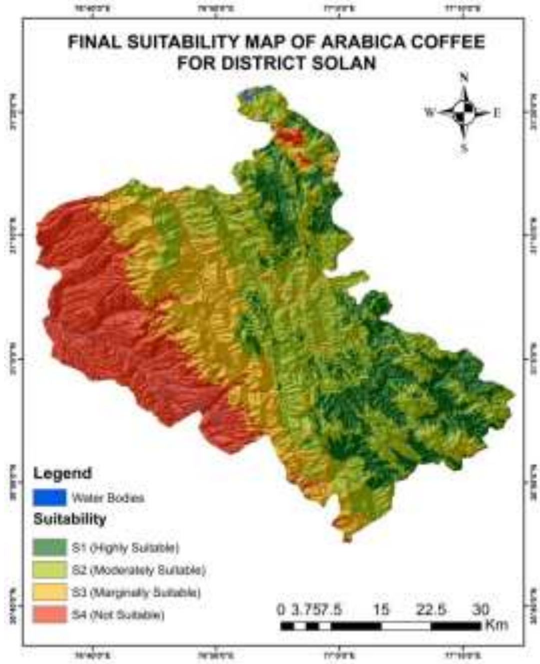

Figure 8: Final Suitability Map for Arabica Coffee in District Solan

Figure 9: Final Suitability Map for Arabica Coffee in District Sirmaur

Table 3 Area under different suitability classes for *C. arabica*

Suitability Class	Area under different final suitability classes (sq. Km.)							
	Una	Hamirpur	Bilaspur	Kangra	Mandi	Solan	Sirmaur	Total
S1 (Highly Suitable)	355.4	384.8	141.9	1291.3	1003.0	413.5	516.5	4106.4
S2 (Moderately Suitable)	338.5	406.7	413.7	1901.8	1537.3	651.9	1061.7	6311.6
S3 (Marginally Suitable)	489.9	226.7	329.7	1367.4	716.8	441.6	631.9	4203.9
S4 (Not Suitable)	354.0	103.1	280.7	1168.4	692.2	449.5	600.3	3648.2
Total	1537.8	1121.3	1166.1	5728.9	3949.2	1956.5	2810.4	18270.2

4.2.5.2. Final suitability patterns for *Coffea canephora* (robusta)

The final suitability map for *Coffea canephora* was produced using the same AHP-weighted overlay framework, but with species-specific thresholds reflecting robusta coffee's preference for warmer, lower elevations and higher mean annual temperatures. Robusta coffee was classified separately for elevation classes, maximum temperature bands, slope, aspect, LULC and soil variables and integrated to produce composite suitability classes (S1–S4) similar to those for Arabica. The area under different suitability classes for Coffea arabica in the study area districts is shown in table 4.

The elevation suitability analysis revealed that robusta is highly suitable (S1) in the 200–700 m amsl, moderately suitable (S2) in the 0–200 m band, marginally suitable (S3) in 700–1,200 m amsl and areas above 1,200 m amsl are not suitable (S4). The overlay with the maximum temperature suitability map, where robusta's S1 zone is 22–30 °C and S2 is 20–22 °C and 30–32 °C, results in large S1 and S2 belts in the warmer low-hill valleys and foothills, especially in Kangra and Una. In these districts, extensive areas that are too warm for high-quality Arabica lie well within the optimum thermal and altitudinal envelope for robusta.

For elevation alone, Kangra had 2,97.0 km^2 of highly suitable (S1) robusta land and 1,064.5 km^2 of marginally suitable (S3) land whereas Una had 1,461.4 km^2 of S1 and 76.4 km^2 of S3 area. This trend was also supported by temperature-based suitability, where 3,972.1 km^2 and 1,211.3 km^2 of Kangra and Una were in the S1 thermal range for robusta, respectively, indicating that these two districts together provide the largest continuous warm low- to mid-hill belts for robusta coffee in the study area. In such areas, Robusta can be integrated into existing agricultural and tree-covered LULC classes, particularly on gentle slopes, and thus transform underutilised warm areas into productive coffee agroforestry systems.

Bilaspur was highly suitable for robusta with S1 elevation suitability of 838.5 km^2 and S1 temperature suitability of 1040.2 km^2 and additionally S2 and S3 area. These tracts are mostly in the low to mid hill sectors of the district where slopes are still manageable and agricultural land or tree cover dominates the LULC map. Hamirpur showed 500.5 km2 of S1 elevation suitability and 997.5 km2 of S1 temperature suitability. However, a large part of the area falls under S3 elevation classes (620.8 km2), indicating that robusta can be promoted mainly in the lower and warmer pockets while mid-hill sectors need careful site selection.

By contrast, high altitude districts such as Mandi, Solan and Sirmaur indicated more limited robusta potential. Mandi had only 168.6 km^2 of S1 elevation suitability and large areas in S3 (1,282.6 km^2) and S4 (2,498.1 km^2), indicating the dominance of high-altitude, cool environments that lie outside the optimum range of robusta. Similarly, large areas of S3 and S4 were found in Solan and Sirmaur due to cooler temperatures and higher altitudes, but warm pockets in valleys and lower slopes in these districts still provide S1–S2 zones where robusta can be grown successfully. In these mid-hill districts, robusta should thus be seen as a niche species for specific low-elevation corridors, and not as a diversification option on a broad scale.

In all districts aspect and slope further define robusta suitability. S1 and S2 classes are preferred by moderate thermal extremes and mechanisation potential on north- and east-facing slopes and gentle terrain (≤15%), whereas south-facing slopes and steep gradients often downgrade areas to S3 or S4 classes due to moisture stress and susceptibility to erosion. Built-up, barren and water body land use classes limit the expansion of robusta suitability while agricultural land and tree cover land use classes generally enhance the robustness suitability due to their existing agroforestry frameworks. The final suitability maps for arabica coffee are shown in figures 10 to 16 for selected districts of study.

Overall, the final robusta suitability map shows large contiguous belts of S1 and S2 land for robusta coffee in warm low-hill districts like Kangra, Una and Bilaspur, while high-altitude, cooler districts such as Mandi, Solan and Sirmaur are mainly suitable for Arabica. Thus the combined Arabica and robusta suitability assessment provides a species-specific zoning framework; Arabica should be given priority in mid-hill cooler belts with suitable terrain and soils while robusta should be targeted to lower warmer valleys and foothills, allowing complementary utilization of the diverse agro-ecological niches across Himachal Pradesh. The stacked bar and heatmap of area under different suitability classes of both species are presented in figures 17 and 18, respectively.

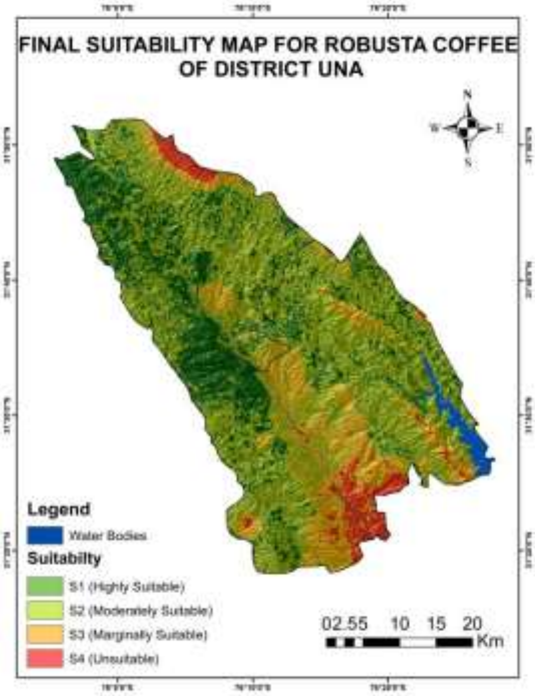

Figure 10: Final Suitability Map for Robusta Coffee in District Una

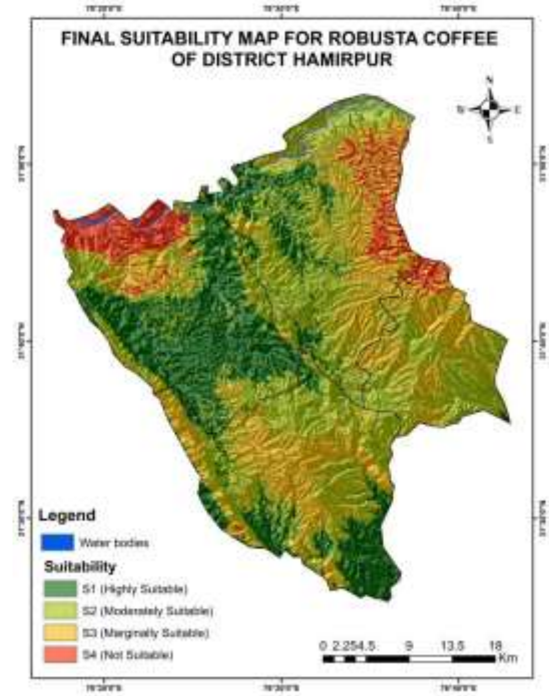

Figure 11: Final Suitability Map for Robusta Coffee in District Hamirpur

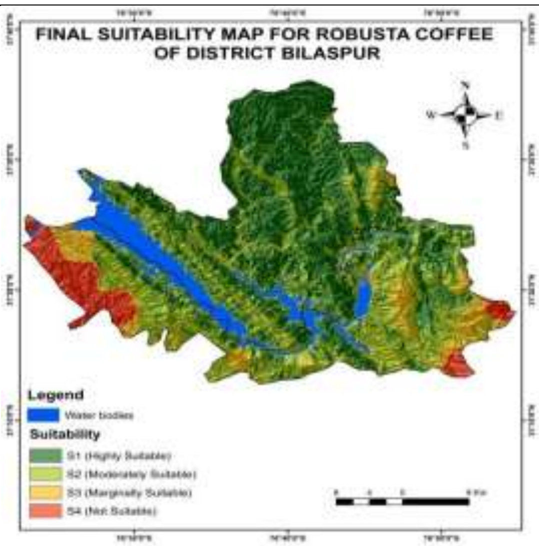

Figure 12: Final Suitability Map for Robusta Coffee in District Bilaspur

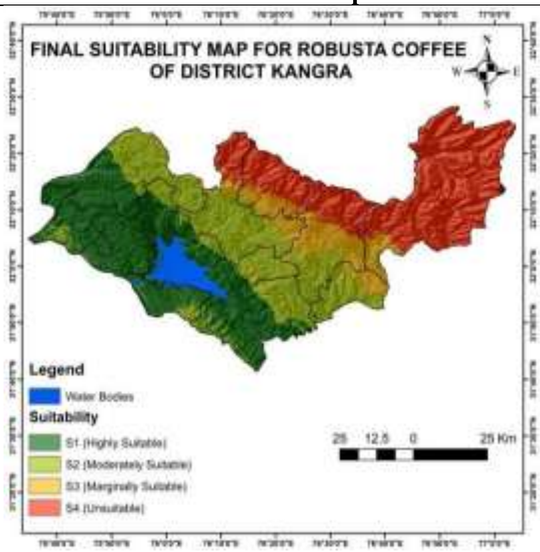

Figure 13: Final Suitability Map for Robusta Coffee in District Kangra

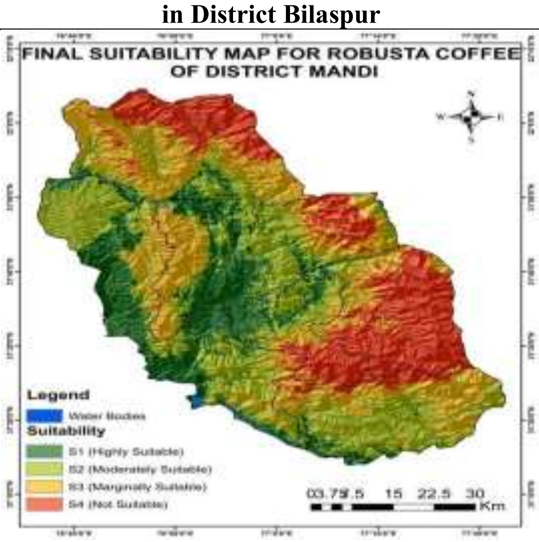

Figure 14: Final Suitability Map for Robusta Coffee in District Mandi

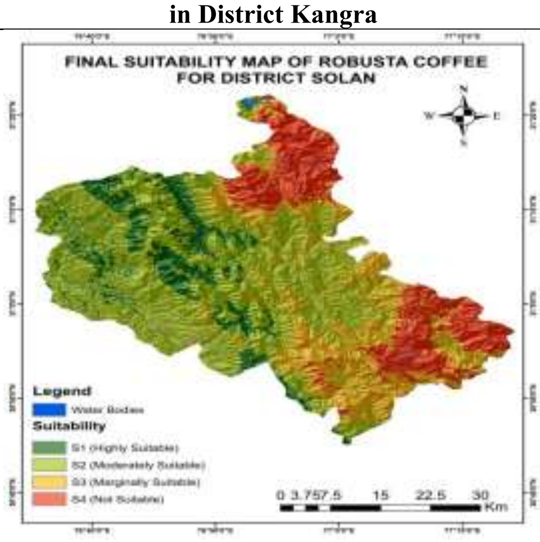

Figure 15: Final Suitability Map for Robusta Coffee in District Solan

Figure 16: Final Suitability Map for Robusta Coffee in District Sirmaur

Table 4 Area under different suitability classes for *C. canephora*

Suitability Class	Area under different final suitability classes (sq. Km.)							
	Una	Hamirpur	Bilaspur	Kangra	Mandi	Solan	Sirmaur	Total
S1 (Highly Suitable)	424.0	276.9	469.4	2199.0	784.9	297.0	702.7	5153.8
S2 (Moderately Suitable)	719.8	430.8	438.3	1322.9	1143.6	765.6	770.2	5591.1
S3 (Marginally Suitable)	302.7	347.2	169.9	589.5	1121.1	510.4	848.1	3888.9
S4 (Not Suitable)	91.4	66.3	88.5	1617.5	899.7	383.5	489.4	3636.3
Total	1537.8	1121.3	1166.1	5728.9	3949.2	1956.5	2810.4	18270.2

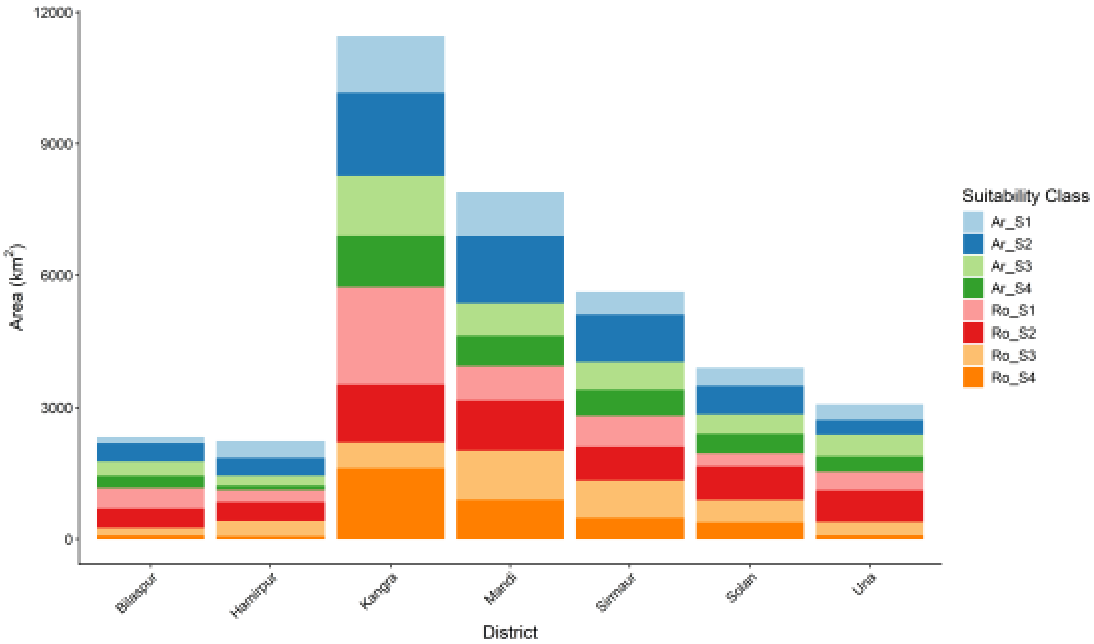

Figure 17: Stacked bar graph showing area under different suitability classes of both coffee species in study area districts (Ar= *C. arabica*, Ro= *C. canephora*)

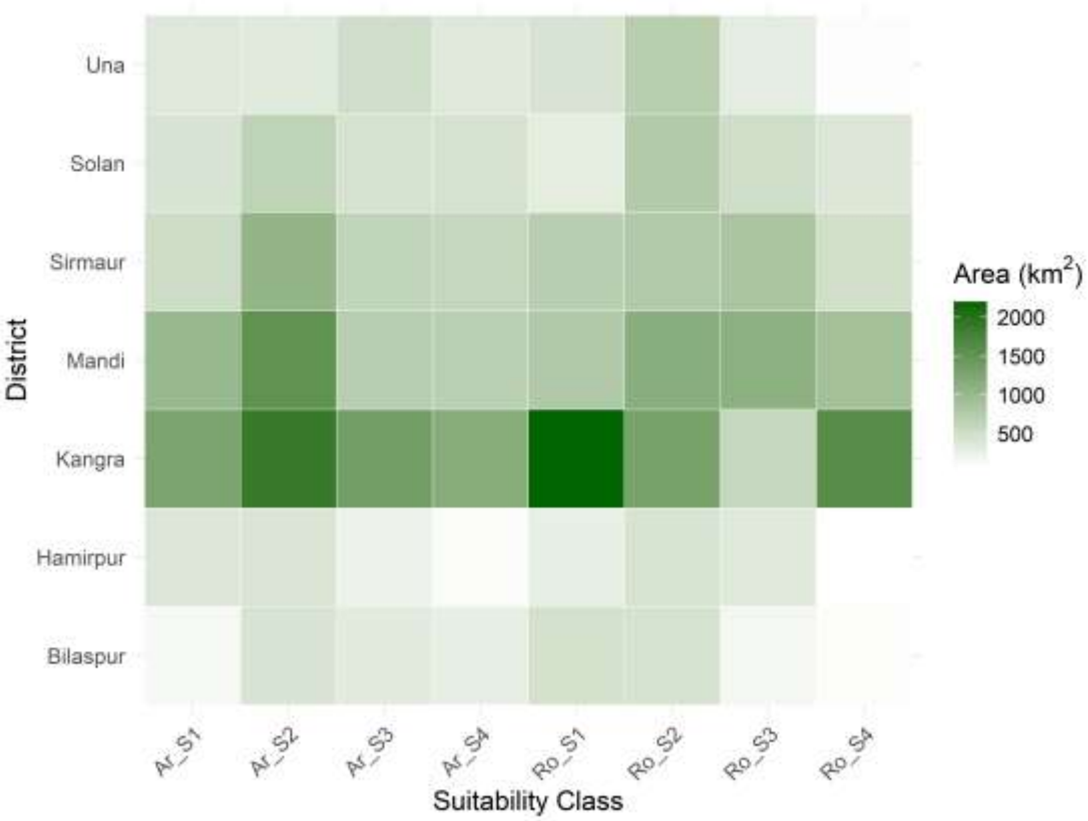

Figure 18: Heatmap presenting area under different suitability classes of both coffee species in study area districts (Ar= *C. arabica*, Ro= *C. canephora*)

4. DISCUSSION

4.1 Comparison with previous global studies of coffee suitability

This suitability assessment aligns with international evidence where climate (especially rainfall distribution, minimum temperature of coldest month and length of dry season) is a dominant factor controlling coffee potential (Fekadu and Andreage, 2025; Juita et al., 2021; Marbun et al., 2020). The moderate temperature mid hill districts of Himachal Pradesh with sufficient rainfall were found suitable for Arabica and the warmer humid zones with shorter dry spells were found suitable for Robusta.

The availability of highly suitable land is limited and moderate and marginal classes dominate as reported elsewhere indicating that sustainable coffee development in new areas will be heavily reliant on management interventions and careful selection of species/varieties (Fekadu and Andreage, 2025; Nzeyimana et al., 2014).

4.2 Effect of slope and aspect on mountain environments

Slope and aspect are important for mountain suitability, but are not like more uniform terrain. This is in line with studies that have shown that slope limitations greatly reduce the suitable area of land due to the risk of erosion and management restrictions (Juita et al., 2021). The result is that coffee grows better on moderate slopes than on steep slopes. Likewise, aspect directly affects the coffee productivity by resulting in variations in the interception of sunlight, conservation of moisture and intensity of erosion especially in Himalayan conditions (Fekadu and Andreage, 2025).

The AHP-MCDA framework incorporating slope and aspect provides a more realistic, terrain sensitive picture of coffee potential than climate only models. This is particularly so in Himachal Pradesh where most of the land is steep and there are strong differences in site level microclimate between different orientations.

4.3 Impacts on soil suitability

The strong influences of organic carbon and pH on the suitability classes show the importance of considering soil management in the strategies for the expansion of coffee. Better root development, nutrient cycling and moisture retention improve arabica performance and resilience of long-term plantations. These are augmented by deep, well drained, organic rich soils with moderately acidic reaction (Fekadu and Andreage, 2025).

In moderately suitable areas with low organic carbon or suboptimal pH suitability can be improved by interventions such as adding organic matter, mulching, green manuring and liming. This is in line with the general recommendations that land of moderate suitability can be improved to higher levels of productivity through agronomic and conservation measures (Nzeyimana et al., 2014).

4.4 GIS Planning and AHP-MCDA

The present study shows the applicability of AHP-based MCDA combined with GIS and interpolation methods for spatial coffee suitability mapping. In Ethiopia and other countries, similar approaches based on inverse distance weighted interpolation, AHP and GIS were successfully used to predict the suitability of climatic, topographic and soil factors for coffee (Fekadu and Andreage, 2025; Fachruddin et al., 2021; Zhang et al., 2021;Rono and Mundia, 2016).

The suitability maps developed for Himachal Pradesh provide a scientific basis for identification of potential coffee growing regions for both Arabica and Robusta and can be used as decision support tools for planners, researchers and farmers. When integrated with the socio-economic data, these maps would further enhance the planning for coffee expansion in the state.

5. CONCLUSIONS

Climatic, physiographic and soil parameters based GIS integrated AHP-MCDA approach for site suitability assessment identified the spatial pattern of coffee potential in the low and mid-hill districts of Himachal Pradesh. The highly suitable (S1) region for Arabica is confined to mid-elevation belts with a favourable climate, gentle to moderate slopes, appropriate aspects and fertile, moderately acidic soils. Moderately suitable (S2) area to larger extents need specific management treatments.

These results also highlights the need of careful targeting of coffee expansion in Himachal Pradesh towards ecophysiographically favorable zones and the need for appropriate soil, water and shade management for sustainable productivity. The AHP-MCDA framework and maps produced in the present study constitute a strong and transparent basis for land-use planning and can be further improved as more detailed climatic and edaphic data become available. This suitability analysis, together with the ecophysiographic characterization and coffee quality assessment, is an integral component of a broader strategy to develop resilient coffee-based agroforestry systems in the western Himalayas.

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