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Cropland suitability assessment using multi criteria evaluation techniques and geo-spatial technology: A review

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ABSTRACT

Cropland suitability assessment is an essential technique for agricultural development and future planning. It is an evaluation to determine how suitable the land is for growing a specific crop in a particular region based on multiple parameters like soil, climate, topography, socio-economic condition, infrastructure, irrigation, existing land use/land cover and environmental aspects. The paper presents different multi-criteria evaluation (MCE) techniques such as Analytical Hierarchy Process (AHP), Fuzzy Analytical Hierarchy Process (FAHP), Analytic Network Process (ANP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and ELimination Et Choice Translating REality (ELECTRE) approaches integrated with geospatial technology, namely remote sensing and Geographical Information System for cropland suitability assessment. Review findings indicate that the AHP technique was used by 53% of the researchers, followed by FAHP (16%); ANP (6%); TOPSIS (6%); ELECTRE (3%) and other techniques (16%) with or without geospatial technology. The integrated approach of MCE with geospatial was used by 69%, among which AHP technique of MCE was used by 72%; whereas, 22% used geospatial and 9% used MCE techniques alone. The results from the selected research articles also indicated that the most important input parameters were soil, topography and climate used by 97%, 88% and 74% of the researchers, respectively. The review can be helpful for researchers and decision-makers to select the most robust methods and standard parameters required for cropland suitability assessment to achieve higher agricultural production on a sustained basis.

Keywords: Cropland suitability, Geographical Information System, Multi-criteria evaluation, Remote sensing

The cropland suitability analysis is the process of assessing the appropriateness of a given type of land for growing a particular crop based on its optimum growth requirements (FAO 1976). It is a function of different parameters such as climate, soil, topography, land use, infrastructure, water availability, socio-economic and environmental factors etc. The relative importance of these parameters can be evaluated to determine the suitability by different statistical techniques such as MCE (Nagasawa *et al.* 2005) integrated with geospatial techniques such as RS (Remote sensing) and GIS (Geographic Information System) (Trigoso *et al.* 2020). It also involves major decisions at various levels starting from choosing significant land-use types, selecting criteria, deciding suitability limits for each class of the criteria and deciding the preferences, both qualitative and quantitative. Remote Sensing (RS) data provides reliable information on land use/land cover, topography etc. on a spatial scale in less time and money which can be integrated into GIS along with data on bio-climate, soil, crop etc. that will be helpful to decision-makers for increasing the crop productivity and reducing the cost of production. Kumar *et al.* (2021) analyzed cotton yield in Haryana and reported that phosphorus addition increased the yield but simultaneously increased cost of cultivation. Some researchers used either the MCE technique (Gautam *et al.* 2017, Jain *et al.* 2020) or the geospatial technique (Dhami *et al.* 2012, Ranjan *et al.* 2018), and they found that handling weights of parameters are indigent or insufficient in determining the crop suitability index. Hence, the integrated approach of MCE and geospatial techniques in cropland suitability assessment has great potential to increase the accuracy and effectiveness of the results (Chivasa *et al.* 2019, Ramamurthy *et al.* 2020). Chand *et al.* (2021) opined that the cultivation of non-suitable crops leads towards unsustainability of agriculture in the affected area. Hence, cropland suitability assessment is vital for matching the land characteristics with crop requirements (Mustafa *et al.* 2011, Pan and Pan 2012, Kihoro *et al.* 2013, Sharma *et al.* 2018) which can answer the questions such as where to

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grow and what to grow? Identification of suitable crop/crops will further facilitate environmentally friendly sustainable agriculture by developing optimum crop plans. There are reports (Kadao *et al.* 2001, Prasad *et al.* 2009, Likhar and Prasad 2011) and review (Jain *et al.* 2018) for suitability evaluations, however, most of the methodologies for optimum plans are based on existing cropping pattern and do not cover crops on the basis of land suitability (Jain *et al.* 2015, Jain *et al.* 2019). Applicability of such methods is more relevant when the crops used in the model are suitable for the region as per their bio-physical applicability.

The growing population pressure and competing demand for natural resources such as land, water and biomass exerts tremendous pressure on these resources. A large proportion of land is used either excessively or inadequately to grow different crops without considering its potential and constraints. Under present situations, it is not possible to bring more area under plough and hence productivity has to be increased from existing cultivable land to meet the growing demand for food for our future generations. Therefore, to increase food production and provide food security, it is essential to grow the crops in areas where they are best suited. There are various criteria and approaches available in literature for cropland suitability assessment. From the selected research articles, it was noticed that different input criteria such as soil, climate, topography, socio-economic, infrastructure, irrigation and land use/land cover (LULC) were used by researchers. Using these criteria, the MCE techniques such as AHP, FAHP, ANP, TOPSIS and ELECTRE etc. have been applied with or without geospatial techniques (RS and GIS) for suitability assessment, but there is no review available on the essential criteria and popular approach. The present review describes and analyses the MCE technique and geospatial tools and techniques and, corresponding criteria requirements for cropland suitability assessment. Based on the analysis, and the standard parameters, the most robust approaches are identified that can help researchers, decision makers and policymakers to develop guidelines on cropland suitability for improved crop productivity.

The present review is based on the latest research papers from last 10 years, barring a few basic ones. The papers were selected using the key words like "crop suitability", "MCE", "GIS", "RS", "AHP", "Fuzzy AHP", "ANP", "Best Worst method", "land suitability" from Springer, IEEE Xplore, Elsevier, Science Direct, MDPI, Taylor and Francis, Google Scholar, and other Scopus indexed journals and conference proceedings. The papers with reputed and high impact factor journals were selected for the review. Where available, full-length articles were downloaded, and research details were extracted, such as the country where the study was carried out, the study's objective, methods or model used, crop(s) studied and the thematic factors used in assessing the suitability. We developed a Microsoft Excel spreadsheet to enter and later quantitatively assessed the extracted data. We assumed no selection bias as the literature search and curatorship was done by two independent researchers.

Identification of criteria for cropland suitability

Determination of optimum land-use type for an area involves integrating data from various sources and domains such as soil science, social science, meteorology, and crop science. All these significant streams can be considered in separate groups; each group can have various parameters (criteria) in itself. However, all criteria are not equally important; every criterion will contribute to suitability at different degrees (Gundimeda 2007). The relative degree of various criteria contribution can be addressed well when grouped into various groups and organized at various hierarchies. Considering the soil (soil texture, soil *p*H, soil drainage), climate (temperature and humidity), topography (slope) and LULC parameters, Kihoro *et al.* (2013) studied the cropland suitability for rice crop using AHP technique. While, Kaunakaran *et al.* (2019) included clay content, exchangeable sodium percentage, available water content, saturated hydraulic and organic carbon content in their suitability evaluation for cotton using AHP-method. Maddahi *et al.* (2017) used the soil parameters (soil texture, surface stoniness, soil depth, *p*H, EC, phosphorus, potassium, OM), climate (temperature and relative humidity), topography (slope and aspect), infrastructure (distances from road, rice milling plant, residential areas with work opportunities), LULC and irrigation (distance from river and stream, from water well) using fuzzy AHP technique. In an empirical study, Mugiyo *et al.* (2021) used the soil parameters (soil depth), climate (temperature and rainfall, LGP, ET_0), topography (slope and elevation), infrastructure (distance from road) and LULC for under-utilised crops (sorghum, cowpea, amaranth and taro) in South Africa by using AHP. Seyedmohammadi *et al.* (2018) studied the soil parameters (depth, *p*H, electrical conductivity, exchangeable sodium percentage, calcium carbonate, gypsum), slope and climate to estimate the land suitability for maize, rapeseed and soybean crops using SAW, TOPSIS and FAHP techniques. Yohannes and Soromessa (2018) used soil parameters , (depth, soil texture, soil drainage *p*H, EC, CEC, carbonate, OM, total nitrogen, available phosphorus) along with temperature, rainfall, slope, aspect, altitude, erosion hazard, distance from road, river distance and LULC for cropland suitability assessment of wheat and barley using ANP technique whereas, Fekadu and Negese (2020) used soil parameters (texture, depth, BD, *p*H, OC,NP,CEC,PBS), temperature, rainfall, slope, elevation, AWC using AHP technique in Ethiopia. Jain *et al.* (2020) used temperature, rainfall, relative humidity, length of the growing period, soil texture, soil depth, *p*H, EC, OC, slope, net returns per ha, market concentration and road density for different crops for cropland suitability evaluation using AHP technique in the Bundelkhand region, India. The different researchers used different parameters, tools and techniques to address the suitability (Table 1).

Tools and techniques used for cropland suitability

Geospatial tools and techniques: Geographic information system (GIS) is an efficient tool for input, storage and

Table 1 Parameter, tools and techniques for cropland suitability assessment

Soil	Climatic	Topography & LULC	Socio-economic/ Infrastructure	Irrigation	Tools/ Techniques	Crop	Reference
Texture, drainage, depth, *p*H, EC, OC, ESP, $CaCO_3$, gypsum	Temperature and rainfall	Slope		Flooding	GIS & TOPSIS	Wheat	Bagherzadeh and Gholizadeh (2016)
Texture, surface stoniness, depth, *p*H, EC, phosphorous, potassium, OM	Temperature and RH	Slope, aspect, LULC	Distances from road and rice milling plant, distance from residential areas	Distance from river and stream, distance from water well	GIS & FAHP	Rice	Maddahi *et al.* (2017)
Texture, drainage, *p*H, EC, Leaf emergency, tillering, panicalprimoda, flowering, milky dough, ripening	Temperature	LULC			GIS & AHP	Rice	Raza *et al.* (2017)
Soil depth, *p*H, EC, ESP, calcium carbonate and gypsum	Climate	Slope			GIS & SAW, TOPSIS, Fuzzy AHP	Maize, rapeseed and soybean	Seyedmohammadi *et al.* (2018)
Soil depth, soil texture, soil drainage *p*H, EC, CEC, carbonate, OM, total nitrogen and available phosphorous	Temperature and rainfall	Slope, aspect, altitude, erosion hazard, LULC	Distance from road	River distance	GIS & ANP	Wheat and barley	Yohannes and Soromessa (2018)
Total nitrogen, available phosphorus and OC	Temperature, length of growing period	Slope gradient, altitude		Available water capacity, mean weight diameter	GIS & fuzzy AHP	Sorghum	Kahsay *et al.* (2018)
Drainage, depth, *p*H, slope, soil texture	Rainfall	Slope, LULC	Distance to major roads and closest town	Flooding risk	GIS & FAHP	Sugarcane, wheat, paddy, and oilseed	Jamil *et al.* (2018)
Texture, *p*H, depth	Temperature and rainfall	Slope, LULC		Ground water depth	GIS & AHP	Wheat, mustard, gram, pearl millet, cluster bean	Mehra and Rajeshwari (2018)
Texture, land type, *p*H, BD, water holding capacity, permeability	Temperature and rainfall	Slope, elevation		Flood prone	GIS & AHP	Rice	Islam *et al.* (2018)
Texture, depth, *p*H, TN, AP, exchangeable potassium, micro nutrients	Temperature and rainfall	Slope		Relief, water resources	GIS & AHP	Rice	Roy and Saha (2018)
Texture, depth, gypsum (%), $CaCO_3$ (%), *p*H, EC, drainage, ESP	Temperature and RH	Slope		AWC	GIS & ANP, FAHP	Maize	Seyedmohammadi *et al.* (2019)
Texture	Temperature	Slope, LULC			GIS & AHP	Tomatoes, capsicums, raspberries, beans	Seif-Ennasr *et al.* (2020)

Contd.

Table 1 (*Concluded*)

Soil	Climatic	Topography & LULC	Socio-economic/ Infrastructure	Irrigation	Tools/ Techniques	Crop	Reference
Drainage, depth, *p*H, OM	Rainfall	Slopes, erosion			ELECTRE Method	Rice	Ali *et al.* (2020)
Texture, drainage, depth, *p*H, OM, NPK		Slope, erosion, LULC		Flooding	GIS & AHP	Potato, cauliflower, and radish	Thapa *et al.* (2020)
Texture, depth, *p*H, EC, OC	Temperature, rainfall and RH, LGP	Slope	Net returns per ha, market concentration and road density	Irrigation water availability and requirement	AHP	Pigeonpea, pearl millet, chick pea, ground nut, sorghum, maize, mustard, paddy, potato, sesamum, soybean, sugarcane, wheat	Jain *et al.* (2020)
Soil type, *p*H, OM, NPK, EC, and CEC	Temperature and rainfall	Elevation, slope, aspect, LULC	Distance to roads	Distance to rivers	GIS & AHP	Potato	Trigoso *et al.* (2020)
Texture, depth, BD, *p*H, OC, nitrogen, phosphorus, CEC, PBS	Temperature and rainfall	Slope, elevation		AWC	GIS & AHP	Wheat and barley	Fekadu and Negese (2020)
Texture, soil *p*H, soil drainage.	Humidity, temperature	Slope			GIS & AHP	Rice, maize, cassava	Peter (2020)
Soil depth	Temperature and rainfall, LGP, ET_0	Elevation, slope, LULC	Distance from road		GIS & AHP	Sorghum, cowpea, amaranth and taro	Mugiyo *et al.* (2021)
			Markets, Road, irrigation, extension, credit availability, cold storage	Per cent area under irrigation	Infrastructure index	Agriculture	Jain *et al.* (2021a), Jain *et al.* (2021b)

ESP, Exchangeable sodium percentage; LGP, Length of growing period; BD, Bulk density; TN, Total nitrogen; AP, Available phosphorus; AK, Available potassium; OC, Organic carbon; ET_0, Reference evapotranspiration; EC, Electrical conductivity; OM, Organic Matter; CEC, Cation exchange capacity; PBS, Percent base saturation; AWC, Available water content; $CaCO_3$, Calcium carbonate.

retrieval, manipulation and analysis, and output of spatial data (AbdelRahman *et al.* 2016). These data contain both thematic and geometric (spatial) information, which can be represented in raster or vector form. GIS can integrate many geographic technologies such as GPS, RS etc. and it can also perform various tasks using spatial and attribute data stored in it. It allows the construction of models that helps to create cropland suitability map from a set of thematic maps such as soil, climatic, topography maps etc. (Zolekar and Bhagat 2015). Remote sensing (RS) gives information regarding numerous spatial criteria like topography (aspect, slope, elevation) (Bisht *et al.* 2013), land use/land cover (LULC), drainage density, etc used for cropland suitability assessment at larger scale. The thematic layers of various input parameters namely temperature, rainfall, relative humidity, texture, drainage, soil *p*H, OC, EC, depth etc. along with spatial inputs derived from RS data, and can be incorporated in GIS (Bisht *et al.* 2019, Shaloo *et al.* 2021) for cropland suitability classification (Perveen *et al.* 2007).

Multi-criteria evaluation (MCE) techniques: The Multi-Criteria Evaluation (MCE) technique is a powerful tool for solving multiple criteria decision-making problems. It enhances decision-making when a set of alternatives must be evaluated based on conflicting and unequal criteria. This technique examines many choice possibilities in light of multiple criteria and objectives. Following are the commonly used MCE techniques for cropland suitability assessment.

a. The Analytical Hierarchy Process (AHP): AHP method of MCE is the most widely used technique to obtain the weights of criteria by constructing a pairwise comparison matrix using a scale value from 1–9 points for decision-making. Saaty (1980) developed this method for solving complex problems (Yu *et al.* 2011) related to crop suitability (Rabia and Terribile 2013), land use planning (Zolekar and Bhagat 2015) etc. The weights of criterion were calculated in four steps in pairwise comparison matrix, i.e. (1) formation of judgments, (2) calculation of assigned ranks, (3) preparation of normalized pairwise comparison matrix and finally, (4) calculation of weights. Judgments of ranks were formed based on expert opinion and compared in pairwise comparison matrix.

b. Analytic Network Process (ANP): The analytic network process (ANP) is a generalized form of AHP which structures a decision-making problem into a network (Eldrandaly *et al.* 2014, Mokarram *et al.* 2019). It also uses a pair-wise comparison system to estimate the structure components weights and finally rank the alternatives in the decision.

c. Fuzzy Analytical Hierarchy Process (FAHP): Fuzzy Analytic Hierarchy Process (FAHP) is a method of AHP developed with fuzzy logic theory which sets the AHP scale into the fuzzy triangle scale (fuzzy numbers) to access the criterion's priority (Srisawat *et al.* 2017, Kahsay *et al.* 2018). This method deals with uncertain data and precious knowledge, which can be used by the decision-makers in uncertain circumstances.

d. Best-Worst Method (BWM): BWM method is used to estimate a set of alternatives regarding a set of decision criteria (Rezaei 2016). This method is based on a structured pair-wise comparison of the decision criteria. The decision-maker (DM) determines two criteria (the best criterion and the worst criterion), after identifying the decision criteria where the best criterion (most important) is the one that has the most vital role in decision making (Everest *et al.* 2022). In contrast, the worst criterion (least important) has the opposite role. The DM then provide their preferences of the best criterion over all the other criteria and preferences of all the criteria over the worst criterion using a predefined scale value ranging from 1–9. These two sets of pair-wise comparisons are utilized as input for an optimization problem, the adequate results of which are the weights of the criteria.

e. TOPSIS method: The technique for order of preference by similarity to ideal solution (TOPSIS) is based on the principle that the alternative chosen must have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution (Hwang and Yoon 1981). Bagherzadeh and Gholizadeh (2016) evaluated the cropland suitability for rice crop in Iran using TOPSIS method integrated with GIS.

F. ELECTRE method: ELimination Et Choice Translating REality (ELECTRE) method is one of the out-ranking methods for MCE which comprises a systematic analysis between pairs of different alternatives from a set of evaluation criteria. This method can be used to produce the best alternative ranking relationship assuming that one alternative can dominate over the other alternatives (Govindan and Jepsen 2016). Likewise, when the alternatives are equally good, weights are needed for all criteria as a comparison to assess (Rogers *et al.* 2000).

Integration of MCE and Geospatial techniques

Several GIS-based approaches such as interpolation, weighted overlay and modelling etc. of geospatial data can be used for cropland suitability mapping. Though these approaches are not having a well-defined mechanism for incorporating decision makers' choices in GIS, they can be solved by integrating MCE techniques with GIS. Interpolation technique present in GIS is used to create thematic layers of input parameters such as air temperature, rainfall, soil texture, drainage, *p*H, electrical conductivity, organic carbon, slope etc. MCE technique such as AHP, Fuzzy AHP, ANP etc. can be utilized to determine the weights of each parameter using expert opinions. The combined approach can be used for developing crop suitability models as per the optimum crop growth requirements in terms of input parameters of specific crop (Otgonbayar *et al.* 2017) (Fig 1). The integrated approach of MCE and geospatial techniques have excellent potential to find suitable land for crops that save resources, time, money and provide valuable information to farmers and policymakers to reduce costs and increase production (Singh *et al.* 2018).

Following the systematic search, 121 research papers were selected for analysis. After removing all duplicates,

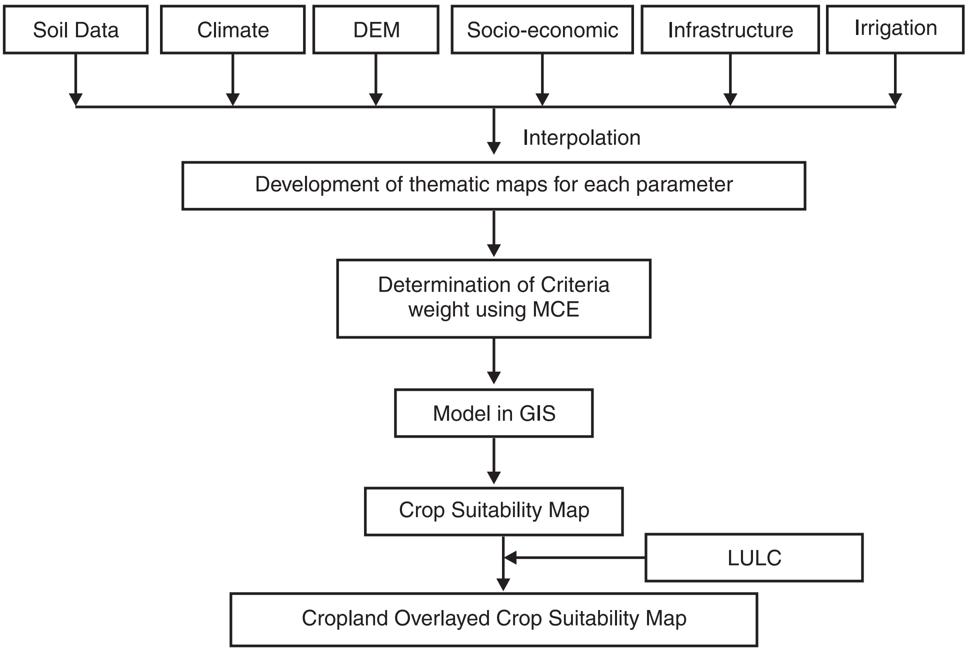

Fig 1 Flow chart for cropland suitability assessment.

articles selection was done emphasizing peer-reviewed articles from reputed journals and conference papers. Papers that were based on land suitability but not related to crops were excluded. Finally, we used 79 researches for this analysis. Several researchers used MCE techniques for obtaining the weights of parameters, among which AHP technique was used by 53% of the researchers followed by FAHP, ANP, TOPSIS and ELECTRE with 16%, 6%, 6% and 3%, respectively, while 16% researchers used some other techniques as shown in Fig 2. From the identified literature used in this review, 69% used the integrated approach of MCE with geospatial among which 72% used AHP technique of MCE. Whereas, 22% used geospatial and only 9% used MCE techniques alone. AHP was found better than other techniques due to its relative ease in handling multiple criteria and compensating both qualitative and quantitative data (Moeinaddini *et al.* 2010). Most of the researchers used the GIS tool with MCE techniques for developing model for cropland suitability as shown in Table 1. A total of seven input parameters namely, soil, climate, topography, socio-economic, infrastructure, irrigation and LULC were used by researchers of which soil, topography and climate were used by 97%, 88%, and 74%, respectively. Among the input parameters, the most important parameters were soil (soil texture, drainage, soil depth, *p*H, OC and EC), climate (temperature and rainfall) and topography (slope) for cropland suitability assessment. In recent study Jain *et al.* (2021a) demonstrated the methodology for computation of infrastructural suitability in agriculture at district, state and country level. Composite infrastructural classes highlighted that all the states in the country have infrastructural inadequacy in one or more parameters (Jain *et al.* 2021b). The authors analyzed that improvement in agricultural infrastructure in the country calls for huge investments to enhance the income of the farmers. Such estimations are helpful in determining the potential areas where public or private investments are needed. Further, Jain *et al.* (2021c) have reported that suitability identification should be followed by optimum area under allocation of suitable crops failing which may lead to over-exploitation of natural resources and unsustainability of the crop for the region. With advent of cheaper computational power and storage, latest machine learning based methods should also be explored for suitability analysis based on computer vision (Nigam *et al.* 2021).

The analysis clearly reveals that soil, climatic and topography parameters are essential parameters for crop suitability analysis. Latest research also recommends use of socio-economic and infrastructural variables as these govern the farmer's decision to adopt the crops in the region of interest. Detailed methodology for the same is available in Jain *et al.* (2021a,b).

Conclusion

The present review used a scoping method to obtain and incorporate information on cropland suitability. The review is expected to provide researchers and decision-makers the most robust methods for cropland suitability assessment which can be used to improve current and future planning

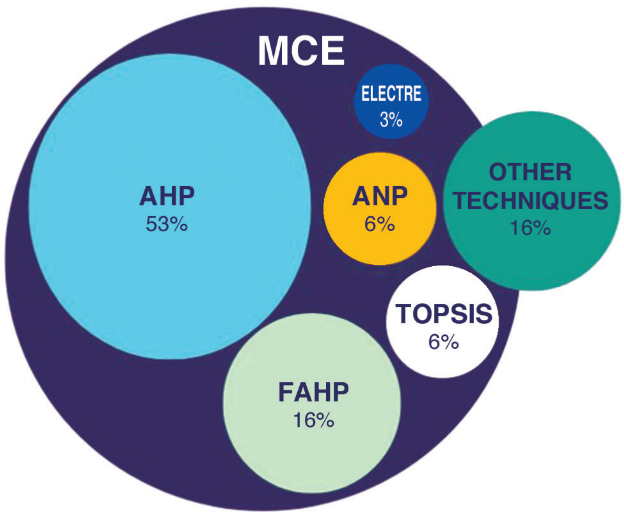

Fig 2 Per cent use of MCE techniques in cropland suitability assessment with or without geo-spatial technology.

on climate change issues, environmental management and crop production guidelines. Many studies have used AHP method of MCE techniques for obtaining the weights of criteria in GIS platform for suitability evaluation. Most of the studies used soil, topography and climate as important input parameters. However, for better land use planning especially in small holder farming systems, socio-economic, infrastructure, irrigation factors and pollution load should also be considered. Future studies should focus on using artificial intelligence (AI) and machine learning methods (MLMs) which are gaining popularity in recent years and can be integrated with MCE and GIS for improving crop suitability mapping for climate-smart agriculture. Finally, these tools and techniques can be integrated in the form of a spatial decision support system (SDSS) to smoothen the decision-making process for management, planning, operations or satisfactory solution path recommendation. SDSS provides support for decision making and recommendations to researchers, farmers, decision-makers and policymakers to solve complex problems related to crop production in the agriculture sector.

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