

Crop Suitability Analysis in the Bijnor District, UP, Using Geospatial Tools and Fuzzy Analytical Hierarchy Process

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Abstract Land suitability analysis allows identifying limiting factors for agricultural production and enables decision-makers to formulate efficient agricultural management plans. In the present study, GIS-based multi-criteria decision-making (MCDM) land suitability analysis was carried out for sustainable development of agriculture. Ten variables such as drainage, depth, rainfall, pH, slope, soil texture, distances to a major road and the closest town, and flooding risk were investigated to access cropland suitability in Bijnor. These suitability factors were ranked by Fuzzy analytical hierarchy process and the resulting weights were used to generate suitability map layers. The final suitability maps of major crops were using weighted overlay analysis. The findings revealed that sugarcane, wheat, paddy, and oilseed had largest area under moderately suitable class as land in this category had minor limitations. Alkaline soil reaction, gentle slope and shallow soil depth were the main limiting factors in this category. A fairly remarkable area under each crop selected was also found under marginal suitable category. These areas could be made suitable by modifying land-quality parameters. The methodology adopted and its application procedures can be utilized to evaluate land suitability and to suggest best agricultural practices.

Keywords Crop suitability · Geospatial tools · Suitability factors · Fuzzy analytical hierarchy process · Bijnor

Introduction

Agriculture is the mainstay of Indian economy and source of 17% of the gross domestic product (GDP). Over 58% of the total rural households in India depend on agriculture as their principal means of livelihood [54]. *Bijnor* is one of the agriculturally prosperous Districts of Uttar Pradesh State in India. About 90% of the total reporting area of the district is available for agricultural land use [32]. Continuing land degradation and rapid population growth have put an enormous pressure on available land resource [22, 30, 37, 41]. Thus, management of the land resource is

essential for ensuring food security and agricultural sustainability in the district.

Cropland suitability assessment becomes imperative to determine which type of crop is most appropriate in a limited resource region [8]. Land suitability is defined as “the fitness of a given type of land for specified kind of use” [20]. Sustainable agriculture could only be attained through prior land suitability analysis [4, 6, 15, 19, 25, 34]. The land evaluation process includes the assessment of the land potential for a given type of land use. Reliable and accurate land evaluation analysis also helps in identifying the priority areas and formulation of economically viable, socially acceptable and environmentally sound management for sustainable agricultural development [14, 24, 42].

In land suitability evaluation, two major trends can be outlined: qualitative and quantitative. The difference between the two approaches lies in the level of detail in the technical procedures adopted for physical land evaluation, i.e. it may be simple or detailed. Qualitative approach

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evaluates land on a broader scale depending largely on farmers' experience and intuitive knowledge. The quantitative approach, on the other hand, comprises more detailed technical procedures wherein arithmetical or parametric methods consisting of statistical analysis are applied [46]. The integration of qualitative and quantitative approaches to land evaluation has improved the accuracy/reliability as well as the applicability of the models. Presently, both FAO guidelines and physical land evaluation methods are being used for land suitability assessment [19, 21, 53].

Globally, several studies have been conducted to assess land suitability; Burrough in his study [10] emphasized on the importance of fuzzy methods in land suitability evaluation for growing maize in Kenya. In another study by Ahamed et al. [2], GIS-based fuzzy membership model was used for accessing ground nut suitability. The fuzzy screening was given preference over conventional screening method for analyzing land suitability [33]. A study by Joss et al. [28] utilized fuzzy membership model for accessing hybrid poplar suitability in Canada. Rasheed and Venugopal [45] used agro-ecological characteristics for assessing cropland suitability. Shearer and Xiang [52] assessed land suitability in North Carolina. They identified suitable lands for park land-banking program. Qiu et al. [44] explored the effectiveness of fuzzy evaluation method for analyzing and mapping land suitability/capability while Zhang et al. [58] demonstrated the efficiency of fuzzy and analytical hierarchy process (AHP) for calculating the weights of multiple factors.

Factors influencing land suitability are selected and given weight according to their importance. The weights of these criteria could be determined using several methods such as ideal vector approach, parametric approach, fuzzy logic, AHP, quantitative and statistical algorithm. The AHP given by Saaty [48] is most widely used for land suitability assessment [4, 9, 11, 31, 40, 57]. However, several researchers have demonstrated its limitations in a multi-criteria evaluation [16, 18, 36]. AHP requires an exact numerical value to express the strength of stakeholders' preferences. Such exact pairwise comparison judgments may be inconsistent in many practical situations. Fuzzy analytical hierarchy process (FAHP) on the other hand provides complex algorithms to process uncertain or inaccurate information. FAHP is more reliable as it uses a range of values instead of a crisp value to incorporate decision-maker's uncertainty. FAHP involves the use of fuzzy pairwise comparison matrices for weight derivation.

Geographic Information System (GIS) and multi-criteria decision analysis (MCDA) can be effectively used for agricultural land use planning and management [1, 5, 23, 27, 29, 35, 43, 49, 50]. With the help of GIS, complex raw data can be stored, processed and analyzed at various levels. MCDA combined with GIS helps in making

decisions regarding complex and dynamic agricultural systems.

Sugarcane, paddy, wheat, and oilseeds (mustard and toria) are the main crops grown in the study area. More than half of the available agricultural land in the study area is under sugarcane cultivation. With the advancement in agricultural technology (introduction of high yielding variety of seeds, fertilizers, irrigation, insecticides and pesticides), there has been a tremendous increase in agricultural production and productivity, but at the same time, the land has been exposed to several environmental challenges. Hence, land suitability assessment becomes imperative to meet the human needs and also to ensure long-term agricultural sustainability. This work uses an integrated approach of GIS and MCDA to assess cropland suitability. It is aimed at identifying the area best suitable for a specific crop and the areas where better management is required.

Materials and Methods

Study Area Profile

Bijnor district of Uttar Pradesh state in northern part of India is well known for its agricultural production and productivity. It is located between 29°2' and 29°57' north latitude and 77°59' and 78°56' east longitude in the upper *Ganga* plain. It has five sub-districts (tehsils) and 11 community development blocks (Fig. 1). River *Ganga* serves as an important source for irrigation. It also separates the district from neighboring districts. The population density of the district is 808 inhabitants/km². According to the census of 2011, there has been a population growth of 17.6% during 2001–2011. Out of the total population, 25% lives in urban areas, whereas 75% still reside in rural areas of the district [12]. The economy of the study area is directly dependent on agriculture. Sugarcane having the highest productivity of 641 quintals/hectare is grown in more than 50% of the agricultural area. The other important crops include rice, wheat, mustard, and toria. Out of the total geographical area of 4510 km², net sown area and area sown more than once account for 3959 and 1302 km², respectively [32]. The average annual temperature ranges between 24 and 27 °C. This part of the state receives moderate rainfall ranging between 90 and 140 cm [26]. Typic haplustepts, udic haplusterts, and typic ustipsamments are predominant soils found in the district. About 80% of the total agricultural area of the study area is under irrigation. Tube wells and canals are the main source of irrigation for agricultural purposes.

Soil, climate, and satellite data were collected, and ArcGIS and ERDAS were used to produce corresponding

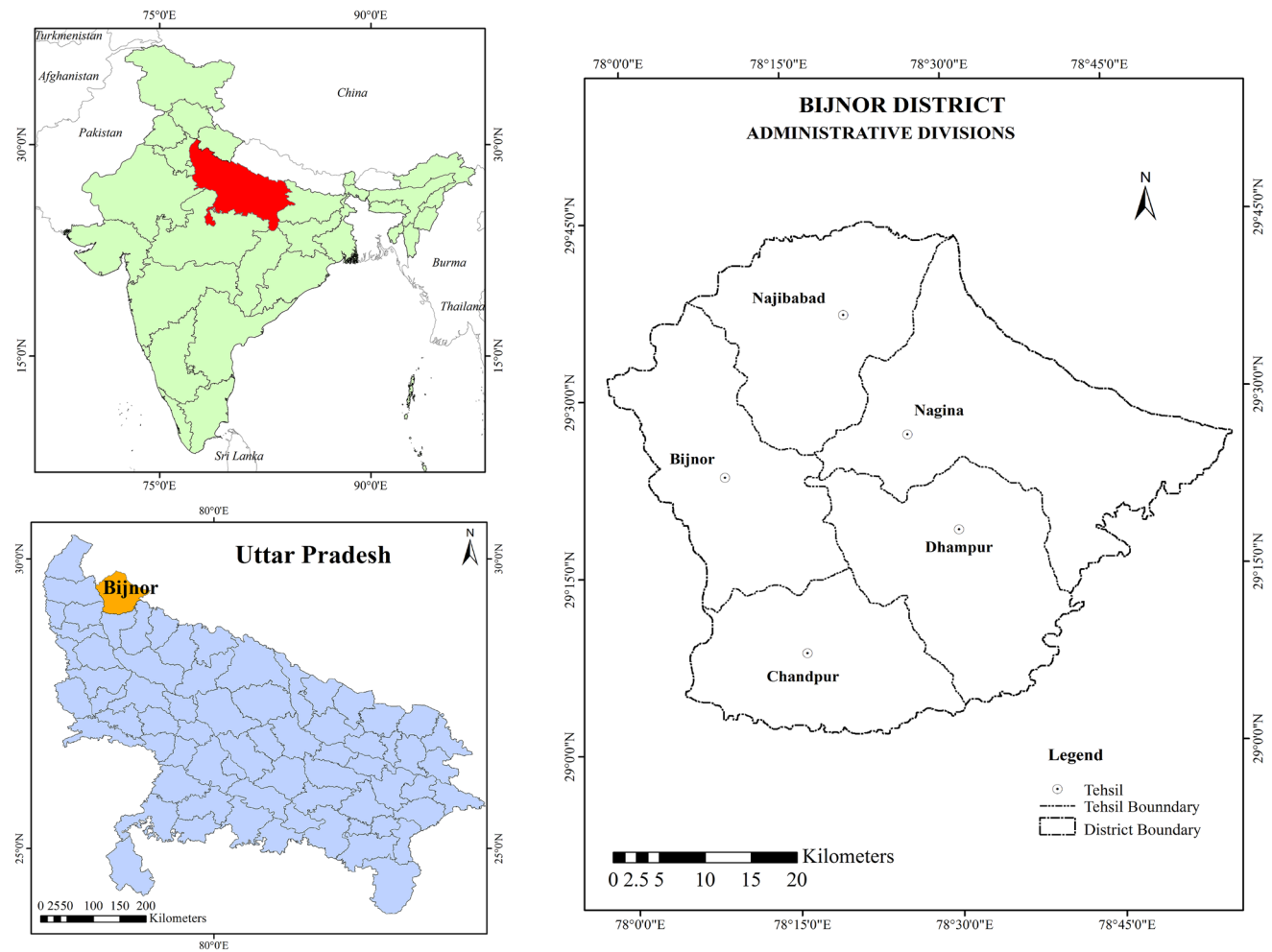


Fig. 1 Map of study area **a** Uttar Pradesh in India, **b** Bijnor in Uttar Pradesh, **c** Administrative divisions of Bijnor

criteria maps. Subsequently, the maps were recategorized according to the FAO land suitability classification. The weight of each criterion was computed using FAHP. The suitability maps were generated through weighted overlay analysis (WOA). Figure 2 shows the flow diagram of the methodology applied.

Criteria Selection

Criteria for evaluating the suitability of agricultural land at various scales have differed in previous studies (Table 1). Through detailed literature review and guidelines on land evaluation, we selected ten site-specific parameters to determine cropland suitability in Bijnor district: drainage density, land slope, soil texture, soil depth, pH, rainfall, distances to major road and the nearest town, and flooding risk. GIS raster datasets on each of these indicators were acquired and processed from several sources for the study area. Table 2 presents the data sources used in the study.

The slope layer was derived using data from the Cartosat-1 digital elevation model [7]. Soil characteristics (e.g., pH, depth, and texture), which primarily determine the suitability of land for agriculture, were selected and corresponding maps were generated using data obtained from Ministry of Agriculture and Farmers Welfare, Bijnor [39]. The point data pertaining to these criteria were converted to spatial layer through kriging, which is a geostatistical interpolation technique. Spatial proximity to the closest town and roads markedly influence cost efficiency, which then affects the decisions of farmers. Therefore, spatial proximity to major road and nearest town was selected as important factors affecting crop suitability. Respective maps were generated by line buffer and point buffer feature in ArcGIS software. Drainage density map was produced using the Survey of India (SOI) toposheet on 1:50,000 scale. Rainfall map for the study area was extracted using IMD's rainfall map of Uttar Pradesh state [26]. Criteria maps for flooding risk and erosion hazard were produced through digitization of maps prepared by

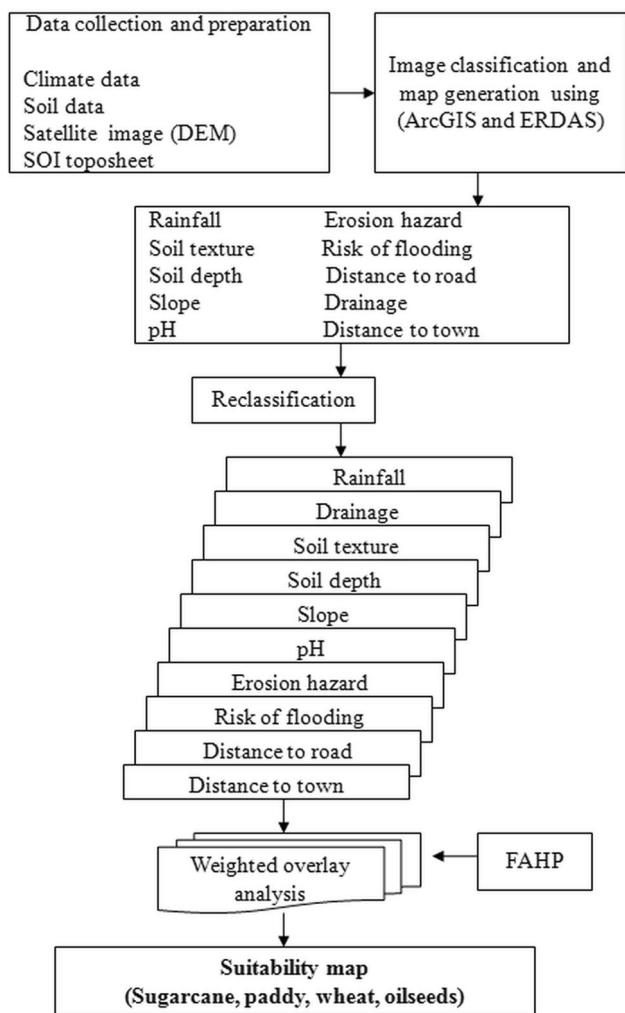


Fig. 2 Flowchart of the methodology of integrated GIS-MCDA for cropland suitability analysis

National Bureau of Soil Survey and Land Use Planning [47]. The available maps were georeferenced and area of interest was extracted; subsequently vector layers were generated by on-screen digitization. These criteria vector layers were rasterized through conversion tool in ArcGIS. The criteria maps are shown in Figs. 3, 4 and 5.

Standardization of Criteria Layers

Water bodies, built-up area, and areas that cannot be reclaimed even after constraint removal were excluded from the classification because they may be unavailable for agricultural use (Table 3). All the criteria considered for cropland suitability analysis were standardized based on the soil classification and characterization guide for agricultural suitability by FAO [51], and other guidelines defining natural and artificial constraints for agriculture suitability [55, 56]. Further, land was categorized by

assigning a score on a scale of 1–5 in an increasing order of suitability (5 = highly suitable (S_1), 4 = moderately suitable (S_2), 3 = marginally suitable (S_3), 2 = currently unsuitable ($N1$), and 1 = permanently unsuitable ($N2$). The ranking system was assigned by following Yalew et al. [57]. For the WOA, the criteria layers were standardized following the FAO land suitability classification. Table 4 presents the standardization criteria used for the suitability assessment of different crops.

Weight Derivation

The FAHP transforms judgments from crisp to fuzzy, thereby allowing the decision-maker to eliminate ambiguous criteria parameters [3, 38]. According to how each criterion affects another criterion, triangular fuzzy numbers (TFN) were assigned to the criteria selected for suitability assessment. The highest TFN value was considered as very strongly important (VSI—2, 2.5, 3), the second highest value was considered as strongly important (SI—1.5, 2, 2.5), and the lowest value was considered as weakly important (WI—1, 1.5, 2). If both parameters exhibited an equal influence, they were considered as just equal (JE—1, 1, 1). To generate criterion weights, the TFN were applied in a pairwise comparison matrix in the FAHP (Table 5). Values of each criterion through extent analysis can be presented as follows:

$$g_i = X_{gi}^1, X_{gi}^2, X_{gi}^3, X_{gi}^4, \dots, X_{gi}^n,$$

where g_i ($i = 1, 2, 3, 4, \dots, n$) is the goal set for each criterion. All values of X_{gi}^j are triangular fuzzy number ($j = 1, 2, 3, 4, \dots, m$). The step-wise description of FAHP as given by Chang [13] is given below: Fuzzy synthetic extent value (S_1) is expressed as:

$$S_1 = \sum_{j=1}^m X_{gi}^j \otimes \left[\sum_{i=1}^n \sum_{j=1}^m X_{gi}^j \right]^{-1}. \tag{1}$$

It involves calculation of

$$\sum_{j=1}^m X_{gi}^j. \tag{2}$$

Through Fuzzy addition operation, X extent value of particular matrix is obtained as expressed in the following equation. The new set is obtained for further use, i.e. (a, b, u).

$$\sum_{j=1}^m X_{gi}^j = \left(\sum_{j=1}^m a_j, \sum_{j=1}^m b_j, \sum_{j=1}^m c_j \right), \tag{3}$$

where a is lower limit value, b is middle limit value and c represents upper limit value. From the set of a, b and c we obtain the following equation:

Table 1 Criteria considered for agricultural suitability

S.N	Author	Study area	Factors considered for agricultural suitability evaluation	Technique/method
1	Bojorquez-Tapia et al. (2001)	Costa Norte	Soil type, distance to major road, flooding	Geographic resource analysis support system (GRASS)
2	Kumar et al. (2010)	Punjab (India)	Soil characteristics, topography and erosion hazard	Soil productivity Index; FAO framework
3	Mendas and Delali (2012)	Mleta (Algeria)	Agronomic and socio-economic factors	ELECTRE Tri method
4	Abdel Kawy and Abou El-Magd (2013)	Farafra Oasis (Egypt)	Climate; geomorphology; geology; water resources, and; natural vegetation	Automated land evaluation system (ALES)
5	Olaniyi et al. (2015)	Malaysia	Soil physical units, bio-physical, social and economic variables	AHP
6	Zhang et al. (2015)	China	Climatic condition, soil nutrients and topography	AHP
7	Romano et al. (2015)	Southern Italy	Slope gradient and aspect, distance from (road, coastline, urban dwellings, stream, and industrial area) and land use	AHP; Boolean overlay; weighted linear combination (WLC); ordered weighted averaging (OWA)
8	Zabihi et al. (2015)	Ramsar (Iran)	Altitude, aspect, distance to road, Climatic condition, population	Analytical network process (ANP)
9	Yalew et al. (2016)	Abbay basin (Ethiopia)	Soil properties, slope, elevation, proximity to water, roads and towns	AHP; modified FAO framework
10	Rahaman and Hedge (2016)	Karnataka (India)	Climate, topography, Soil characteristics, land use	FAO; U.S Soil conservation service

Table 2 Data Sources

Data sources	Specification	Method	Maps Generated
Cartoset-1	2.5 m resolution	DEM	Slope
LISS III	23.5 resolution	Supervised classification	LULC
Soil texture (Soil Testing Lab, Ministry of Agriculture and Cooperation and Farmers Welfare)	1 sample/hectare	Interpolation (Kriging) A total of 550 data points were used	pH, Soil dept and soil texture
SOI (Toposheet)	1:50,000 scale	Proximity analysis	Drainage density, spatial proximity to major roads and closest town
IMD	1:50,000 scale	On screen digitization	Rainfall map
NBSS-LUP	1:50,000 scale	Geo-referencing/on screen digitization	Erosion and flood hazard

$$\left[\sum_{i=1}^n \sum_{j=1}^m X_{gi}^j \right]^{-1} \quad (4)$$

Further operation on fuzzy value for X_{gi}^j ($j = 1, 2, 3, 4, \dots, m$) is performed, the inverse vector is computed as:

$$\sum_{i=1}^n \sum_{j=1}^m X_{gi}^j = \left(\sum_{j=1}^m a_j, \sum_{j=1}^m b_j, \sum_{j=1}^m c_j \right) \quad (5)$$

The inverse vector of convex fuzzy number is calculated as:

$$\left[\sum_{i=1}^n \sum_{j=1}^m X_{gi}^j \right]^{-1} = \left[1 / \sum_{i=1}^n c_i, 1 / \sum_{i=1}^n b_i, 1 / \sum_{i=1}^n a_i \right] \quad (6)$$

The degree of possibility for $X_1 \geq X_2$ can be calculated as:

$$V(X_1 \geq X_2) = \sup_{x \geq y} [\min(\mu_{X_1}(x), \mu_{X_2}(y))], \quad (7)$$

where x and y are the membership function value of each criterion. Since X_1 and X_2 are convex fuzzy numbers we have

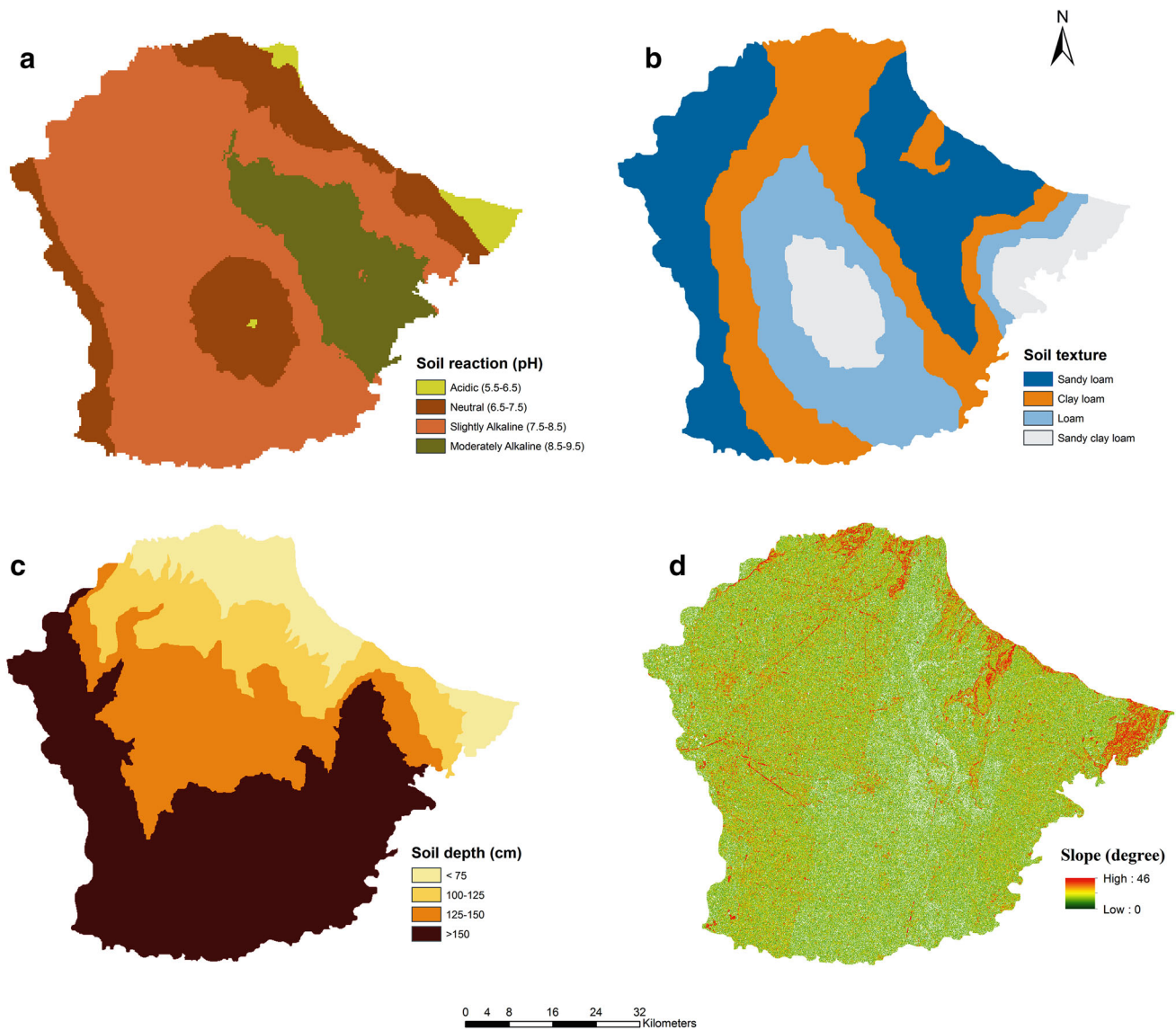


Fig. 3 Criterion layers: **a** soil reaction (pH), **b** soil texture, **c** soil depth, **d** slope

$$\begin{aligned}
 V(X_1 \geq X_2) &= 1, \\
 V(X_2 \geq X_1) &= hgt(X_1 \cap X_2) = \mu_{b_1}(d),
 \end{aligned}
 \tag{8}$$

where d is the highest intersection point between (μ_{X_1}) and (μ_{X_2}) .

When $X_1 = (a_1, b_1, c_1)$ and $X_2 = (a_2, b_2, c_2)$, the ordination of d is expressed as below:

$$V(X_2 \geq X_1) = hgt(X_1 \uparrow X_2) = \frac{a_1 - c_2}{(b_2 - c_2) - (b_1 - a_1)}.
 \tag{9}$$

The convex fuzzy number and its degree of possibility to be greater than k convex fuzzy number X_1 ($i = 1, 2, 3, 4, \dots, k$) can be expressed by:

$$\begin{aligned}
 V(X \geq X_1, X_2, \dots, X_k) &= V[(X \geq X_1) \text{ and } (X \geq X_2) \text{ and } \dots \text{ and } (X \geq X_k)] \\
 &= \min V(X \geq X_i), i = 1, 2, 3, \dots, k.
 \end{aligned}$$

Equation (10) is supported by:

$$d(A_1) = \min V(S_i \geq S_k),$$

where $k = 1, 2, 3, \dots, n; k \neq i$.

The weight vectors are expressed as

$$W_1 = [d(A_1), d(A_2), d(A_3), \dots, d(A_n)]^T, \tag{11}$$

where $A_i (i = 1, 2, 3, \dots, n)$.

The following equation expresses the process of normalization for weight vectors,

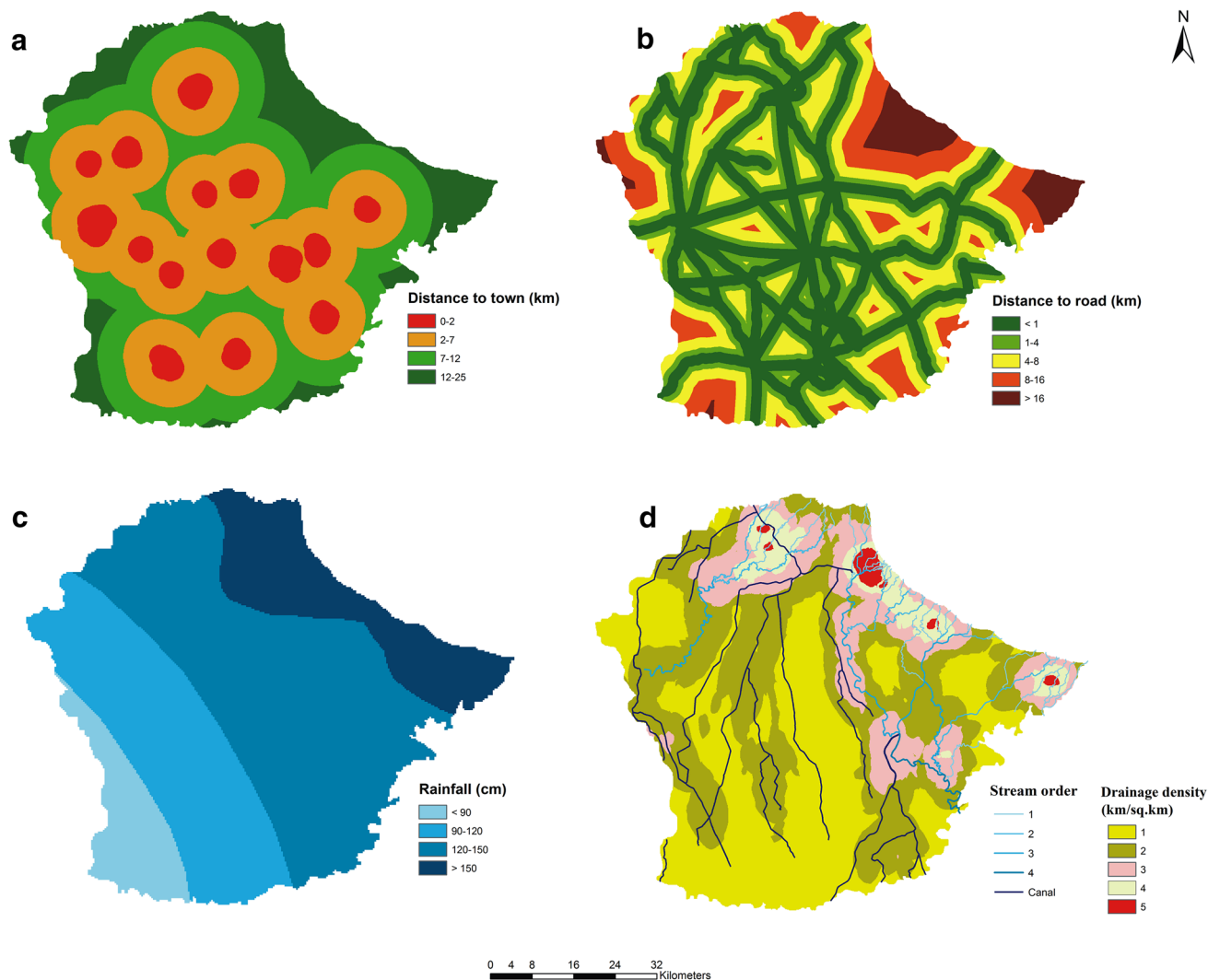


Fig. 4 Criterion layers: **a** distance to closest town, **b** distance to road, **c** rainfall, **d** drainage density

$$W = [d(A_1), d(A_2), d(A_3), \dots, d(A_n)]^T. \quad (12)$$

Weighted Overlay Analysis

Land suitability in an ArcGIS environment includes analysis of several criteria layers. After standardizing and calculating the weight of each criterion using the FAHP, the WOA was performed. Each criteria raster layer was assigned a weight in the suitability analysis. The dissimilar weighted layers were reclassified into a common suitability scale ranging from 1 to 5. These layers were then overlaid where the product of each sub-criteria layer and the weight assigned to each criterion were calculated and a summation of the products was used to obtain the final suitability map (Eq. 13). Assigning a weight to each raster layer in the overlay process allows controlling the influence of different criteria in the suitability model.

$$S = \sum_{i=1}^n W_i X_i, \quad (13)$$

where S represents suitability index for each map pixel, W_i is the weight of the i th criteria layer, X_i is the sub-criteria score of the i th criteria layer, and n is the number of suitability layers [17]. The analysis was carried out using weighted overlay tool in ArcGIS.

Results and Discussion

Agricultural land was evaluated for assessing its suitability for growing different crops. Suitability maps of selected crops were generated by integrating the criteria layers with their respective weights obtained through WOA. Out of the total area of the district (4510 km²), 88% of area (3959 km²) was available for agricultural land use and

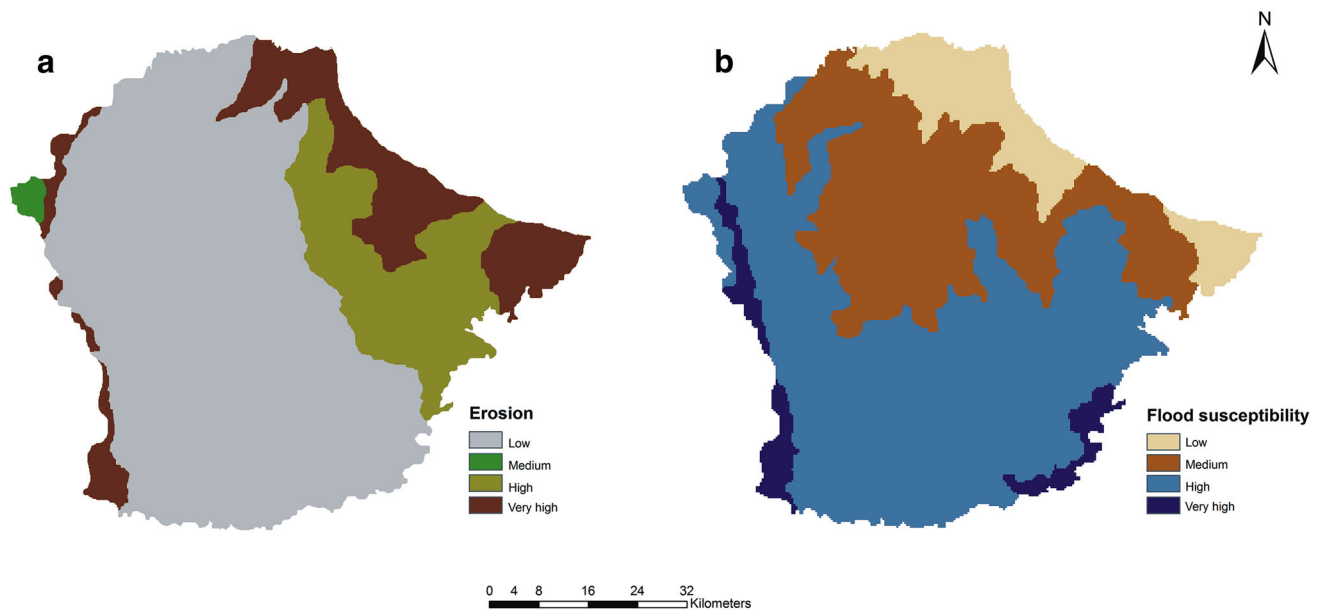


Fig. 5 Criterion layers: **a** erosion, **b** flood susceptibility

Table 3 Showing agricultural, unsuitable and unavailable land

Class	Area (ha)	Percentage to total area
Agricultural area	363,020.7	80.48
Unsuitable	32,930.6	7.30
Unavailable*	55,106.7	12.22
Total	451,058	100

*This includes built-up area and water bodies

remaining 12% of area (551 km²) including build-up, water bodies and land which cannot be recovered by expelling limitations was considered as unavailable hence it was excluded from the suitability analysis. The suitability classes were divided into five categories as shown in Table 6.

Suitability of Crops

In this section, suitability of crops grown in the study area was assessed. Sugarcane and rice were the major crops grown during the summer season while wheat and oilseeds (mustard and toria) were grown during the winter season.

Sugarcane (Saccharum officinarum)

The productivity of sugarcane, which is extensively grown in the study area, was the highest among all cultivated crops. The results revealed that 10.1% (39,633 ha) of the agricultural area under sugarcane cultivation was highly suitable, 50% (1,95,891 ha) was moderately suitable, 25%

(99,138 ha) was marginally suitable, 10.4% (40,990 ha) was currently unsuitable, and 5% (20,700 ha) was permanently unsuitable. Sub-district-wise variation in land suitability for sugarcane cultivation is presented in Table 7 and Fig. 6. Largest area under highly suitable category was found in Dhampur (29%) followed by Chandpur (15%), Bijnor (7%), and Nagina (2%). High suitability of the area in all the aforementioned sub-districts is attributable to favorable soil characteristics, good road connectivity, and closeness to town. The largest area under the moderately suitable category for sugarcane cultivation was found in Bijnor (70%) followed by Chandpur (57%), Dhampur (45%), Nagina (44%), and Najibabad (35%). These sub-districts have stiff slopes with moderate soil depth and acidic soil reaction. Soil erosion, which results in nutrient loss from the topmost layer of the soil, is also observed in these areas. Najibabad has the largest area (40%) under marginally suitable class followed by Nagina (34%), Chandpur (21%), Bijnor (14%), and Dhampur (12%). These sub-districts are categorized by moderate slopes (5–8 degrees), shallow soil depth (< 70 cm), low content of soil nutrients, and high erosional activities. These regions include the peripheral areas of the district and are located far away from major roads and town. The resulting high transportation cost will minimize the farmers' profit; therefore, land in these areas is marginally suitable for sugarcane cultivation. The transportation cost incurred by farmers' is shown in Table 8. Najibabad has the largest area (19%) under currently unsuitable followed by Dhampur (14%), Nagina (10%), Chandpur (7%), and Bijnor (2%). These areas have an extreme slope (25–35 degrees) with prominent soil erosion, acidic soil, and low soil

Table 4 Standardization criteria used for crop suitability

Soil and land quality	Suitability class	Sugarcane	Paddy	Wheat	Oilseed
Rainfall (cm)	<i>S1</i>	140–160	160 >	80–100	80–100
	<i>S2</i>	120–140	140–160	100–110	100–110
	<i>S3</i>	100–120	120–140	110–120	110–120
	<i>N1</i>	80–100	100–120	120–130	120–130
	<i>N2</i>	> 80/< 160	> 100	< 130	< 130
Soil drainage	<i>S1</i>	Well drained	Imperfect to poor	Well drained	Well drained
	<i>S2</i>	Moderately drained	Moderately drained	Moderately drained	Moderately drained
	<i>S3</i>	Imperfect	Well drained	Imperfect	Imperfect
	<i>N1</i>	poor	Somewhat excessive	poor	poor
	<i>N2</i>	Very poor	excessive	Very poor	Very poor
Soil texture	<i>S1</i>	Clay loam	Clay loam	Loam	Sandy loam
	<i>S2</i>	Sandy clay loam	Sandy loam	Clay loam	Clay loam
	<i>S3</i>	Sandy clay	Sandy clay loam	Sandy loam	loam
	<i>N1</i>	Clay	Coarse sandy loam	Loamy sand	Sandy clay
	<i>N2</i>	Sandy	Sandy	fragmental	sandy
Soil depth	<i>S1</i>	Very deep	Deep	Very deep	Deep
	<i>S2</i>	Deep	Moderately deep	Deep	Moderately deep
	<i>S3</i>	Moderately deep	Moderately shallow	Moderately deep	Moderately shallow
	<i>N1</i>	shallow	Shallow	shallow	Shallow
	<i>N2</i>	Very shallow	Very shallow	Very shallow	Very shallow
pH	<i>S1</i>	Slightly acidic	Slightly acidic	Slightly alkaline	Alkaline
	<i>S2</i>	Neutral	Neutral	Moderately alkaline	Moderately alkaline
	<i>S3</i>	Slightly alkaline	Slightly alkaline	Alkaline	Slight alkaline
	<i>N1</i>	Alkaline	Alkaline	Neutral	neutral
	<i>N2</i>	Too alkaline/acidic	Too alkaline/acidic	Acidic	Acidic
Slope	<i>S1</i>	level	level	Flat to level	Nearly level
	<i>S2</i>	Very gentle	Very gentle	Gentle	Gentle
	<i>S3</i>	Gentle	Gentle	Moderate	Moderate
	<i>N1</i>	moderate	moderate	Steep	Steep
	<i>N2</i>	Steep	Steep	Very steep	Very steep
Erosion hazard	<i>S1</i>	None	None	Very low	Very low
	<i>S2</i>	Low	Low	Low	Low
	<i>S3</i>	Moderate	Moderate	Moderate	Moderate
	<i>N1</i>	High	High	High	High
	<i>N2</i>	Very high	Very high	Very high	Very high
Risk of flooding	<i>S1</i>	None	Very low	Very low	None
	<i>S2</i>	Low	Moderate	low	Low
	<i>S3</i>	Moderate	High	Moderate	Moderate
	<i>N1</i>	High	Very high	High	High
	<i>N2</i>	Very high	Severe	Severe	Very high
Distance to road (km)	<i>S1</i>	0–2	1–4	1–4	1–4
	<i>S2</i>	2–4	4–8	4–8	4–8
	<i>S3</i>	4–8	8–12	8–12	8–12
	<i>N1</i>	8–15	12–15	12–15	12–15
	<i>N2</i>	< 15	< 15	< 15	< 15
Distance to market (km)	<i>S1</i>	0–5	0–5	0–5	0–5
	<i>S2</i>	5–10	5–10	5–10	5–10
	<i>S3</i>	10–15	10–15	10–15	10–15
	<i>N1</i>	15–20	15–20	15–20	15–20
	<i>N2</i>	<20	<20	<20	<20

Table 5 Pairwise matrix of crop suitability parameters

	Rainfall	Drainage	Soil texture	Soil depth	PH	Slope	Erosion hazard	Risk of flooding	Distance to road	Distance to town	Wc
Rainfall	(1,1,1) (0.33,0.4,0.5)	(2,2,5,3)	(1,1,5,2)	(1,1,5,2)	(1,1,5,2)	(1,1,5,2)	(2,2,5,3)	(2,2,5,3)	(1,1,5,2)	(1,1,5,2)	0.17
Drainage	(0.33,0.4,0.5)	(1,1,1) (0.5,0.66,1)	(1,1,5,2)	(1,1,5,2)	(1,1,5,2)	(0.5,0.66,1)	(2,2,5,3)	(1,5,2,2,5)	(1,1,5,2)	(1,1,5,2)	0.14
Soil texture	(0.5,0.66,1)	(0.5,0.66,1)	(1,1,1) (1,5,2,2,5)	(0.4,0.5,0.66)	(1,1,5,2)	(0.4,0.5,0.66)	(1,1,5,2)	(1,5,2,2,5)	(1,1,5,2)	(1,1,5,2)	0.11
Soil depth	(0.5,0.66,1)	(0.5,0.66,1)	(1,5,2,2,5)	(1,1,1) (0.5,0.66,1)	(1,1,5,2)	(0.33, 0.4,0.5)	(0.33, 0.4,0.5)	(1,1,5,2)	(1,1,5,2)	(1,1,5,2)	0.10
pH	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(1,1,1) (1,1,5,2)	(0.5,0.66,1)	(1,1,5,2)	(1,1,5,2)	(1,1,5,2)	(1,1,5,2)	0.9
Slope	(0.4,0.5,0.66)	(1,1,5,2)	(1,5,2,2,5)	(2,2,5,3)	(1,1,5,2)	(1,1,1) (2,2,5,3)	(0.33,0.4,0.5)	(2,2,5,3)	(1,1,5,2)	(1,1,5,2)	0.15
Erosion hazard	(0.33,0.4,0.5)	(0.33,0.4,0.5)	(0.5,0.66,1)	(2,2,5,3)	(0.5,0.66,1)	(2,2,5,3)	(1,1,1) (0.5,0.66,1)	(1,1,5,2)	(1,1,5,2)	(1,1,5,2)	0.12
Risk of flooding	(0.33,0.4,0.5)	(0.4,0.5,0.66)	(0.4,0.5,0.66)	(0.5,0.66,1)	(0.5,0.66,1)	(0.33, 0.4,0.5)	(0.5,0.66,1)	(1,1,1) (0.4,0.5,0.66)	(1,5,2,2,5)	(1,1,5,2)	0.05
Distance to road	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.4,0.5,0.66)	(1,1,1) (0.5,0.66,1)	(1,1,5,2)	0.04
Distance to town	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(1,1,1) (0.5,0.66,1)	0.03

Bold indicates equal importance of the parameters

depth. Very steep slopes (35–45 degrees) along with higher erosion susceptibility have led to land degradation and thus made the land currently unsuitable for cultivating sugarcane. Nagina has the largest permanently unsuitable area (9%) for sugarcane cultivation followed by Bijnor (8%) and Najibabad (6%). Most of this area was found along the river Ganga and in the upper reaches of the district. Permanently unsuitable areas were not found in Chandpur and Dhampur.

Wheat (Triticum aestivum)

The results reveal that 20% (78,475 ha) of agricultural area under wheat cultivation was highly suitable, 43% (1,71,148 ha) was moderately suitable, 22% (86,510 ha) was marginally suitable, 14% (56,231 ha) was currently unsuitable and only 1% (4005 ha) was permanently unsuitable. The sub-district-wise variation among suitability classes for wheat cultivation is shown in Table 9 and Fig. 7. Chandpur (41%) has the largest area under highly suitable category followed by Dhampur (34%), Bijnor (23%), Nagina (8%) and Najibabad (0.4%). Chandpur, Dhampur, and Bijnor have plain and gentle sloping (3–5 degrees) areas with loam and clay loam textured soil. Loam and clay loam are considered best for wheat cultivation. Moderate slope (5–8 degrees) and sandy textured soils were the limiting factors in Nagina and Najibabad, thus these two sub-districts have less area under highly suitable class. Largest area under moderate suitability class was found in Bijnor (62%) followed by Dhampur (56%), Chandpur (47%), Najibabad (32%) and Nagina (27%). The land in this category had higher annual rainfall and moderate to severe risk of erosion. Najibabad has the largest area (42%) under marginally suitable category followed by Nagina (28%) and Bijnor (14%), Chandpur and Dhampur, each of which have about 11% area under this category. These lands are characterized by moderately shallow soil depth and less organic content. Nagina and Najibabad were the only sub-districts having an area under the currently unsuitable category. Nagina (36%) had the largest area followed by Najibabad (22%). The permanently unsuitable area was found only in Najibabad (4%) and Nagina (1%). These two sub-districts are characterized by shallow soil depth and very high erosional activity.

Paddy (Oryza sativa)

The results show that 24% (93,321 ha) of the agricultural area was highly suitable, 36% (1,41,714 ha) was marginally suitable, 28% (1,11,698 ha) was moderately suitable, 8% (33,276 ha) was currently unsuitable and 4% (16,341 ha) was permanently unsuitable for rice

Table 6 Land Suitability classification categories. *Source:* FAO

Class	Suitability	Description
S1	High	No or minor constrains for particular land use
S2	Moderate	Land having imitation which reduces productivity or profitability thus increases required input
S3	Marginal	Serious restrictions for specific use
N1	Currently unsuitable	Extreme restrictions which might be amended in time with existing knowledge within satisfactory cost limits
N2	Permanently unsuitable	Land with unmanageable impediments where there is no probability of maintained utilization of land

Table 7 Variation in land suitability classes for sugarcane cultivation in Bijnor (area in hectares)

Class	Bijnor	%	Chandpur	%	Dhampur	%	Nagina	%	Najibabad	%	district	%
S1	5035.2	6.9	9048.2	14.8	22,963.5	29.1	2533.2	2.2	0.0	0.0	39,633.1	10.1
S2	50,764.8	69.6	35,209.2	57.5	35,639.2	45.2	49,865.5	43.9	24,196.3	34.9	195,891.2	49.5
S3	10,205.3	14.0	12,718.4	20.8	9121.3	11.6	38,971.0	34.3	28,041.0	40.4	99,137.6	25.0
N1	1167.4	1.6	4281.2	7.0	11,093.5	14.1	11,357.8	10.0	13,057.3	18.8	40,989.9	10.4
N2	5771.9	7.9	–	–	–	–	10,822.4	9.5	4087.8	5.9	20,699.5	5.2
U*	14,251.3	–	9812.2	–	10,654.4	–	11,643.2	–	8745.5	–	55,106.6	–
Total	87,195.9	100	71,069.2	100	89,471.9	100	125,193.1	100	78,127.9	100	451,058.0	100

*Area unavailable for suitability evaluation

cultivation. Sub-district-wise variation in land suitability for paddy cultivation is presented in Table 10 and Fig. 8. The largest area under highly suitable category was found in Dhampur (54%) followed by Chandpur (31%), Bijnor (23%), Nagina (12%) and Najibabad (2%). These areas have plain and nearly level fields with deep clayey loam soils and adequate irrigation facility. Bijnor had the largest area under moderately suitable category followed by Chandpur (35%), Dhampur (34%), Najibabad (32%) and Nagina (30%). In marginally suitable category, Najibabad (40%) had the largest area followed by Chandpur (35%), Nagina (31%), Bijnor (25%) and Dhampur (12%). These lands include the excessively drained area along the river Ganga and Ram Ganga. High risk of flooding was the other limiting factor for paddy cultivation. Under currently unsuitable category, Nagina had the largest area (18%) followed by Najibabad (17%) and Bijnor (2%). The permanently unsuitable area was found only in Nagina (9%) and Najibabad (8%). Steep slope, shallow soil depth, flooding hazard, and soil erosion were the limiting factors for paddy cultivation.

Oilseeds (*Brassica*, *Brassica napus*)

Oilseeds are mainly grown as *Rabi crop* (winter season crop) in a mixed form with wheat in the study area. The results revealed that 3.5% (14,050 ha) agricultural area was

highly suitable, 51% (2,00,500 ha) was moderately suitable, 29% (1,15,371 ha) was marginally suitable, 15% (57,775 ha) was currently unsuitable and 2% (8253 ha) was determined to be permanently unsuitable for oilseed cultivation. Table 11 and Fig. 9 show the sub-district-wise variation among suitability categories for oilseed cultivation. Largest area under highly suitable category was found in Nagina (5.5%) followed by Najibabad (4%), Dhampur (4%), Bijnor (1%) and Chandpur (1%). In the moderately suitable category, Chandpur had the largest area (67.1%) followed by Dhampur (61%), Bijnor (54%), Nagina (39%) and Najibabad (39%). Najibabad has the largest area (53%) under marginally suitable category followed by Bijnor (32%), Dhampur (26%), Nagina (21%) and Chandpur (19%). Oilseed can grow on moderate slopes having shallow soil depth. However, additional inputs of manure and fertilizers may be required. Nagina (29%) had the highest area under currently unsuitable category followed by Chandpur (13%), Bijnor (13%), Dhampur (9%) and Najibabad (0.4%). The lands in the upper reaches of Nagina and Najibabad are characterized by steep slopes and excessive erosional activity. These areas do not support oilseed cultivation, hence were permanently unsuitable. Nagina (5%) and Najibabad (3%) had area permanently unsuitable for oilseed cultivation. It should be noted that no area was permanently unsuitable in Bijnor, Dhampur and Chandpur sub-district.

Fig. 6 Variation in land suitability classes for sugarcane cultivation in Bijnor

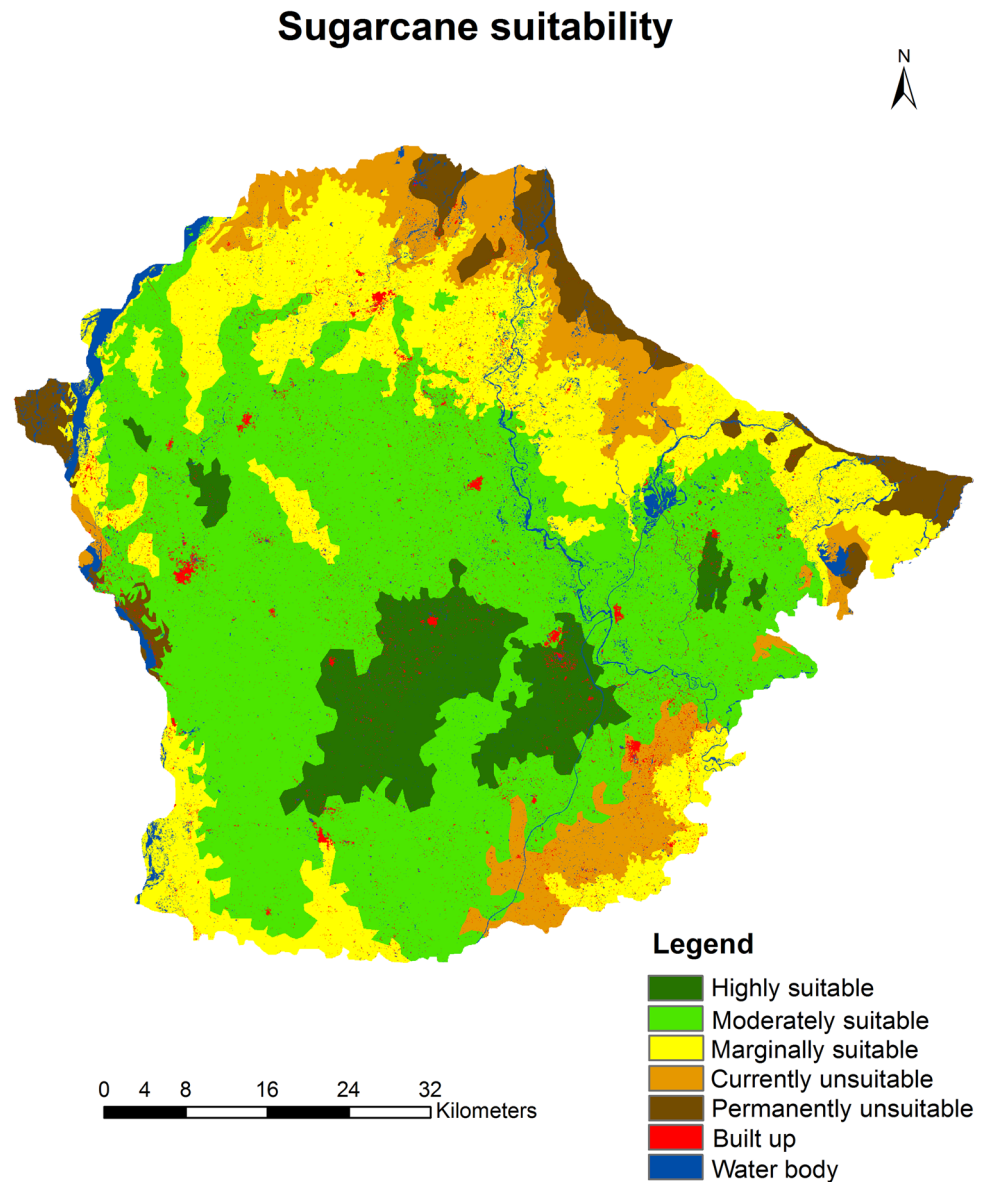


Table 8 Transportation cost incurred by farmers

Distance (km)	Truck (₹)	Tractor (₹)	Buffalo cart (₹)
> 10	10/quintal	8/quintal	5/quintal
10–20	15/quintal	12/quintal	10/quintal
20 <	20/quintal	20/quintal	20/quintal

Conclusions

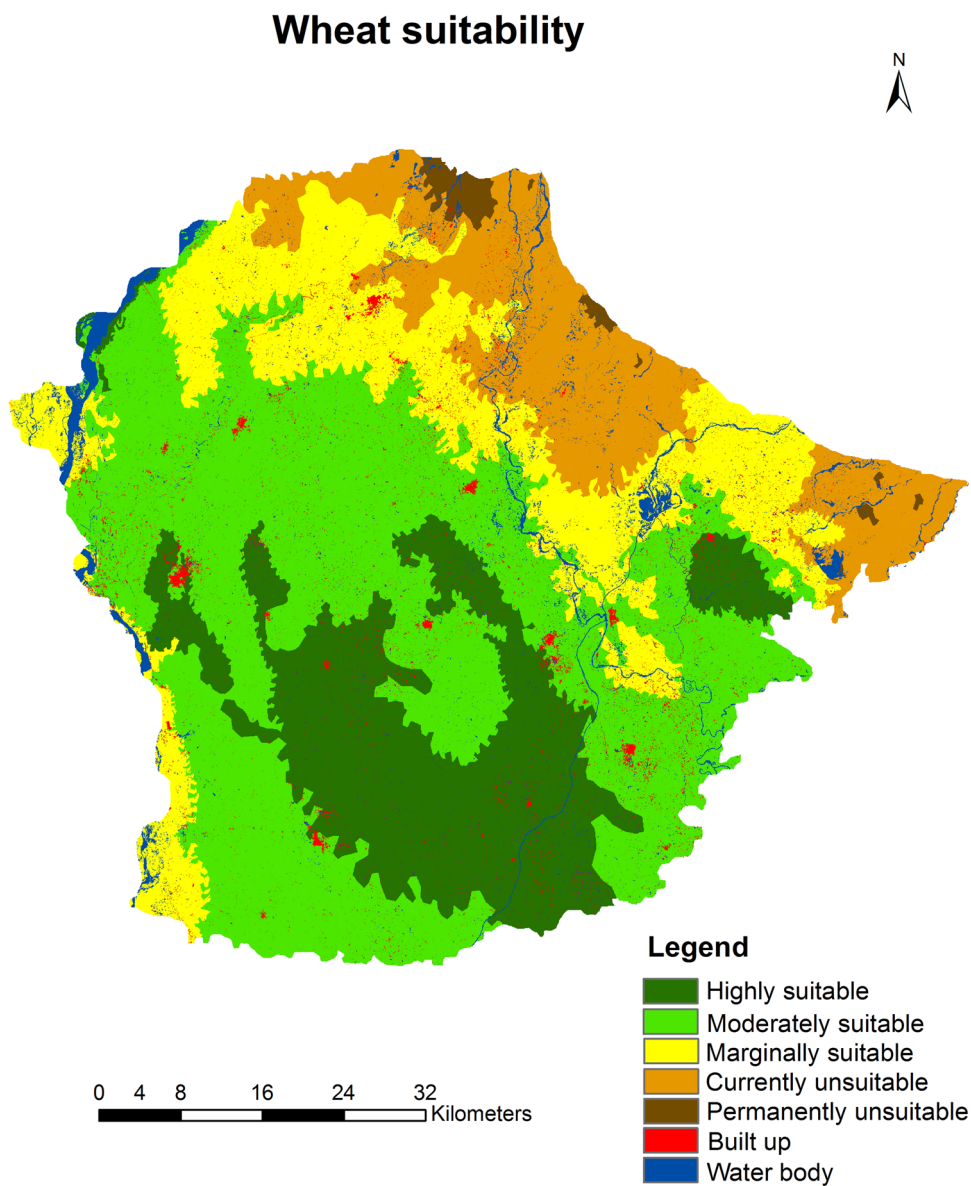
The paper evaluated land suitability for major crops (sugarcane, wheat, paddy, and oilseeds) in one of the agriculturally advanced districts in India using FAO framework and MCDA approach. The weight of criteria maps was derived from FAHP and finally, land suitability analysis for

each crop was accessed through WOA. The results revealed that the largest area under highly suitable class was found for paddy cultivation (24%) followed by wheat (20%), sugarcane (10%) and oilseeds (3.5%). These areas include lands having no limitations on crop cultivation. Largest area under moderately suitable category was found for oilseeds (51%) followed by sugarcane (50%), wheat (43%) and paddy (36%). Land in this class has minor or no significant limitations. Shallow soil depth, gentle slope and alkaline soils were found to be the main limiting factors for moderate crop suitability. The crops also had a significant area under marginal suitability class. Largest area of this class was found for oilseeds (29%) followed by paddy (28%), sugarcane (25%) and wheat (22%). Steep slope, moderately alkaline soil reaction, sandy soil texture, and soil erosion were found to be the limiting factors in this

Table 9 Variation in land suitability classes for wheat cultivation in Bijnor (Area in hectares)

Class	Bijnor	%	Chandpur	%	Dhampur	%	Nagina	%	Najibabad	%	district	%
<i>S1</i>	16,966.5	23.3	25,418.8	41.5	26,548.5	33.7	9182.2	8.1	252.5	0.4	78,475.0	19.8
<i>S2</i>	45,472.5	62.3	29,028.0	47.4	43,796.7	55.6	30,429.3	26.8	22,229.2	32.0	171,147.8	43.2
<i>S3</i>	10,505.6	14.4	6810.2	11.1	8472.3	10.7	31,768.5	28.0	28,889.4	41.6	86,510.2	21.8
<i>N1</i>	–	–	–	–	–	–	41,027.3	36.1	15,149.8	21.8	56,213.2	14.2
<i>N2</i>	–	–	–	–	–	–	1142.6	1.0	2861.5	4.1	4005.1	1.0
<i>U*</i>	14,251.3		9812.2		10,654.4		11,643.2		8745.5		55,106.6	
Total	87,195.9	100	71,069.2	100	89,471.9	100	125,193.1	100	78,127.9	100	451,057.97	100

*Area unavailable for suitability evaluation

Fig. 7 Variation in land suitability classes for wheat cultivation in Bijnor

category. Judicious use of organic manures in combination with inorganic fertilizers may help in achieving sustainable yields and maintaining the soil health. Largest area under

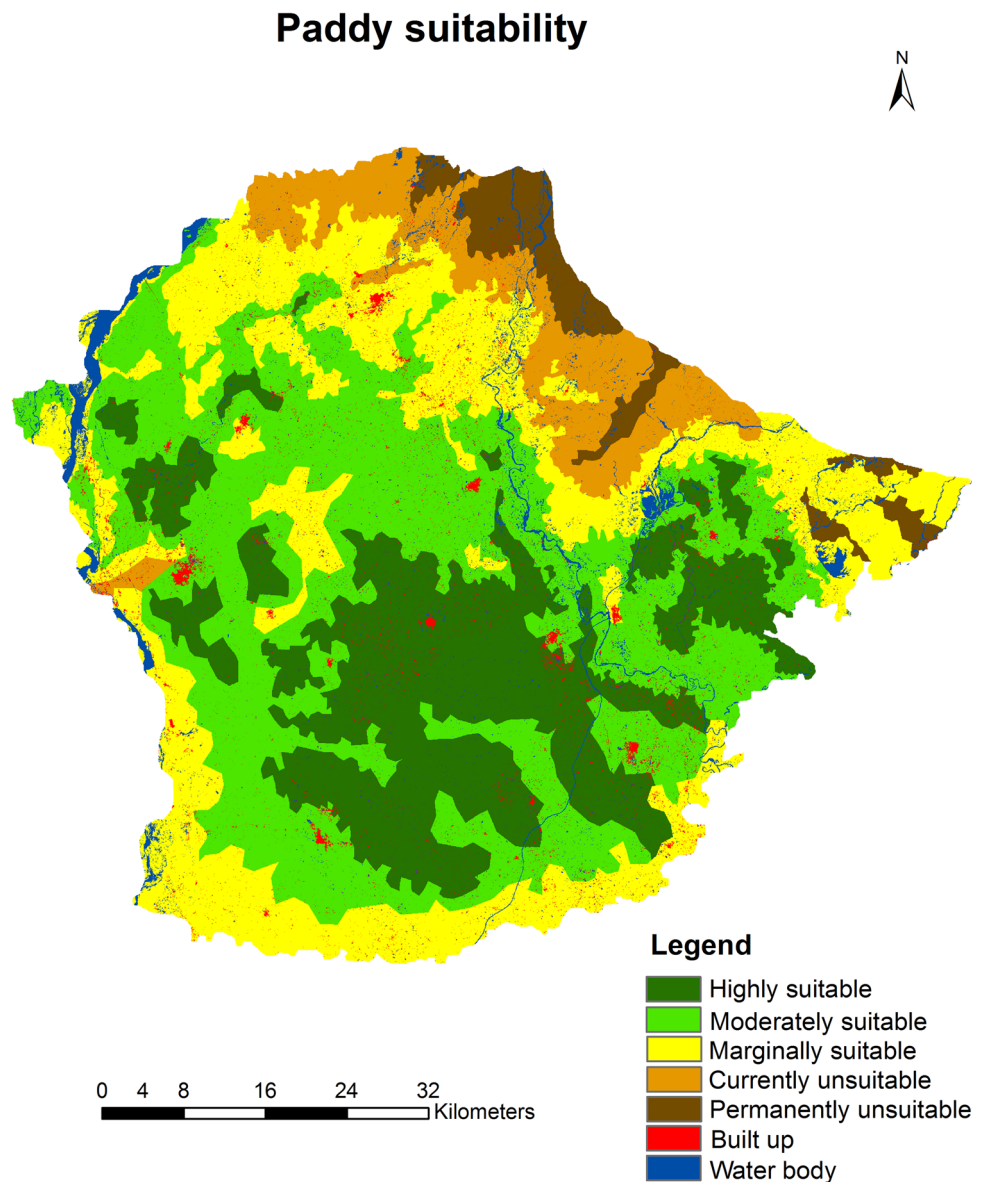
currently unsuitable class was found in oilseeds (15%) followed by wheat (14%), sugarcane (10%) and paddy (8%). The permanently unsuitable class included lands

Table 10 Variation in land suitability classes for paddy cultivation in Bijnor (area in hectares)

Class	Bijnor		Chandpur		Dhampur		Nagina		Najibabad		district	
<i>S1</i>	16,839.2	23.1	18,818.8	30.7	42,331.3	53.7	13,827.8	12.2	1384.7	2.0	93,321.5	23.6
<i>S2</i>	36,866.7	50.5	21,201.2	34.6	26,763.8	34.0	34,323.5	30.2	22,410.0	32.3	141,714.5	35.8
<i>S3</i>	18,012.5	24.7	21,237.0	34.7	9722.4	12.3	34,705.4	30.6	27,918.8	40.2	111,698.4	28.2
<i>N1</i>	1226.2	1.7	–	–	–	–	20,008.5	17.6	12,022.0	17.3	33,276.0	8.4
<i>N2</i>	–	–	–	–	–	–	10,684.7	9.4	5646.9	8.1	16,341.0	4.1
<i>U*</i>	14,251.3		9812.2		10,654.4		11,643.2		8745.5		55,106.6	
Total	87,195.9	100	71,069.2	100	89,471.9	100	125,193.1	100	78,127.9	100	451,058.0	100

*Area unavailable for suitability evaluation

Fig. 8 Variation in land suitability classes for paddy cultivation in Bijnor



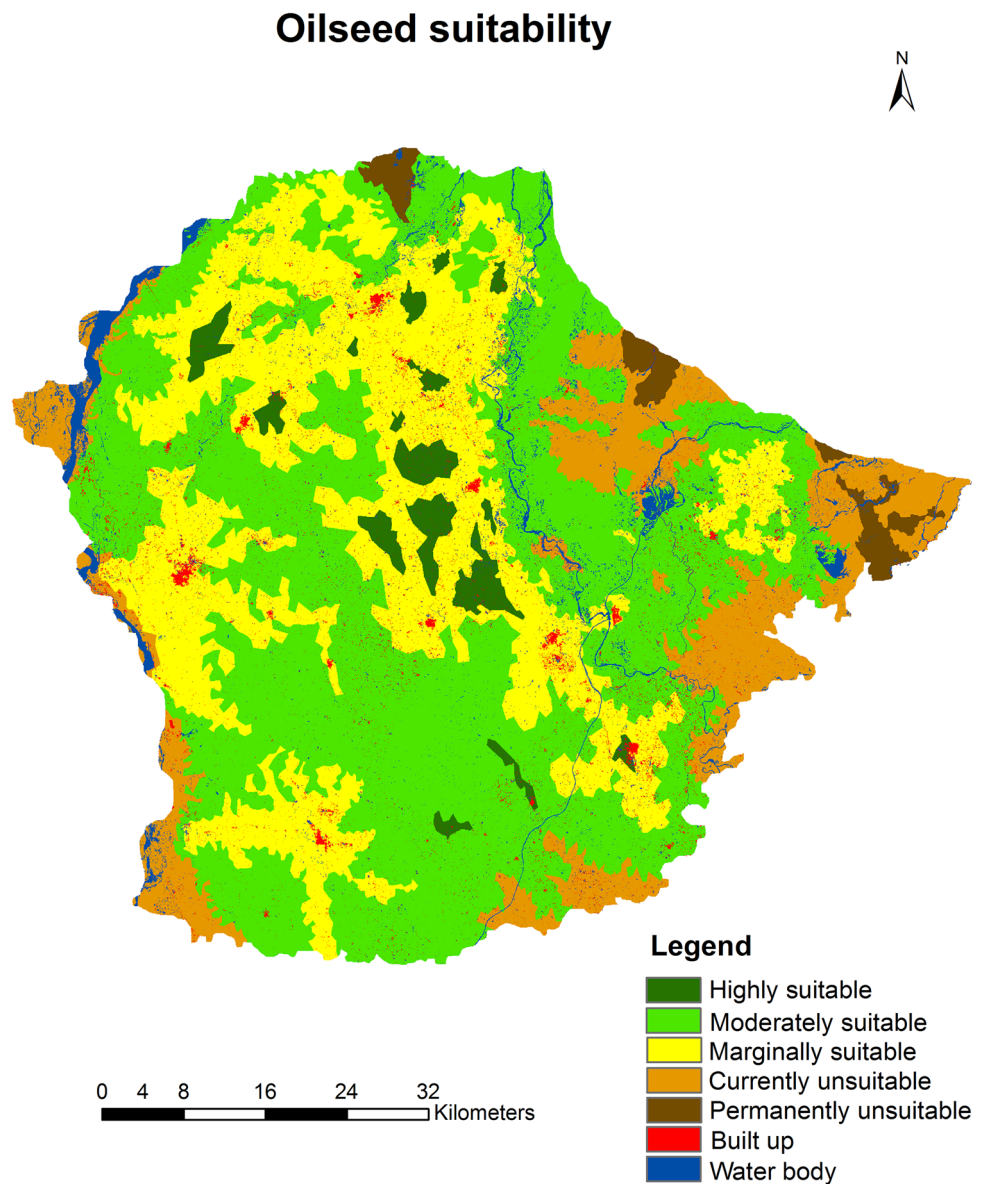
having permanent physical constraints which cannot be corrected. Largest area under this category was found for sugarcane (5%) followed by paddy (4%), oilseed (2%) and

wheat (1%). Land in this class was found to be excessively drained. The soil reaction was either acidic or too alkaline. The steep slope and severe soil erosion restrict any

Table 11 Variation in land suitability classes for oilseeds cultivation in Bijnor (Area in hectares)

Class	Bijnor	%	Chandpur	%	Dhampur	%	Nagina	%	Najibabad	%	District	%
<i>S1</i>	748.4	1.0	478.0	0.8	3382.8	4.3	6297.0	5.5	3144.0	4.5	14,050.2	3.5
<i>S2</i>	39,310.2	53.9	41,127.5	67.1	48,079.4	61.0	44,722.8	39.4	27,259.9	39.3	200,499.7	50.6
<i>S3</i>	23,345.0	32.0	11,518.5	18.8	20,235.1	25.7	23,752.0	20.9	36,520.8	52.6	115,371.4	29.1
<i>N1</i>	9541.0	13.1	8133.0	13.3	7120.3	9.0	32,716.0	28.8	265.3	0.4	57,775.5	14.6
<i>N2</i>	–	–	–	–	–	–	6061.3	5.3	2192.5	3.2	8253.8	2.1
<i>U*</i>	14,251.3		9812.2		10,654.4		11,643.2		8745.5		55,106.6	
Total	87,195.9	100	71,069.2	100	89,471.9	100	125,193.1	100	78,127.9	100	451,058.0	100

*Area unavailable for suitability evaluation

Fig. 9 Variation in land suitability classes for oilseed cultivation in Bijnor

possibility of land utilization, hence the land was considered as permanently unsuitable for crop cultivation. From the study, the following inferences were deduced.

Bijnor has the highest suitability of growing sugarcane followed by Dhampur, Chandpur, Nagina, and Najibabad. Dhampur has the highest suitability of growing wheat and

paddy followed by Bijnor, Chandpur, Nagina, and Najibabad. Chandpur has the highest suitability of growing oilseeds followed by Dhampur, Bijnor, Nagina, and Najibabad. Overall, wheat is the most suitable crop in the district followed by sugarcane, paddy, and oilseeds. For removing the limitations of the land and increasing its suitability, improved irrigation facilities and pH specific fertilizers are recommended. Tube wells and canals serve as the main source of irrigation in the study area. Surface irrigation through basins and furrows were the most common irrigation methods practiced by the farmers. Soil conservation practices and an improvised network of roads may also act as a catalyst for increasing land suitability. FAHP has proved to be a useful tool for assessing crop suitability. The results obtained from this study may help in the sustainable development and efficient management of cropland in the study area. The methodology adopted in the study may be useful for analyzing crop suitability of other areas at various scales.

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