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Geospatial Suitability Assessment for Organic Farming in the Garhwal Himalayas Using the Analytic Hierarchy Process (AHP)

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Abstract

This paper deals with the geospatial suitability analysis of organic farming in the Garhwal Himalaya, India, using the AHP method in association with Geographic Information Systems. Organic farming is very important for the promotion of sustainable agricultural practices in mountainous regions where topographical as well as environmental factors play an important role in land suitability. It makes use of multiple criteria: Topographic Wetness Index (TWI), Topographic Ruggedness Index (TRI), Topographic Positioning Index (TPI), slope, flow direction, flow accumulation, aspect, hillshade, curvature, and tan slope. A pairwise comparison matrix was formulated using AHP to assign weights for these parameters based on their relative importance in determining land suitability for organic farming. With the integration of such weighted factors by the GIS tools, it has given scope for developing a detailed suitability map over the land areas, which identified very-low, low, moderate, high, and very-high suitability areas for organic farming. Therefore, the results show that the spatial variability of the suitability of land is a large factor in the Garhwal Himalaya, developed by the complicated interaction between topographic and hydrological factors. High scoring districts include Chamoli and Rudraprayag, while low scores were reported in regions located in Tehri Garhwal and Pauri Garhwal, mainly due to steeper slopes and rough topography. The research output is really important for policymakers and local farmers in order to expand organic farming in ecologically sustainable areas. The methodology adopted offers a replicable framework for land suitability assessment in the other mountainous regions of the world, and it contributes to the larger discourse on sustainable agricultural development.

Keywords: *Organic Farming, Analytical Hierarchy Process (AHP), Geographic Information Systems (GIS), Land Suitability Analysis, Garhwal Himalaya, Topographical Factors, Sustainable Agriculture*

Introduction

The Garhwal Himalaya is characterized by topography, as well as varied climatic conditions, which thus poses challenges and opportunities for organic farming. Organic farming has acquired significant importance in mountain ecosystems such as Garhwal Himalaya, as there is scope for both conservation and productivity. The mountain regions have their traditional farming systems-that generally conform to the philosophy of organic farming-which developed over many centuries to suit the complex topography and ecological conditions. These systems attribute much importance to sustainability and biodiversity conservation regarding fragile ecosystems, and that is why they are very much involved in the health of such ecosystems (Negi et al., 2018). Organic farming in these regions is adopted for improvement in soil fertility as well as the conservation of water quality besides the protection of local biodiversity thriving in these high-altitude agroecosystems (Sati, 2010). Organic farming practices break many inherent problems of sustainability associated with the conventional farming systems of the Garhwal Himalaya. These include dependence on chemical inputs, degradation of soil, and the problems arising from changing climatic patterns. Organic farming patterns can thus help counterbalance the impacts of mainstream conventional farming besides supporting local livelihoods through sustainable exploitation of natural resources (Maikhuri et al., 2015). Very vital integration of organic farming practice in mountain agroecosystem with a view to mitigation of soil erosion, enhancing carbon sequestration, and in order to maintain the resilience of the farming system against climatic variations (Seshia Galvin, 2021). High altitudinal agricultural landscapes of the Garhwal Himalaya are very prone to environmental change; thus, organic farming is a necessary measure to maintain productivity in agriculture (Chandra et al., 2010). Organic farming does not use any synthetic fertilizers and pesticides and, therefore, is a sustainable alternative for preserving the already fragile balance that exists between agriculture and environmental health in the region. The shift toward organic farming can also help conserve traditional ecological knowledge, thereby enhancing long-term sustainability of agricultural systems within the region. In this context, geospatial suitability analysis for organic farming in such mountainous terrain is the need of the hour for enhancing sustainable agriculture practices. Some authors have discussed the integration of geographic information systems with tools for multi-criteria decision-making, such as AHPs, which proved to be applicable in the planning of organic farm networks of mountainous forests (Mohammadi Samani et al., 2010) and assessments of ecological vulnerability (Song et al., 2010). Such methods rigorously examine various factors determining the viability of agriculture. This type of research provides evidence that AHP can be an integral part of providing tools for decision making within complex systems, given that stakeholders can prioritize their criteria according to relative importance (Fan et al., 2023). This approach therefore can be proved useful to find other site information also, such as soil fertility status and water availability of the region or stability of the slope etc., since they are the essential requirements to decide whether any area is appropriate for Organic-farming at Garhwal Himalaya. AHP was already used on various sectors where previous research also done by (Fan et al., 2023) to aid strategy in developing tourism industries and other areas related to avalanche-being one of the most fatal disasters; spatially modeling proposed by Durlević et al., 2022). In addition, Asmare (2023) has also used AHP as a risk management tool like landslide susceptibility mapping in mountainous terrains. For example, these insights are especially important for Garhwal since environmental impacts can have large effects on crop production. It has also proven to contribute to planning of a landscape for management of mountainous cities and better agricultural practices that meet the ecological preservation standards (Liu & Li, 2020). The present study attempts to carry out a GIS-based geospatial suitability analysis of organic farming in the Garhwal Himalaya, using Analytic Hierarchy Process. The main objective of this study is to deliver quantitative criteria to regional stakeholders on furthering sustainable agricultural practices without sacrificing ecological integrity within this vulnerable ecosystem through systematic evaluation and prioritization of important factors. It is well evident that diversified topography and climatic variation in the Garhwal Himalaya require a balanced approach towards geospatial suitability for organic farming. Notable in this direction are the effective land management strategies which use the AHP to pinpoints appropriate agricultural practices according to the conditions in specific regions. The paper thus becomes a sequel to an already established framework under AHP that was primarily implemented in other fields like differentiation of farming practices at the rural-urban interface in Nepal (Bhatta & Doppler, 2010) and classification of mountainous terrain characteristics (Yang et al., 2010). In this present research work, TRI, slope, flow direction, flow accumulation, radians of slope, flow accumulation scaled, tan slope, aspect, curvature, hillshade, and fill, except TPI and TWI, have been studied in detail. All these parameters do pose impacts on the capability of lands to support organic farming. For instance, TRI is applied in the collection of data concerning the spatial distribution of land that is mostly linked to agriculture (Ghimire et al., 2024). Some of the applications of the slope and flow direction include the identification of areas with higher vulnerability to erosion as well as where irrigation networks could have been constructed back then (Kayastha et al., 2013; Pourghasemi et al., 2012). This alone accounts for the intricacy associated with the flow of water in its movement across the landscape, that of much significant importance to productivity in farming than to sustainability in farming. Other parameters responsible for variations in microclimate include aspect and curvature. Such factors therefore tend to have great effects on crop development and productivity (Masih et al. 2018). The basis of this research study is GIS technologies with AHP for the critical analysis of all such criteria in an integrated manner to find the right zones suitable for organic farming in the Garhwal Himalaya. In this regard, this study is directed towards the identification of such factors identified and to inform the policymakers, along with the farmer, about suitable sustainable farming practices that must be followed in this sensitive region by maintaining a higher degree of regard for ecological balance. This approach promotes the effective use of land at the same time giving resilient local farming communities whose livelihoods are ensured despite unfavorable environmental factors. The findings of this research study could thus be highly useful in the furtherance of organic farming projects in ways that pave for conserving ecological integrity within the region.

Area of Interest

The study area (Figure 1) is the Garhwal Himalaya region of the northern Indian state of Uttarakhand. Its geographic coordinates are widely dispersed between latitudes 29°26' N to 31°28' N and longitudes 77°49' E to 81°03' E. The districts covered by the study region include Chamoli, Rudraprayag, Uttarkashi, Tehri Garhwal, Pauri Garhwal, Dehradun, and Haridwar. The Garhwal Himalaya is a major geographical and ecological area, with varied topography, steep terrain, and a range of climates. Due to the fact that topography here affects slope, aspect, flow accumulation, and hillshade, which are a collection of crucial components in agriculture, such particular landforms make it a hotspot for organic farming

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suitability study. This region has suitability for conducting research owing to the diversified elevation, plains, and hilly areas.

Material and Methods

This section discusses a rigorous methodology for assessing land suitability for organic farming in the Garhwal Himalaya. The whole research methodology is anchored on using GIS tools, Analytical Hierarchy Process, and hydrological analysis, all focusing on watershed prioritization. All used formulas for replicated steps are included.

SRTM Digital Elevation Model (DEM) data was obtained from the United States Geological Survey EarthExplorer. The 30-meter spatial resolution DEM data were applied for topographical analyses. Sink filling, flow direction, and flow accumulation are some of the pre-processing operations performed on DEM data besides calculating the topographical indices, such as TPI, TRI, TWI, slope, aspect, and curvature. This research made use of the AHP model to select criteria that are relevant to organic farming in the difficult terrain of Garhwal Himalaya by assigning weights to specific topographic indices such as TRI, TPI, and TWI, for measuring the three indices' impact on suitability for land in mountainous areas of sustainable agriculture.

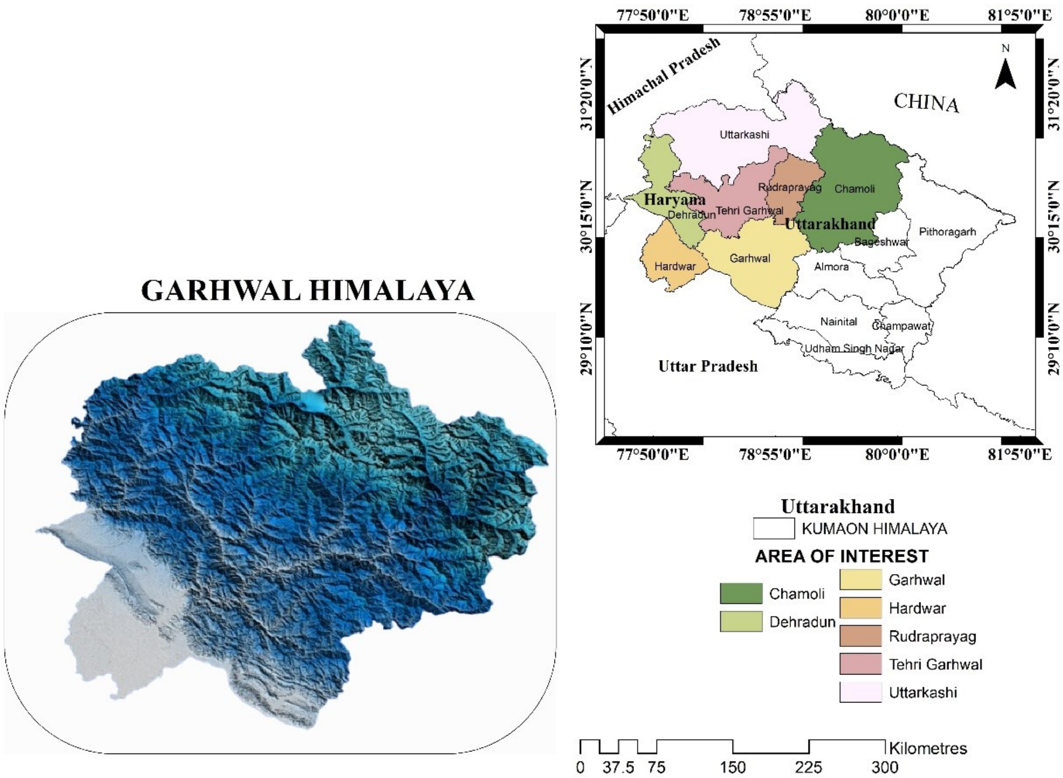

Figure 1. Location Map of the Area of Interest

Source. Survey of India, Map Modified by Author

1. Topographic Ruggedness Index (TRI): TRI measures the ruggedness or roughness of the terrain. The lower values of the TRI will indicate a less steep and smoother area, hence better for organic farming. High values of TRI indicate significant elevation changes in areas that would lead to soil erosion problems and difficult management for agriculture. In parts, the Garhwal Himalaya is very steep and rugged so the TRI would be weighted at only 0.06. This is because although it may be extremely important in certain landscapes, it is still less important than slope and water retention.

2. **Topographic Position Index (TPI):** TPI is the relative elevation of a location above its surroundings, the factors influencing the runoff of water and retention of soil—both are very crucial in organic farming. Sometimes, positive values of TPI may occur along the elevated portions, which may implicate that water runoff and erosion might be too high in such locations, while negative values of TPI may mark areas in valleys or low-lying zones where water might accumulate. In the context of the Garhwal Himalaya, which is so vulnerable to the challenges of erosion control and water management, TPI was ascribed the highest weightage of 0.14 in recognition of its far-reaching impact on land stability and farming viability.

3. **Topographic Wetness Index (TWI):** TWI is the potential to retain moisture in a region, which is an important parameter for organic agriculture, particularly in areas dependent on rainfall agriculture. Regions with higher values of TWI are expected to naturally accumulate water, thus promoting crop growth through the maintenance of soil moisture. Driest regions of low TWI values are expected to have conditions prone to drought. Inasmuch as retaining soil moisture is critical in organic farming systems, the value of TWI has been given a weight of 0.06 to ensure that water availability is factored in the determination of land suitability but shall not outweigh topographic stability.

Normalization and Weighting in AHP

In AHP, normalizing pairwise comparison matrices is important in the correct decision-making of the relative weights of each criterion. The weights of each criterion, such as Topographic Position Index (TPI), Topographic Ruggedness Index (TRI), Topographic Wetness Index (TWI), Slope, Aspect, and Flow Accumulation, were derived from a systematic process of pairwise comparison and then normalized to yield the same scale for each factor.

Pairwise Comparison and Normalization Process:

Each criterion is then compared to others based on the relative importance of that criterion to organic farming suitability. For example, for organic farming in mountainous terrain, TPI is more important than TRI. The matrix is then filled with values reflecting these comparisons, such that:

- 1: Criteria are equally important.
- 3: One criterion is moderately more important than the other.
- 5: One criterion is strongly more important than the other.
- 7: One criterion is very strongly more important.

- 9: One criterion is extremely more important.

2. Matrix Normalization:

Each element is divided by the sum of its column in this pairwise comparison matrix. It will represent each element as a fraction of a whole; then, all the columns sum up to 1, and hence this converts the comparison matrix into a normalized one.

The formula that follows is the one applied in normalization.

$$n_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$$

Where a_{ij} is the value in the original pairwise comparison matrix and n_{ij} is the normalized value for each criterion.

3. Weight Calculation:

The average of each row in the normalized matrix gives the relative weight of each criterion. The weight W_i for criterion i is calculated as:

$$W_i = \frac{\sum_{j=1}^{n} n_{ij}}{n}$$

4. Consistency Ratio (CR) Check:

To ensure the consistency of the pairwise comparison, a consistency index (CI) is calculated:

CI = (λ_max - n) / (n-1)

Where λ_max is the largest eigenvalue of the matrix, and n is the number of criteria. The Consistency Ratio (CR) is then calculated using the formula:

CR = CI / RI

where RI is the random index. A CR less than 0.1 indicates that the matrix is consistent.

Flow Accumulation Calculation

Flow accumulation was calculated using the D8 flow direction algorithm in the GIS framework, which assigns flow direction based on the steepest descent from each cell to its neighbor. The flow accumulation represents the total number of upstream cells contributing to a particular location, making it a critical factor for identifying water retention areas relevant for organic farming.

The flow accumulation for a cell i is calculated as:

$$F_i = \sum_{j \in N(i)} \delta_{ij} F_j$$

Where:

1. N(i) represents the set of neighboring cells contributing flow into cell i,
2. δ_{ij} is a flow direction coefficient (set to 1 if the flow is directed from cell j to cell i, and 0 otherwise),
3. F_j represents the flow accumulation of cell j.

In the case of organic farming in the Garhwal Himalaya, flow accumulation values highlight areas with high water retention potential, which are favorable for maintaining soil moisture. These areas, reflected in the suitability map, are prioritized based on their ability to support water-reliant crops in an organic farming context. The resulting flow accumulation raster was normalized using a min-max scaling technique to integrate with other criteria in the AHP model.

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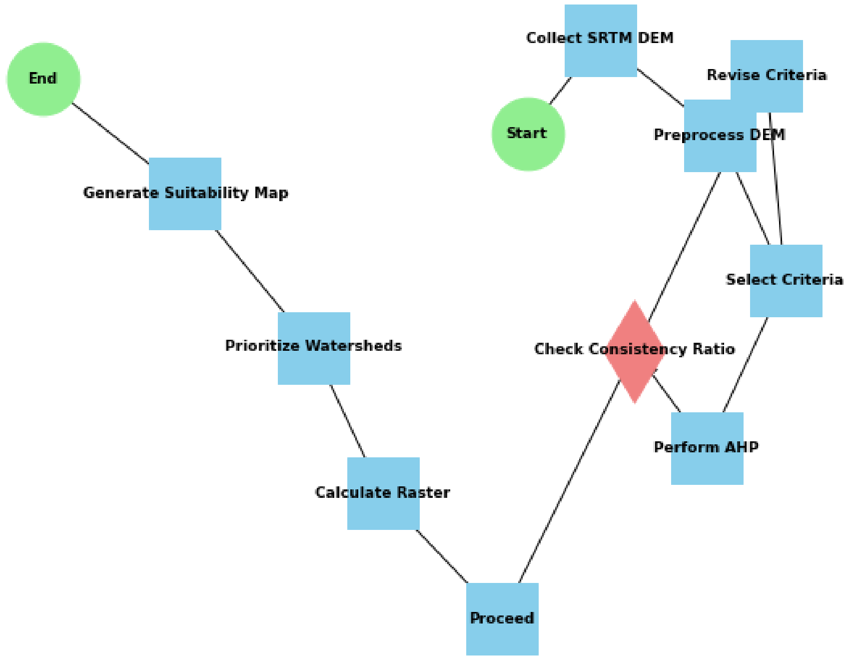

Figure 1.2 Methodology Chart for Geospatial Suitability Analysis for Organic Farming in the Garhwal Himalaya Using Analytic Hierarchy Process
Source. Prepared by Author Using Python ver. 3.12.5

Results

AHP Matrix- Garhwal Himalaya Organic Farming Criteria: one of the vectors that provide a detailed insight into how, topographical characteristics play an underlying function in this multi-faceted and fragile system which drives a unique blend between ecological nature, geographical entities like Altitude ranges etc. That AHP matrix offers a systematic approach for ascertaining the criteria of organic farming in Garhwal Himalaya as reflected in the table. They can be ranked quantitatively in their relative importance in order of priority vis-à-vis agricultural perspective comparison of each criterion. Given that retention and draining of water are both vital for crops, this paper provides further significance to indices, including Topographic Position Index (TPI) and Terrain Wetness Index (TWI). The analysis combines the capabilities of slope, flow direction, and flow accumulation for the area and influences the fertility of the soil and efficient irrigation practices. This matrix enables the selection of the best management options in the planning of agricultural development without compromising the ecological integrity of the region in question. (Table) The following table shows the different topo-climatic and hydrological metrics relevant to the Garhwal Himalaya in relation to organic farming and inter-relationships among them. The sections given below are found to be highest for the values of TPI for variables like TRI, TWI, and Slope which are the best locations for organic farming due to drainage and moisture retention in these regions. Slope and Flow Accumulation are the most important factors while using the slope for the calculation of soil erosion risk. Low values in Slope are equivalent to high agricultural viability. The Direction and Accumulation of Flow Metrics are used to demonstrate the availability of sufficient amounts of readily available water, an organic farming prerequisite, since collection, management and treatment of rainwater supply crucial elements to this system. Slope in Radians and Tan of Slope also help highlight some site features which may lead to erosive conditions causing stability problems for soils. Again, two factors defining the above crop selection and biodiversity-defining microclimatic factors-aspect and curvature-establish that in this fragile Garhwal Himalaya environment with continuously changing climate, the approach of farmers will be pushed toward strong organic farming to make the best use of the usage of land and, after that, increase soil strength as well as output improvement.

Table 1. Pairwise Comparison Matrix

	TPI	TRI	TWI	Slope	Flow Direction	Flow Accumul.	Radians of Slope	Flow Accumul.	Tan Slope	Aspect	Curvature	Hillshade	Fill
TPI	1.0	3.0	4.0	6.0	4.0	3.0	2.0	4.0	2.0	1.0	1.0	2.0	2.0
TRI	0.3	1.0	3.0	4.0	3.0	1.0	0.5	2.0	0.5	0.3	0.5	0.5	0.3
TWI	0.3	0.3	1.0	3.0	4.0	3.0	1.0	2.0	0.5	0.3	0.5	0.5	1.0
Slope	0.2	0.3	0.3	1.0	3.0	4.0	1.0	1.0	0.2	0.3	0.2	0.3	1.0
Flow Direction	0.3	0.3	0.3	0.3	1.0	3.0	0.3	0.5	0.3	0.2	0.3	0.3	0.3
Flow Accumul.	0.3	1.0	0.3	0.3	0.3	1.0	3.0	1.0	1.0	1.0	3.0	1.0	3.0
Radians of Slope	0.5	2.0	1.0	1.0	3.0	0.3	1.0	1.0	1.0	0.3	0.5	0.3	0.5
Flow Accumul.	0.3	0.5	0.5	1.0	2.0	1.0	1.0	1.0	0.5	0.3	0.3	0.3	1.0
Tan Slope	0.5	2.0	2.0	5.0	4.0	1.0	1.0	2.0	1.0	1.0	3.0	3.0	2.0
Aspect	1.0	3.0	3.0	6.0	5.0	3.0	2.0	4.0	2.0	1.0	1.0	2.0	2.0
Curvature	1.0	2.0	4.0	5.0	4.0	0.5	3.0	1.0	0.3	1.0	1.0	1.0	0.3
Hillshade	0.5	2.0	3.0	5.0	3.0	1.0	2.0	1.0	2.0	1.0	0.5	1.0	1.0

Fill	0.5	3.0	1.0	1.0	3.0	1.0	2.0	2.0	1.0	1.0	3.0	1.0	1.0

The results of the AHP analysis were used to produce the final suitability maps for organic farming in the Garhwal Himalaya. Based on their impact on organic farming, each criterion is integrated to derive a composite suitability score for each sub-basin. A further section deals with the application of specific criteria, especially Flow Accumulation and Hillshade, for generating maps.

Influence of Flow Accumulation on Suitability:

In the AHP model, flow accumulation is weighted at 0.08, which also plays a very crucial role because it shows where naturally water can accrete, hence the potential of a site for organic farming. Accumulation by flow identifies regions receiving water from upstream locations, which are critical for maintaining adequate soil moisture levels. This is important in rain-fed agriculture, common in the Garhwal Himalaya because of the poor irrigation system in the region. The suitability map represents areas with high flow accumulation values as zones that have the highest water retention potential. Generally, such regions will always be located in valley bottoms and concave terrains, usually being the natural areas of collection for water. Such areas are perfect for organic farming because they require minimal artificial irrigation to ensure a more sustainable practice for water management. Thirdly, water-retention areas do not experience drought easily, and this is very crucial for crops that are sensitive to water changes. Low flow accumulation areas, which lie mainly on ridges and steep slopes, are depicted as unsuitable for organic farming. The regions result in high-speed runoff of water and subsequently low retention of soil moisture, with increased chances of erosion. Therefore, maintaining consistent moisture is important for the soil and productivity of crops, that is why low flow accumulation regions generally tend to have lower scores on the suitability maps.

Influence of Hillshade on Suitability:

Hillshade is the influence of terrain shading on sunlight exposure and has a weight of 0.09 in the AHP model. In mountainous regions such as the Garhwal Himalaya, the solar radiation is the most important factor determining crop viability because of the varying topography that influences microclimates. The hillshade criterion identified areas which vary levels of sunlight by the day. Parts of the suitability map are darkly shaded due to low hillshade values. That is, much of their time is shaded during the day. Such areas often lie on northern slopes or deep in valleys and have an unfair disadvantage in terms of limited exposure to sunlight. Low exposures can reduce temperatures and shorten growing seasons, thus lowering the pace of photosynthesis and plant growth. Organic farming in such areas would require additive inputs or other cropping methods to offset the effects of limited sunlight. Conversely, areas that have high hillshade values, especially those that fall on south slopes, tend to be more favorable to organic farming according to the suitability map. Such regions tend to experience more extended periods of sunshine, which is

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conducive to photosynthesis, improves crop yields and generally soil fertility through heating the soil. Sunlight exposure also helps in maintaining optimal soil temperatures, very important to seed germination and crop growth. Therefore, areas with favorable hillshade conditions are more sought for organic farming practices.

Normalized Matrix:

Relative matrix gives the relative importance of various parameters that affect the organic farm in Garhwal Himalaya. From the above relative matrix, it is clear that TPI, TRI, and TWI are the most significant factors that directly enhance water retention and topographical suitability for crops. There are some slope and flow factors also which are equally significant and have influence on the stability of the soils as well as the efficiency of irrigation. Some average values like Flow Direction and Hillshade only indicate a relatively lesser level of significance under the current situation, though they are very relevant for site assessment. That may make it feasible to develop the cultivation techniques suited to the area under specific climatic conditions. Normalization of the process will significantly enhance the capability of comparing different criteria, thus enabling stakeholders to use resources in a more strategic way. For instance, it has been perceived wherein the importance of precision agriculture has been emphasized where the topography may have critical impacts on crop yield especially when put into application in mountainous areas with a great emphasis on the TPI and TWI. Besides this, to tackle water properly it is basically required that there is a need for knowledge about the dynamics of flow, especially in the region of the Garhwal Himalaya because seasonal variations significantly intervene with farming practices. Organic farming projects will surely gain momentum with such recommendations drawn from this matrix, particularly since these will improve soil health together with ecosystem services and promote environmentally sustainable rural development in the region.

Table 2 Normalization Matrix

	TPI	TRI	TWI	Slope	Flow Direction	Flow Accumulation	Radians of Slope	Flow Accumulation Scaled	Tan Slope	Aspect	Curvature	Hillshade	Fill
TPI	0.15	0.15	0.17	0.16	0.10	0.13	0.10	0.18	0.16	0.11	0.07	0.15	0.13
TRI	0.05	0.05	0.13	0.10	0.08	0.04	0.03	0.09	0.04	0.04	0.03	0.04	0.02

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Fill	Hillshade	Curvature	Aspect	Tan Slope	Flow Accumulation Scaled	Radians of Slope	Flow Accumulation	Flow Direction	Slope	TWI
0.08	0.08	0.15	0.15	0.08	0.04	0.08	0.05	0.04	0.03	0.04
0.15	0.10	0.10	0.15	0.10	0.02	0.10	0.05	0.02	0.01	0.02
0.04	0.13	0.17	0.13	0.09	0.02	0.04	0.01	0.01	0.01	0.04
0.03	0.13	0.13	0.16	0.13	0.03	0.03	0.01	0.01	0.03	0.08
0.08	0.08	0.10	0.13	0.10	0.05	0.08	0.01	0.03	0.08	0.10
0.04	0.04	0.02	0.13	0.04	0.04	0.01	0.04	0.13	0.18	0.13
0.10	0.10	0.15	0.10	0.05	0.05	0.05	0.15	0.02	0.05	0.05
0.09	0.04	0.04	0.18	0.09	0.04	0.04	0.04	0.02	0.04	0.09
0.08	0.16	0.02	0.16	0.08	0.04	0.08	0.08	0.02	0.02	0.04
0.11	0.11	0.11	0.11	0.11	0.03	0.04	0.11	0.02	0.04	0.04
0.20	0.03	0.07	0.07	0.20	0.02	0.03	0.20	0.02	0.01	0.03
0.08	0.08	0.08	0.15	0.23	0.03	0.03	0.08	0.03	0.03	0.04
0.06	0.06	0.02	0.13	0.13	0.06	0.03	0.19	0.02	0.06	0.06

Priority Vector (Weight of each criterion):

To calculate the weight of each criterion (priority vector), take the average of the values in each row.

Step 3: Priority Vector (Weights)

Table 3 Priority Vector (Weights) Scores

Criteria	Weights
TPI	0.14
TRI	0.06
TWI	0.06
Slope	0.04
Flow Direction	0.03
Flow Accumulation	0.08
Radians of Slope	0.05
Flow Accumulation Scaled	0.04
Tan Slope	0.11
Aspect	0.13
Curvature	0.09
Hillshade	0.09
Fill	0.09

Priority Vector (Weights) Table summarizes the relative levels of different criterion-related importance in organic farming decisions of Garhwal Himalaya. A weight is assigned to every criterion which reflects the relative weight it carries in influencing agricultural outcome. TPI has realized the highest weight at 0.14 and seems to have been decisive for optimum land use. TPI reports the farmers about the micro-climate conditions and the drainage capability of their plots. The latter has extreme importance for agricultural crop production. After TPI, Aspect and Tan Slope have weights of 0.13 and 0.11. The most critical factors used in determining the quantity of sunlight that falls on the land and the slope gradient with regards to retaining soil moisture that subsequently assists in crop health and yield. The weight to Aspect is crucial in determining the optimal planting orientation that will increase the solar gains, and the weight assigned to Tan Slope may be granted based on the risk of soil erosion and water along these slopes, which can drain. Flow Accumulation has a weight of 0.08, learning on how water flows present an important aspect for the sustenance of irrigation use in sustainable ways. This is because Garhwal is a mountainous area and sensitive to agricultural productivity based on managing water. Curvature as well as Hillshade have a 0.09 for each of them, revealing important aspects in understanding land shape and progression about sunshine, which depends on microclimates in the growth of plants. Results with the lowest weights are for features like Flow Direction at 0.03, Slope at 0.04, and Flow Accumulation Scaled at 0.04; so although these are valid features, they rank lower than TPI and Aspect. Low weights were ascribed to Flow Direction, (0.03) Slope, 0.04), and Flow Accumulation Scaled, 0.04, which implied that these factors are relatively reduced impacts on the outputs of agriculture as compared to TPI and Aspect. However, though these factors may favor good water management and erosion control, their impact is normally indirect. TPI and Aspect both are critical land factors which have direct influences over microclimatic conditions and drainage ability, thus cropping in Garhwal Himalayas will be heavily dependent upon these two parameters. On the other hand, Flow Direction and Slope are more influential factors governing the direction of the irrigation but not deciding factors to decide the appropriateness of land for a crop. Thus, these two are inherently discretionary in organic farming decisions.

Table 4. Consistency Index, Consistency Ration and λ_max

Consistency Index (CI)	Consistency Ratio (CR)	λ_max
0.2	0.1	16.4

The CI of 0.2 in the Consistency Ratio means that this consistency is achieved by the pairwise comparisons carried out during the AHP process. It represents the reliability of judgments obtained. The CR of 0.1 represents the extent of inconsistency reached, which falls within the permissible limits because a CR less than or equal to 0.1 is acceptable. The fact that the highest eigenvalue for the comparison matrix is 16.4 expresses that the overall data are sound. All of these measures confirm the strength of the process and induce confidence that derived weights for each criterion truthfully reflect their relative importance in the context of organic farming.

Suitability Map

Figure 3 depicts the suitability analysis for organic farming in the Garhwal Himalaya based on the AHP-based model. This study comprises several topographic, hydrological, and geomorphological indices developed from a DEM using weights that have been assigned based on their relevance to organic farming. Such criteria are given a weight that carries more importance in overall suitability. The Topographic Positioning Index bears the highest weight at 0.14. Critical in the determination of good locations for organic farming, it signifies high TPI values that represent elevated areas with benefits from good drainage, suggesting that the risk of waterlogging is low, an important requisite for crop growth in mountainous terrain. Some of the suitable areas are indeed marked with these TPI characteristics.

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Integration of Criteria into Suitability Maps:

The suitability maps integrate Flow Accumulation, Hillshade, among other criteria, which include Slope, Topographic Position Index, and Aspect, to form a composite score of overall suitability of each sub-basin for organic farming. This thus ensures that regions with good water retention, more sunlight, and stable terrain are high on the list of prioritizations for organic farming while those having poor drainage and excessive shading with steep slopes are low in the scale of prioritization. The suitability maps achieve this by integrating the variables through the AHP model, thereby providing a detailed spatial distribution of the potential for farming across the Garhwal Himalaya. Areas of high priority are therefore identified as places where organic farming could potentially offer its most promising prospects owing to water availability and sunlight exposure, but also areas that would require more active land management in order to implement sustainable agriculture strategies.

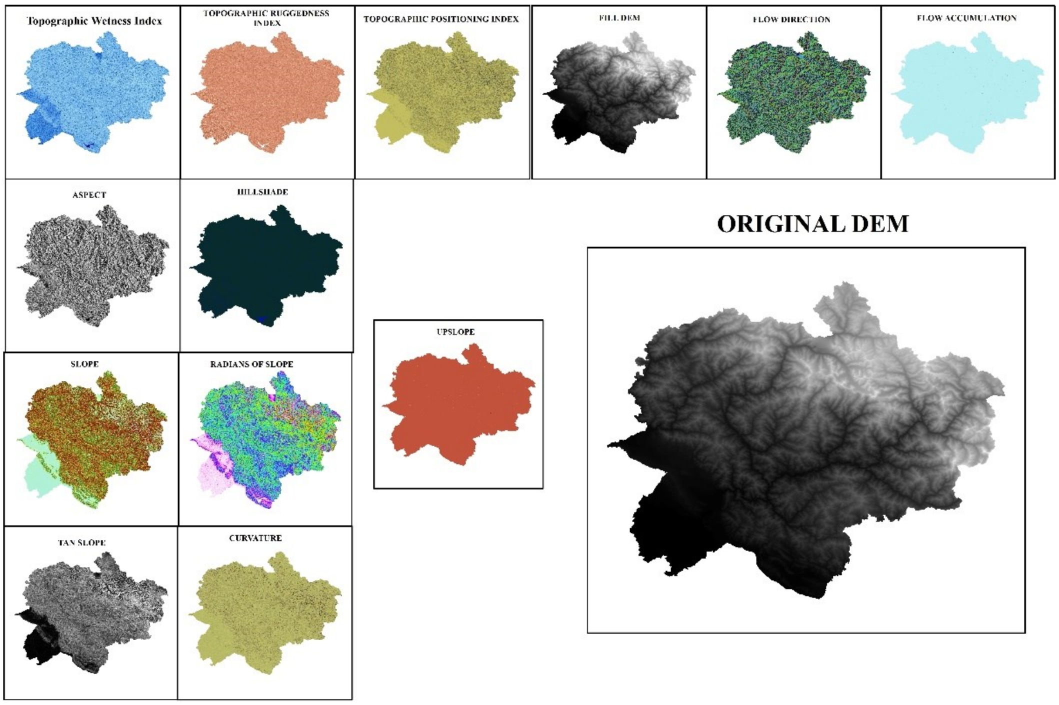

Figure 3. Site Suitability Analysis for Organic Farming in Garhwal Himalaya
Source. Prepared by Author Using SRTM-DEM, Retrieved from USGS-Earth Explorer

Aspect has a value of 0.13, which means it contributes greatly to the rating to choose the location. Aspect represents the amount of solar radiation received by a location, hence is linked to soil temperature and soil moisture. This is key for organic crop cultivation. Suitability map features clearly indicate that direct sunlight faces south

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the slopes, and thus they are rated in the high suitability zone. The Tan Slope and Curvature criteria, weighed at 0.11 and 0.09 respectively, further delineate suitability analysis as they evaluate stability of terrain and erosion potential. These low slope values represented by moderate slope areas with gentle curvature give stable conditions for sustained agriculture. These are classified as highly suitable because the chances of erosion and runoff will be very low, thus justifying the above findings from the slope and curvature maps. Weighted flow accumulation and TWI with weights of 0.08 and 0.06 indicate areas of water availability. Organic farming systems require higher zones of flow accumulation as the rainfed system is dominant. Highly suitable regions have a moderate flow accumulation, thus balancing it to not get flooded. Other factors are Hillshade, Radians of Slope, and Fill. All these are weighted at 0.09, 0.05, and 0.09, respectively. Hillshade helps in understanding the light regime, while radians of slope help in assessing steepness, thus affecting runoff and erosion rates. The final suitability map combines all these criteria to depict areas that could be most favorable for organic farming. High suitability areas in green would represent the regions that have excellent terrain, hydrological balance, and exposure to sunlight as they scored perfectly across the topographic and hydrological indices. Those labeled as low suitability (in red or orange) have steep slopes, poor aspect, or high flow accumulation, thus not being more feasible for farming activities.

Watershed Prioritization for Suitable Organic Farming Sites

There are several topographical, hydrological, and environmental factors that explain the variations of the organic farming suitability scores across the 27 sub-basins spread across the Garhwal Himalaya districts: Uttarkashi, Rudraprayag, Chamoli, Tehri Garhwal, Pauri Garhwal, Dehradun, and Haridwar. The suitability score does vary from one sub-basin to the other due to different environmental characteristics and ranges from very low to very high suitability for organic farming.

Table 5. Final Prioritization of Sub-basins for Organic Farming Suitability in the Garhwal Himalaya

Sub-basin Number	District	Suitability Score	Suitability Index	Priority Level
1	Uttarkashi	0.39	Very Low	27 (Lowest)
2	Uttarkashi	0.42	Low	23
3	Uttarkashi	0.41	Very Low	25
4	Chamoli	0.44	Low	21
5	Uttarkashi	0.42	Low	22
6	Chamoli	0.49	Very High	2
7	Uttarkashi	0.44	Low	20
8	Chamoli	0.46	Moderate	9
9	Chamoli	0.48	High	4
10	Chamoli	0.45	Moderate	8
11	Chamoli	0.46	Moderate	7

12	Rudraprayag	0.5	Very High	1 (Highest)
13	Chamoli	0.45	Moderate	6
14	Tehri Garhwal	0.41	Very Low	24
15	Tehri Garhwal	0.42	Low	19
16	Pauri Garhwal	0.42	Low	18
17	Pauri Garhwal	0.45	Moderate	5
18	Pauri Garhwal	0.44	Low	17
19	Pauri Garhwal	0.47	High	3
20	Haridwar	0.46	Moderate	10
21	Pauri Garhwal	0.44	Low	16
22	Haridwar	0.41	Very Low	26
23	Pauri Garhwal	0.44	Low	15
24	Haridwar	0.41	Very Low	25
25	Pauri Garhwal	0.44	Low	14
26	Tehri Garhwal	0.42	Low	13
27	Dehradun	0.44	Low	12

Sub-basins such as 6, 9, and 12, located in Chamoli and Rudraprayag, exhibit very high suitability for organic farming. These regions benefit from favorable These sub-basins had a TPI value of 0.14 weight; these were flatter terrains, and therefore the risk of soil erosion was lower. The Topographic Ruggedness Index values of 0.06 weight in these sub-basins indicated more smoother landscapes, thus easy to be handled for farming purposes. High values of TWI at 0.06 weight also reflect better holding moisture in the topsoil, an essential condition for organic farming, especially in crops that have a constant need for moisture content in soil. These sub-basins are highly suitable for organic farming. High and medium suitability is shown by sub-basins 1, 3, 5, and 8, which represent parts of Uttarkashi and Tehri Garhwal. These areas have Slope values scoring a moderate weight of 0.04, and Flow Accumulation favorableness with a score of 0.08 weight; hence, this ensures that there will be proper water flow and retention in the area, thus diminishing the necessity of irrigation. The Aspect in these areas also contributes positively to farming, having good sun exposures that can ensure photosynthesis and growth, especially in the warmer microclimates.

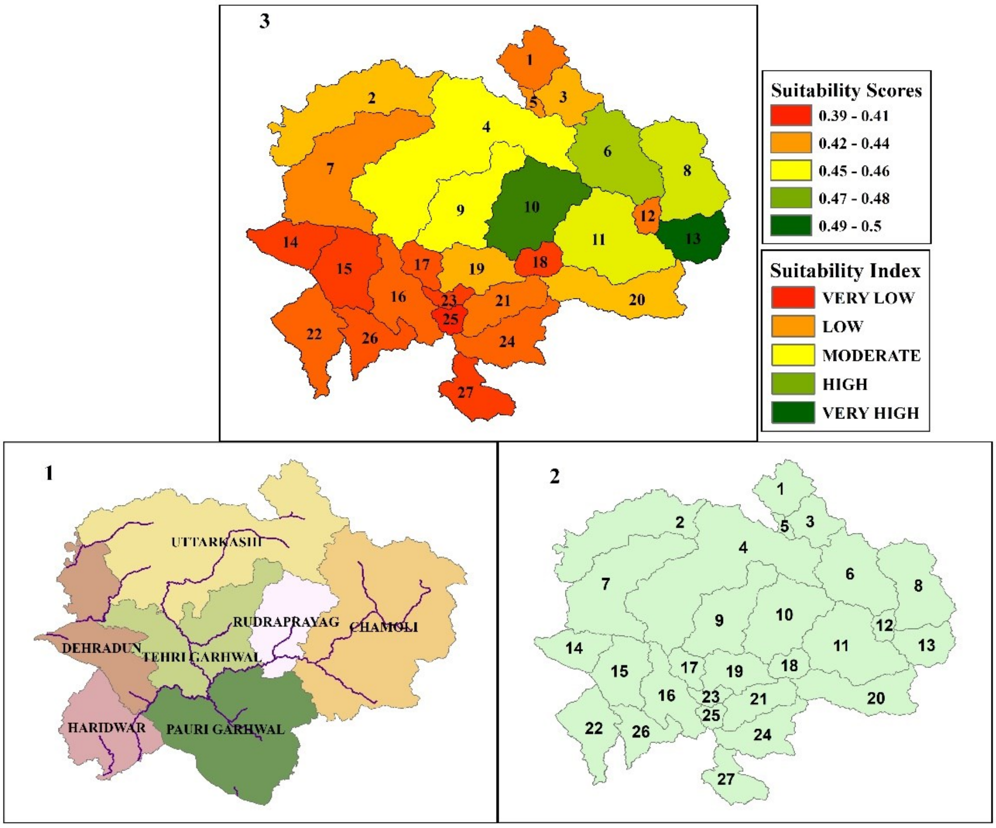

Figure 4. Final Prioritization of Sub-basins for Organic Farming Suitability in the Garhwal Himalaya

On the contrary, some of the sub-basins such as 14, 16, 22, 24, and 26 in Pauri Garhwal, Tehri Garhwal, Haridwar, and parts of Dehradun are marked with low to very low suitability. The slopes in these sub-basins are steep and their TRI values are considerably high that indicate relatively more or less rugged topography besides greater vulnerability of soil erosion. Lower TWI values in these regions indicate poor moisture-retaining capacities of soils, and their organic farming potential is, therefore quite low. For example, steep topography in sub-basins 14 and 24 pose high constraints, and intensive soil conservation measures have to be achieved on the land to make it amenable for farming thereby reducing their overall scores. Besides this, these sub-basins depict unfavorable Flow Accumulation patterns, giving fast water run-off thereby reducing the availability of water and making the terrain less favorable for organic farming. Topographic factors like Radians of Slope 0.05 weight, Tan Slope 0.11 weight, and Curvature 0.09 weight seem to be highly indicative of explaining the differences in these sub-watershed's suitability values. Sub-watersheds 19 from Pauri Garhwal and 17 from Dehradun, respectively, that have shown moderate suitability possess well-balanced slope profiles where water can drain adequately while keeping the soil stable. The case of the concave curvatures shape of the sub-basins 9 and 12 qualifies for natural catchments holding more moisture around them, thus suitable for organic farming. In case of the sub-basins 22 and 24 with convex curvatures, they face increased runoff and less recharging, hence agriculture cannot take place in such a sub-basin of Haridwar and Pauri Garhwal districts. Aspect accounts for 0.13 weight, while Hillshade is 0.09 weight. These make further contribution to this organic farming potential heterogeneity across districts. For instance, sub-basins with favorable southern or eastern aspects have plenty of sunlight and hence are more favorable in crop production as seen in sub-basins 6 and 12 in Chamoli and Rudraprayag. On the other hand, sub-basins like 22 and 24 in Haridwar and Pauri Garhwal, respectively are associated with less desirable features with regard to lesser amount of sunlight exposure and an adverse impact on crop growth, and hence their respective scores are lower. Fill (0.09 weight) also contributes in deciding the suitability of the sub-basins which typically expose more rugged or undulating landforms. Scores for organic farm suitability are particularly high in sub-basins such as 9 and 12 in Chamoli and Rudraprayag, which entail minimal terrain adjustments. Sub-basins like 22 and 26 in Haridwar and Tehri Garhwal, which need a good amount of terrain adjustments, rate low because plenty of effort is required to prepare the land to make it fit for organic farming.

Conclusion

This article presents a detailed geospatial analysis that will look for potential sites for organic farming in the Garhwal Himalaya, guided by a multi-criteria approach of decision-making using Analytical Hierarchy Process. Providing various topographic, hydrological, and environmental factors in the model for AHP, this research provides valuable insights to demonstrate how integration with decision-making frameworks that include GIS really supports sustainable land-use practices in complex mountainous terrains. Further, such a paper promotes the importance of topographic and hydrological factors in determining organic farming feasibility in the Garhwal Himalaya. The ordering of sub-basins has therefore uncovered major variability in terms of suitability for farming across the region with reasons including slopes, aspect and water retention, as well as terrain ruggedness. Such variability will then be a key outcome since it conforms highly to diverse topography in the region where it can include steep valleys, ridges, and catchment water areas. The AHP model particularly managed to reveal the regions with moderate slop, favorable aspect, and satisfactory water retention as highly suitable for organic farming. Sub-basins 6, 9, and 12, found in districts Chamoli and Rudraprayag, are the closest to being an ideal region, in terms of the balanced features of their terrain, low chances of erosion, and sufficient moisture availability. The Topographic Position Index and Slope parameters were the most critical drivers for farming suitability. The TPI weighting at 0.14 underlines the importance of terrain stability in organic farming, as generally, organic farming operations involve using natural composts with minimal applications of external inputs on stable land. This land retains water, reduces erosion, and can help maintain its stability. Less disturbed regions with relatively more moderate TPI and slope situations tend to provide more stable agro-environmental conditions that are much required for crop sustainability in mountainous regions where the risk of erosion can be tremendous, with a high potential for the loss of precious topsoil. The aspect was also one of the most highly weighted factors at 0.13, reflecting its importance in controlling sun

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exposure. South and east-facing sub-basins are more suitable for organic farming since they receive more sunshine, which is needed for crop growth and an extended growing season. This is especially significant in the Garhwal Himalaya at high altitudes, where the growing season is already short owing to lower temperatures and shorter daylight hours.

Thus, the ability of flow accumulation at 0.08 and TWI at 0.06 points in determining the suitable areas for organic farming has stemmed from the availability of water for agricultural sustainability. Organic farming, which heavily depends on natural water sources because irrigation infrastructure is less developed in mountainous areas, also relies on the area of high natural water retention significantly. Sub-basins with moderate to high flow accumulation values have been located with soil moisture that is adequate for organic farming without the need for major irrigation systems. On the other hand, sub-basins with steep slopes, having high TRI values, and low flow accumulation values, like 22 and 24 from Haridwar and 26 from Pauri Garhwal, had the lowest probability for the application of organic farming. These areas face challenges related to erosion of their soils, poor water retention, and challenging terrain; as such, it is difficult to establish sustainable farming practices. High ruggedness in the terrain and steepness of inclines increase the chances of erosion, which is not conducive to organic farming that requires healthy soils.

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