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GIS-MCDA Based Land Capability Analysis for Sustainable Food Production in the Kurdistan Region of Iraq

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Abstract

Food production is vital to global food security, entailing significant social, economic, and environmental implications. The Kurdistan Region of Iraq (KRI) possesses abundant natural and human resources essential for agriculture, including extensive agricultural land, water resources, and a favorable climate. However, challenges such as population growth, displacement of large numbers of residents from other provinces to the Kurdistan Region, unplanned urban expansion encroaching on agricultural areas, useless land accumulation, and agricultural land degradation pose substantial threats to sustainable food production (SFP). The study's primary objective is to assess and map the potential for SFP in the region, enabling stakeholders to formulate strategies for sustainability and ensure food security. The methodology involved classifying land capability using Geographic Information System - Multi-Criteria Decision Analysis GIS-MCDA approaches, including the fuzzy analytical hierarchy process-hybrid model (F-AHP) and fuzzy analytical network process F-ANP. The dataset encompassed variables related to land capability for food production, categorized into six main groups: topography, climate elements, water resources, land use-landcover (LULC), geology, and soil characteristics, each with about eighteen sub-factors. Results from F-AHP and F-ANP indicated consistent findings across factor weights and land capability classifications in KRI, showing no significant disparities. Only 10.72% of the region's total land 4245.7 km^2 exhibited high capability, while 28.68%, 11355 km^2, 34.18%, 13534 km^2, and 18.1%, 7168 km^2, were moderately capable, low capability, and limited capable land, respectively. An 8.32%, 3295.4 km^2 of Kurdistan's land was deemed unsuitable for SFP. The study's insights are crucial for experts, planners, governments, and stakeholders, facilitating the assessment of current food production. Based on these findings, appropriate plans and strategies can be developed to uphold long-term food security in the Kurdistan region.

Keywords: Global food security, Natural and human resources, Agricultural land degradation, Fuzzy Analytic Hierarchy Process F-AHP, and Fuzzy Analytical Network Process F-ANP.

تحليل قدرة الأرض باستخدام نظم المعلومات الجغرافية وتحليل القرار متعدد المعايير لإنتاج الغذاء المستدام في إقليم كردستان العراق

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الخلاصة

يعد إنتاج الغذاء عنصرا حيويا في الأمن الغذائي العالمي، مما ينطوي على آثار اجتماعية واقتصادية وبيئية كبيرة. يمتلك إقليم كردستان العراق موارد طبيعية وبشرية وفيرة ضرورية للزراعة، بما في ذلك الأراضي الزراعية الواسعة وموارد المياه والمناخ الملائم. ومع ذلك، فإن التحديات مثل النمو السكاني، والتوسع الحضري غير المخطط له الذي يتعدى على المناطق الزراعية، وتراكم الأراضي غير المجدية، وتدهور الأراضي الزراعية تشكل تهديدات كبيرة للإنتاج الغذائي المستدام. الهدف الأساسي من الدراسة هو تقييم ورسم إمكانات الإنتاج الغذائي المستدام في المنطقة، وتمكين أصحاب المصلحة من صياغة استراتيجيات للاستدامة وضمان الأمن الغذائي. تضمنت المنهجية تصنيف سعة الأراضي باستخدام مناهج GIS-MCDA، بما في ذلك نموذج العملية الهجين للتسلسل الهرمي التحليلي الغامض (F-AHP) وعملية الشبكة التحليلية الغامضة (F-ANP). وتضمنت مجموعة البيانات متغيرات تتعلق بقدرة الأرض على إنتاج الغذاء، وتم تصنيفها إلى ست مجموعات رئيسية: التضاريس، وعناصر المناخ، والموارد المائية، واستخدام / أغطية الأراضي، والجيولوجيا، وخصائص التربة، ولكل منها حوالي ثمانية عشر عاملاً فرعيًا. أشارت نتائج F-AHP وF-ANP إلى نتائج متسقة عبر أوزان العوامل وتصنيفات سعة الأراضي في إقليم كردستان العراق، ولم تظهر أي تباينات كبيرة. ومن الجدير بالذكر أن 10.72% فقط من إجمالي أراضي المنطقة (4245.7 كيلومتر مربع) أظهرت قدرة عالية، في حين أن 28.68% و34.18% و18.1% كانت ذات قدرة متوسطة، وقدرة منخفضة، ومحدودة القدرة، على التوالي. بالإضافة إلى ذلك، تم اعتبار 8.32% (3295.4 كيلومتر مربع) من أراضي إقليم كردستان غير مناسبة لإنتاج الغذاء المستدام. تعتبر رؤى الدراسة حاسمة بالنسبة للخبراء والمخططين والحكومات وأصحاب المصلحة، مما يسهل تقييم الإنتاج الغذائي الحالي. وبناءً على هذه النتائج، يمكن وضع الخطط والاستراتيجيات المناسبة لدعم الأمن الغذائي على المدى الطويل في إقليم كردستان.

1. Introduction

Earth's population is growing uncontrollably, posing dangers as life's requirements depend on the planet's natural resources [1]. Despite increasing food and general human needs, Earth's resources remain static and constrained, requiring overcoming environmental and human challenges. Overpopulation, Climate Change, Water Scarcity, Fossil Fuel Depletion, Loss of Biodiversity, Land Degradation, Pollution, Unsustainable Consumption Patterns, Inequality, Resource Distribution, and Lack of Sustainable Practices and Policies are major challenges [2, 3]. Humanity faces a significant difficulty in supplying sustainable food for the current 8 billion people and the estimated 9 to 10 billion by 2050 [4]. Addressing overpopulation, climate change, water scarcity, fossil fuel alternatives, biodiversity preservation, land conservation, pollution reduction, sustainable consumption, resource equality, and implementing sustainable practices and policies is crucial. Global cooperation, innovation, and a collective commitment are needed to balance human needs with environmental stewardship for a sustainable future.

SFP encompasses the entire cycle of growing, gathering, processing, and distributing food, focusing on its long-term social, economic, and environmental viability [5, 6]. This approach aims to meet current and future food demands while minimizing adverse environmental impacts, preserving natural resources, and enhancing the well-being of those within the food system [7, 8]. The continuous food production process involves various social, economic, and environmental dimensions, encompassing tasks from field to table [6, 9]. To transform raw resources into final food products, production integrates agricultural techniques such as cultivation, breeding, and livestock husbandry with industrial processes [10]. This intricate process involves diverse economic activities spanning agriculture, industry, and trade, guided by various principles. In summary, SFP is a comprehensive and multifaceted endeavor that strives to balance the present and future demands while considering its broader impact on society, the economy, and the environment.

Agriculture, encompassing plant and animal-based crops, is pivotal for food production and ensuring food security as all agricultural activities occur on land [11]. The land plays a crucial role in each phase of the food production process, serving as the primary source of ingredients [12]. The direct and indirect connection between land's capability to produce food and sustaining food production and security is influenced by natural and human characteristics such as topography, climate, water resources, and soil quality [13, 14]. SFP aims to create a more adaptable, equitable, and ecologically friendly food system that meets present and future demands [15]. However, significant challenges, particularly environmental factors—affect arid and semi-arid regions. These include climate change, water scarcity[16], soil degradation, pests and diseases [17], urban expansion encroaching on agricultural land [18], and deforestation [19]. Limit land's potential. These issues impact productivity, sustainability, and food security and pose risks to current and future generations. Thus, governments, local and international food organizations, and multidisciplinary researchers must conduct thorough and scientific assessments of land capability for sustainable agricultural production. This assessment is crucial for devising strategies that feed the global population, sustain food production, and secure future generations' access to food, all while prioritizing sustainability and minimizing environmental harm to natural resources.

Two primary methods assess a piece of land's potential for specific purposes. The first involves field surveying and direct observation, requiring physical inspection to evaluate the land's characteristics and suitability in quantity and quality [20]. This method monitors soil features, topography, vegetation cover, water resources, drainage patterns, and other relevant traits [21]. Although this approach yields genuine and accurate data [22], it faces challenges due to staffing, skill, budget requirements, and limitations in monitoring capabilities for large land areas [23]. The second technique, an alternative to the first, employs GIS and remote sensing, which is widely used today [24]. Using satellite or aerial photography, remote sensing gathers data about land cover, land use types, vegetation indices, elevation, and other spatial features [21]. This data is then analyzed and integrated using GIS, facilitating mapping, geographical analysis, and visualization of land suitability for various uses [25]. It is important to note that a comprehensive understanding of land characteristics, limitations, and possibilities often requires a combination of both these techniques in land capability evaluation.

Multicriteria Decision Analysis (MCDA) is a vital spatial decision-making method in geographic information systems (GIS), defined as "a process transforming geographical data and value judgments into decision-making information" [26]. GIS-MCDA methods provide a framework for managing complex decision problems by organizing diverse perspectives into a hierarchical structure and examining the relationships between problem elements [27]. MCDA approaches facilitate a systematic decision-making process considering qualitative and quantitative elements [28, 29]. Common GIS-MCDA methods include AHP [30] and ANP [31]. Thomas L. Saaty developed AHP in the 1970s [32]. Aids in structured decision-making by systematically analyzing and ranking criteria or options [33]. AHP finds applications in various domains, such as business, engineering, healthcare, environmental management, and public policy [34]. It evaluates and ranks alternatives based on multiple criteria, facilitating tasks like site selection, product design, performance analysis, and risk assessment [30, 33, 35]. The AHP approach is beneficial for assessing land capability, allowing stakeholders to compare and analyze various land choices [36] systematically. However, the Analytic Network Process (ANP), an extension of AHP, addresses complex decision problems by capturing and modeling interdependencies, feedback cycles, and interactions between criteria and options[36]. Despite the effectiveness of ANP, it has drawbacks, including complexity, limited guidance for complex networks, sensitivity to changes, and inconsistent data [37]. Decision-makers should consider ANP's limitations when determining its suitability for a specific decision problem and available resources. In conclusion, choosing between AHP and ANP for multi-criteria decision analysis depends on the specific problem's complexity and nature [38].

Food production is a key component of global food security and has substantial social, economic, and environmental implications [39]. KRI, the area of this research, is provided with a richness of the natural and human resources required for food production, such as a sizable agricultural area, water resources, a suitable climate, manpower, etc. The most pressing issues are the ongoing population growth, unplanned urban sprawl on agricultural land, the expansion of wasteland and degradation of agricultural land, the effects of land use change, etc. [40]. These issues negatively impact the land's potential and pose significant challenges to sustainable food production. As a result, the main objective of the study is to assess the capability of the land for sustainably producing food in KRI by using and integrating the F-AHP Hybrid model and F-ANP methodology so that the relevant parties may develop plans to achieve this sustainability and ensure food security.

2. Methodology

2.1. Study Area

The Iraqi Kurdistan region, the first federally recognized region according to the Iraqi Republic's constitution, spans from 32°38'43" to 37°22'16" N latitudes and 41°19'58" to 46°20'40" E longitude in northern and north-eastern Iraq, sharing borders with Turkey, Syria, and Iran, Figure 1. Encompassing the Erbil, Sulaimani, and Duhok provinces, it covers approximately 39,602 km^2, with a population of 6.17 million, constituting 15% of Iraq's total population [41]. The region boasts natural and human principles conducive to sustainable food and agricultural production, featuring diverse topographical features, including complex and straightforward mountain ranges, hills, plains, and large valleys, with elevations ranging from 160 m to 3607 m above MSL. The Mediterranean Sea's climatic influence, along with location and seasonal variations, results in distinct climate zones, with annual rainfall ranging from 246 to 1155 mm and average temperatures from 21.6 to 13.58°C [42, 43]. Rich water resources contribute to the region's water supply, including springs, rivers, and significant dams like Dukan, Darbandikhan, and Duhok. Major rivers like the Tigris, Great Zab, Small Zab, and Sirwan are crucial, covering around 36.33% of the region in dense and open forest and 25% as excellent rangeland, indirectly supporting the local population's food supply. Despite variations in soil types and characteristics, agricultural production varies across regions, with around 32.76% of the total agricultural land in the region. Cereal crops like wheat and barley dominate about 29% of the region's area, relying on rainwater for irrigation [40]. The Kurdistan Region holds significance in agricultural production, challenges such as unplanned population growth, urban sprawl, agricultural land degradation, deforestation, mismanagement of natural resources, loss of soil fertility, increased bare lands, exploitation of shared water resources by neighboring countries, and climate change consequences pose significant threats. As well as, urban expansion has significantly reduced agricultural land, with many fertile areas being converted into residential and commercial zones. Additionally, the construction of roads, bridges, and buildings has disrupted the natural flow of water, altering drainage patterns and increasing the risk of flooding in some areas. This underscores the need for ongoing land potential assessment and monitoring to formulate effective plans for SFP and ensure long-term food security in the region.

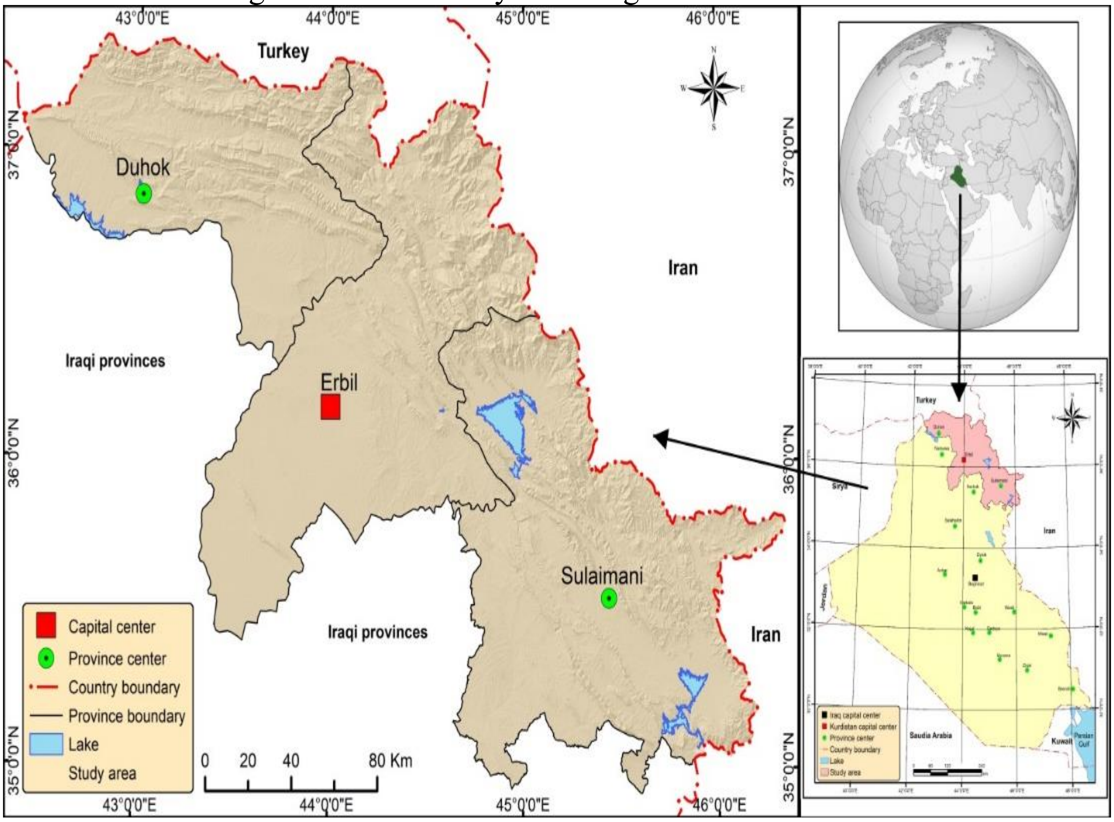

Figure 1: The Kurdistan region according to Iraq country and neighborhood countries.

2.2. Selecting the Assessment Factors

The process of selecting criteria for evaluating alternatives in decision-making is known as the selection of evaluation criteria [44]. Evaluation factors are specific qualities considered crucial for decision-making [45]. Choosing evaluation factors for land capability assessments in SFP ensures environmental, social, and economic considerations [46]. This aids in identifying land suitable for sustainable farming, promoting long-term food security, and mitigating environmental and social impacts [47]. This study incorporates insights from local experts, Ministry of Agriculture standards, previous investigations, and available data to discuss factors influencing a land's capability to generate food. The main factors selected—topography, climate, water resources, land use and land cover (LULCs), geology, soil characteristics, and physical and chemical qualities of soil—are crucial. Eighteen causative factors, including elevation, slope, aspect, temperature, precipitation, proximity to springs, rivers, lakes, LULC, distance from roads, geological formations, soil types, electrical conductivity, soil pH, nitrate, phosphate, potassium levels, and organic matter, were identified. Figure 2 illustrates the hierarchical structure of the Land Capability Assessment and the methodologies employed. All mentioned factors directly and indirectly impact a land's capability to generate food. The availability and suitability of these factors significantly affect land capability [14]. The capability of a piece of land to sustainably produce food is greatly impacted by its topography, which impacts microclimates, soil erosion, water drainage, and general agricultural appropriateness.

A sustainable land use plan must consider topographic factors and manage them. The long-term productivity of agricultural systems is enhanced by practices that consider natural contours, encourage soil conservation, and stop erosion [42]. Another essential component that has a significant impact on crop growth, soil health, and agricultural output overall is the climate elements. Adopting sustainable farming techniques and mitigating climate change require complementary actions. Creating plans that consider climate unpredictability increases the resilience of the systems that produce food and land [42, 43]. Water resources are essential to producing sustainable food because they affect crop development and soil fertility. The long-term viability of agriculture depends on the efficient use, conservation, and appropriate management of water resources. Implementing strategies that handle water-related issues promotes resilience in shifting environmental conditions [48]. Changes in LULC have a major effect on the capacity of the land to produce food sustainably. Ensuring the long-term productivity of agricultural land requires policies that support sustainable farming methods, conservation initiatives, and responsible land use planning. Encouraging human progress and preserving the environment must coexist [49]. Geological characteristics, including soil composition and mineral content, impact agricultural land suitability. Understanding these features is vital for sustainable land management [14]. Soil characteristics are fundamental in determining land's ability to support sustainable food production. Managing soil health through conservation practices and organic amendments is integral to the long-term sustainability of agricultural systems. Adopting these practices ensures optimal conditions for crop growth and overall land productivity [48].

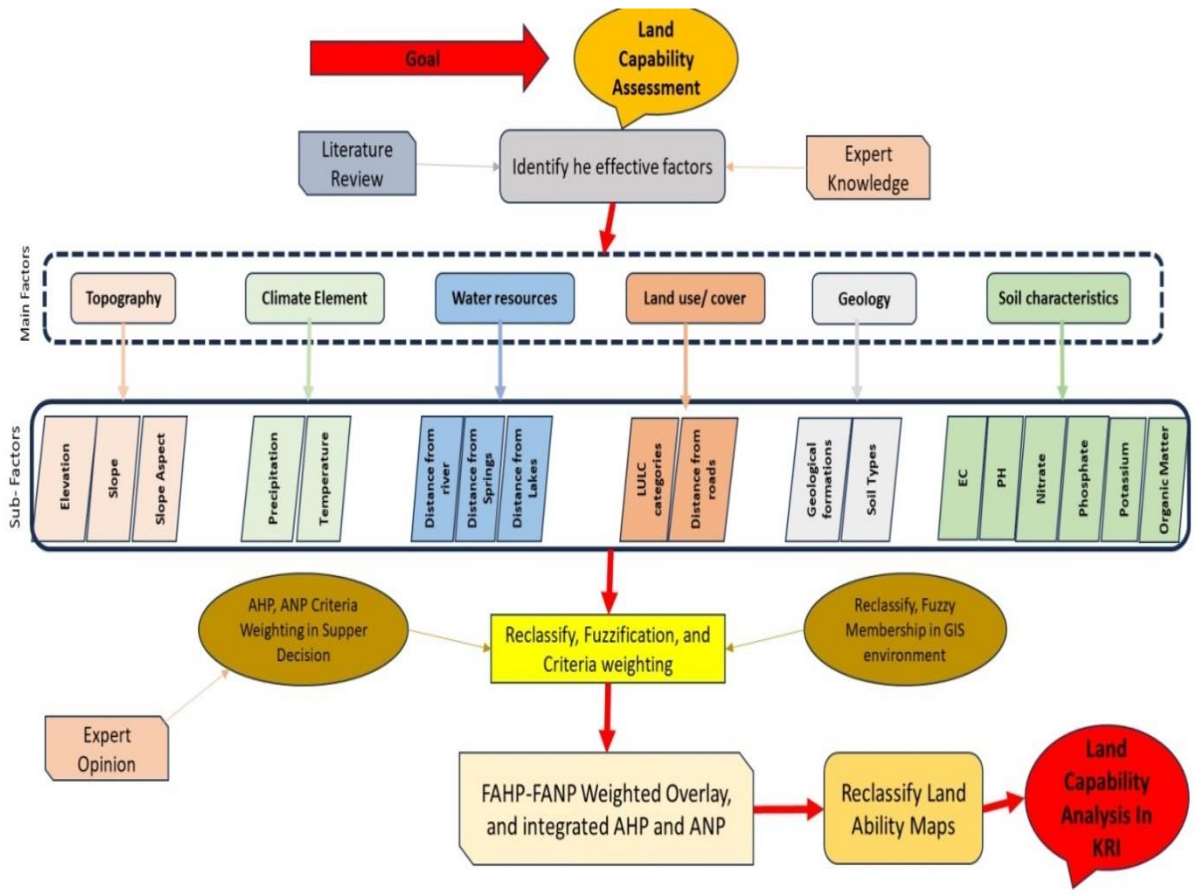

Figure 2: The hierarchical structure of the Land Capability Assessment and a summary of the methodologies employed in the study.

2.3. Collection and Preparation of Data Sets

The study utilized diverse data sets from various sources to assess the quantity and quality of the Kurdistan Region's land suitability for SFP. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and digital elevation model (DEM) data from the United States Geological Survey (USGS) https://earthexplorer.usgs.gov/ with a 30m resolution were employed to analyze physiographic characteristics, such as elevation, slope, slope aspect, river tributaries, and the distribution of springs. The GIS Department of the Ministry of Planning provided data on the points of the Kurdistan Regional Government's springs. Climatic parameters, including temperature and precipitation data, were collected from sixty climate stations across the study area, spanning the past two decades [50]. Landsat OLI-8 satellite images, obtained from the USGS with a 15m spatial resolution, were processed using Object-Based Image Analysis (OBIA) techniques to create a Land Use/Land Cover (LULC) map, categorizing ten classes of LULC[40].

Geological formation maps were derived from Iraq's geological map (Scale 1:250,000) prepared by the FAO Northern Iraq Coordination Office. Likewise, the FAO co-ordination office obtained the soil type map from the FAO representation in Iraq [51]. However, the data on the physical and chemical characteristics of soil, including Electrical Conductivity, pH, Nitrate, Potassium K+, and Organic Matter, were gathered from the agricultural research centers of the provinces of the Kurdistan Regional Government before being produced and processed in the GIS environment. These datasets underwent geometric and thematic editing in the GIS environment, transforming vector layers into raster data with a 30-meter resolution, Figure **3**, 4, and 5. In the inland capability assessment, an exclusive map represents each evaluation factor, and a 'capability score' is assigned to each area unit according to specific criteria. Relative weights for each criterion's contribution to the overall assessment were then assigned as "degrees of capability," reclassified and categorized into five classes with values from 1 to 5 based on their significance (1 being less critical and five being very significant) [45].

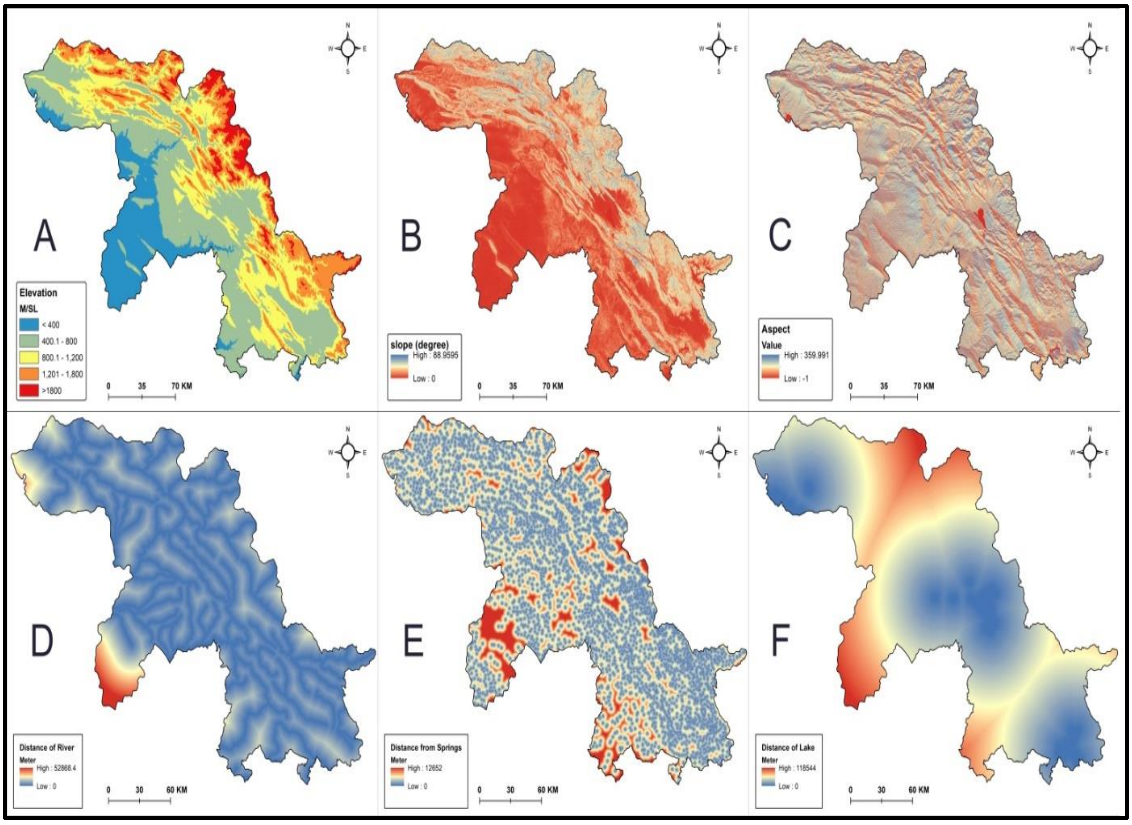

Figure 3: Spatial Distribution of Topographic characteristics and water resources: (A) elevation, (B) Slope, (C) Slope Aspect, (D) Distance from River, (E) Distance from Springs, (F) Distance from Lakes, of the study area.

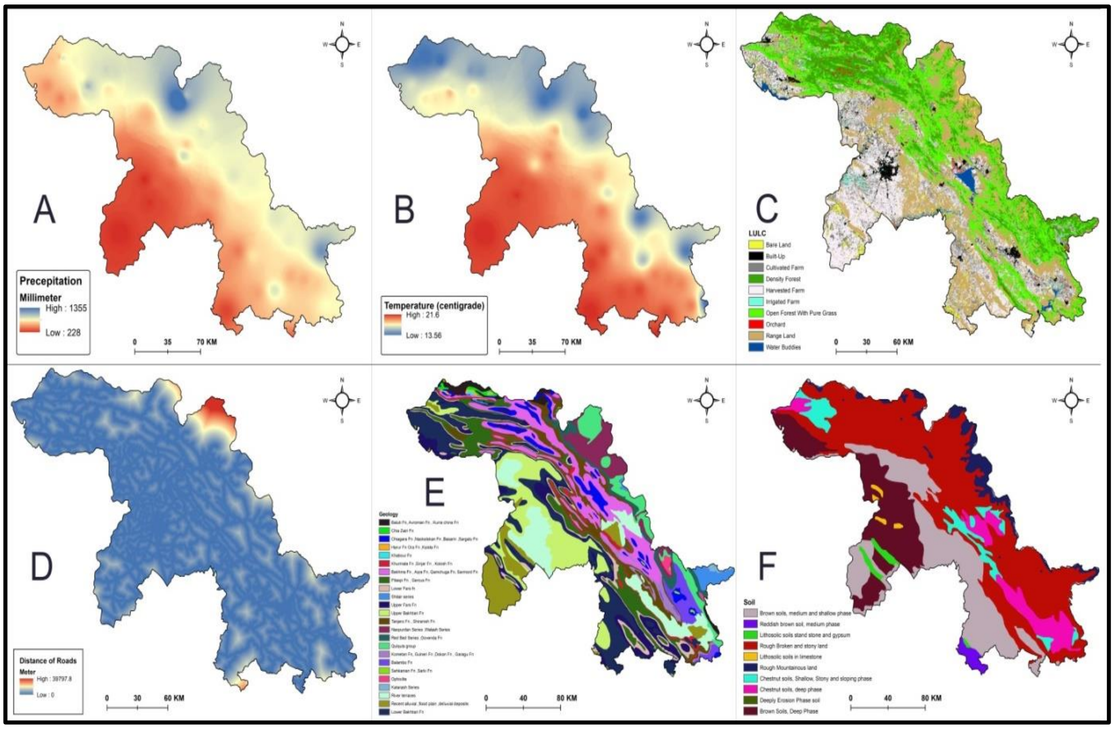

Figure 4: Spatial Distribution of Climate, LULCs, and Geology factors: (A) Average Precipitation, (B) Average Temperature, (C) LULC classes, (D) Distance from Roads, (E) Geological Formations, (F) Soil Types, of the study area.

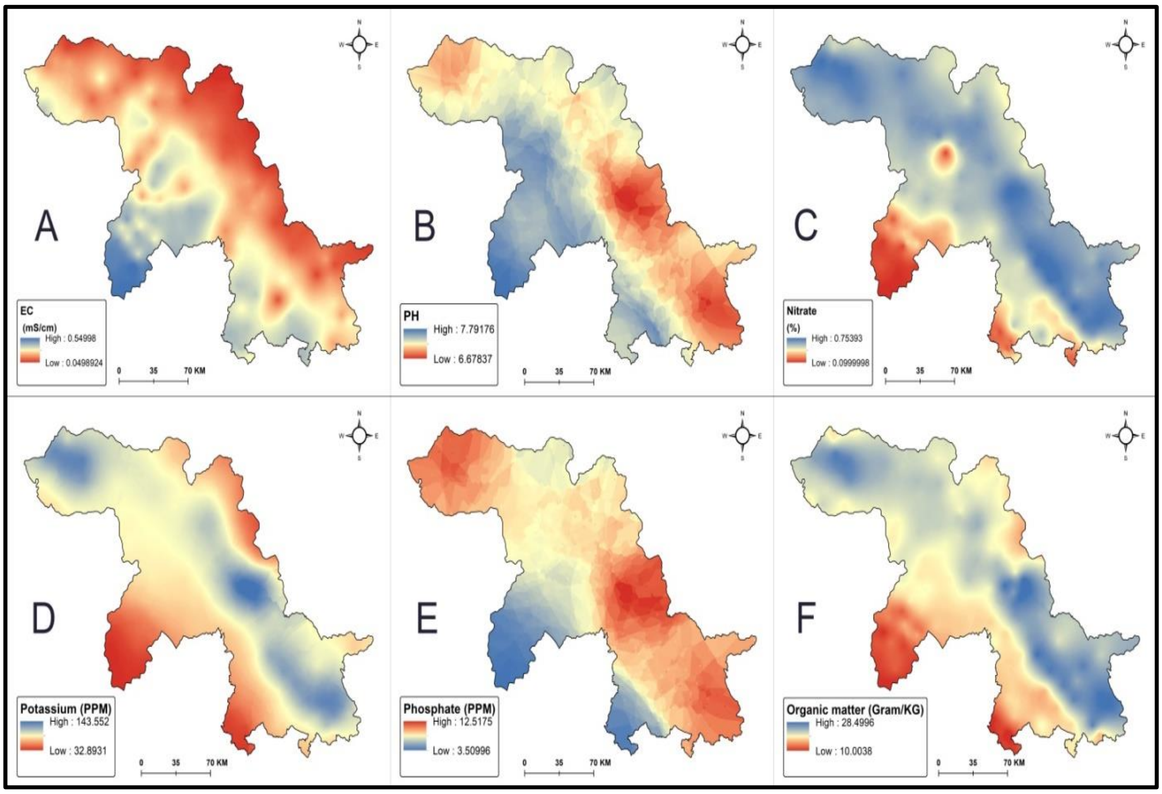

Figure 5: Spatial Distribution of Soil Characteristics: (A) EC, (B) PH, (C) Nitrate, (D) Potassium, (E) Phosphate, (F) Organic matter of the study area.

2.4. Standardization of the Factors

The term "standardization of criteria or factors" in the context of the AHP and ANP methodologies or any Multi-Criteria Decision Analysis (MCDA) method refers to the process of converting the evaluation's criteria to a standard scale or unit of measurement [52]. In MCDA, alternatives were assessed using various criteria, each of which may have a distinct measurement unit, scale, or range. By enabling meaningful comparison and grouping of criteria, standardization ensures they are handled consistently throughout the decision-making process [53]. Put each criterion's raw data on a similar scale, typically from 0 to 1 or 0 to 100 [45]. This phase ensures that all criteria are comparable, regardless of their original measurement scales or units. However, the individual qualities of the criteria and the decision context should be considered while selecting the standardization method. It must ensure that the method chosen is appropriate for the decision problem, meaningful, and free of biases or distortions of the relative relevance of the criteria. Several different techniques were used during the standardization process. In this study, land assessment factors in the Iraqi Kurdistan Region were standardized utilizing the fuzzy membership command in ArcGIS software, considering the benefit/cost context of the indicators. This approach takes into account the degree of fuzzy membership values on a scale of 0–1. Fuzzy input values were linearly transformed on a scale of 0 to 1, where 0 corresponds to the minimum cost value, and 1 denotes the highest benefit value. Refer to

Table 8, while Figure 6 and 7 present the results of the fuzzification process.

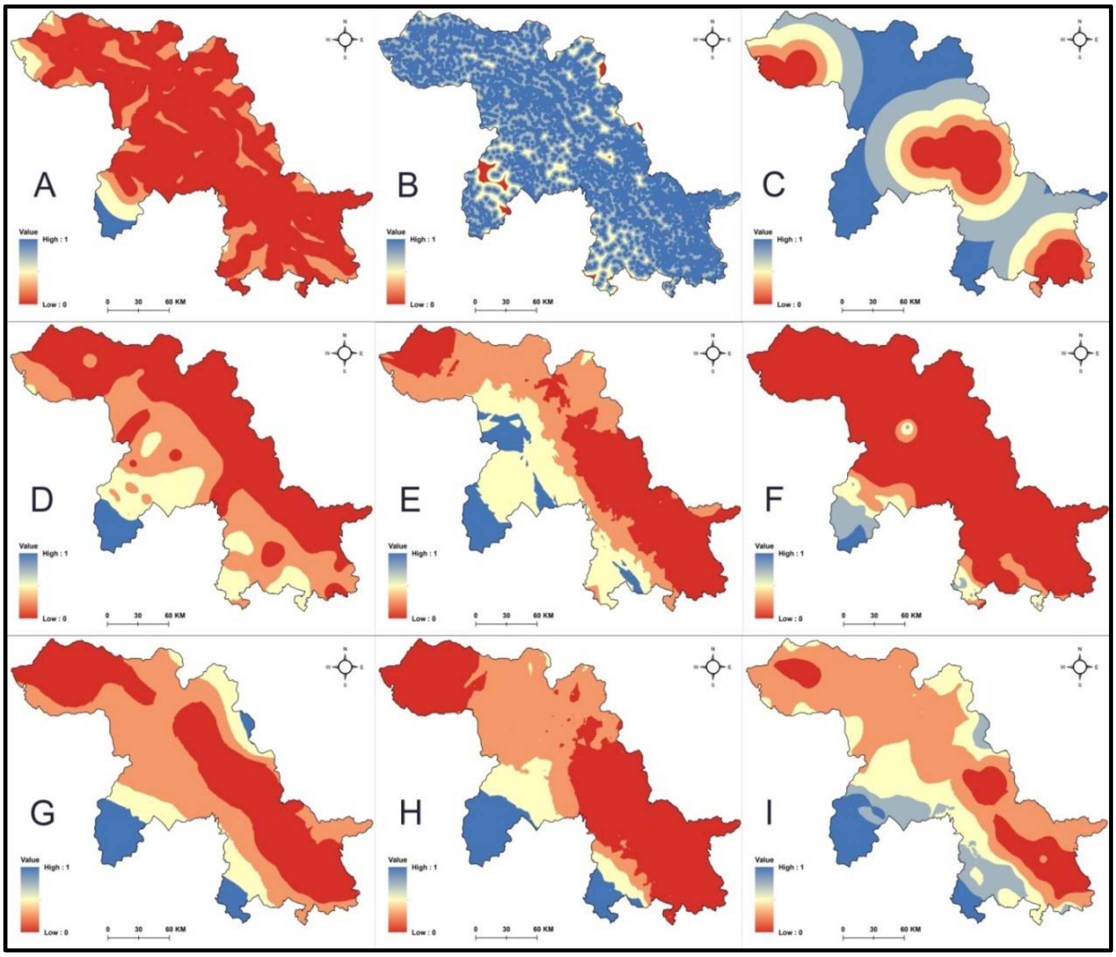

Figure 6: Spatial distribution of fuzzy values of land capability factors: A) River, B) Springs, C) Lakes, D) EC, E) PH, F) Nitrate, G) Potassium, H) Phosphate, and I) Organic Matter.

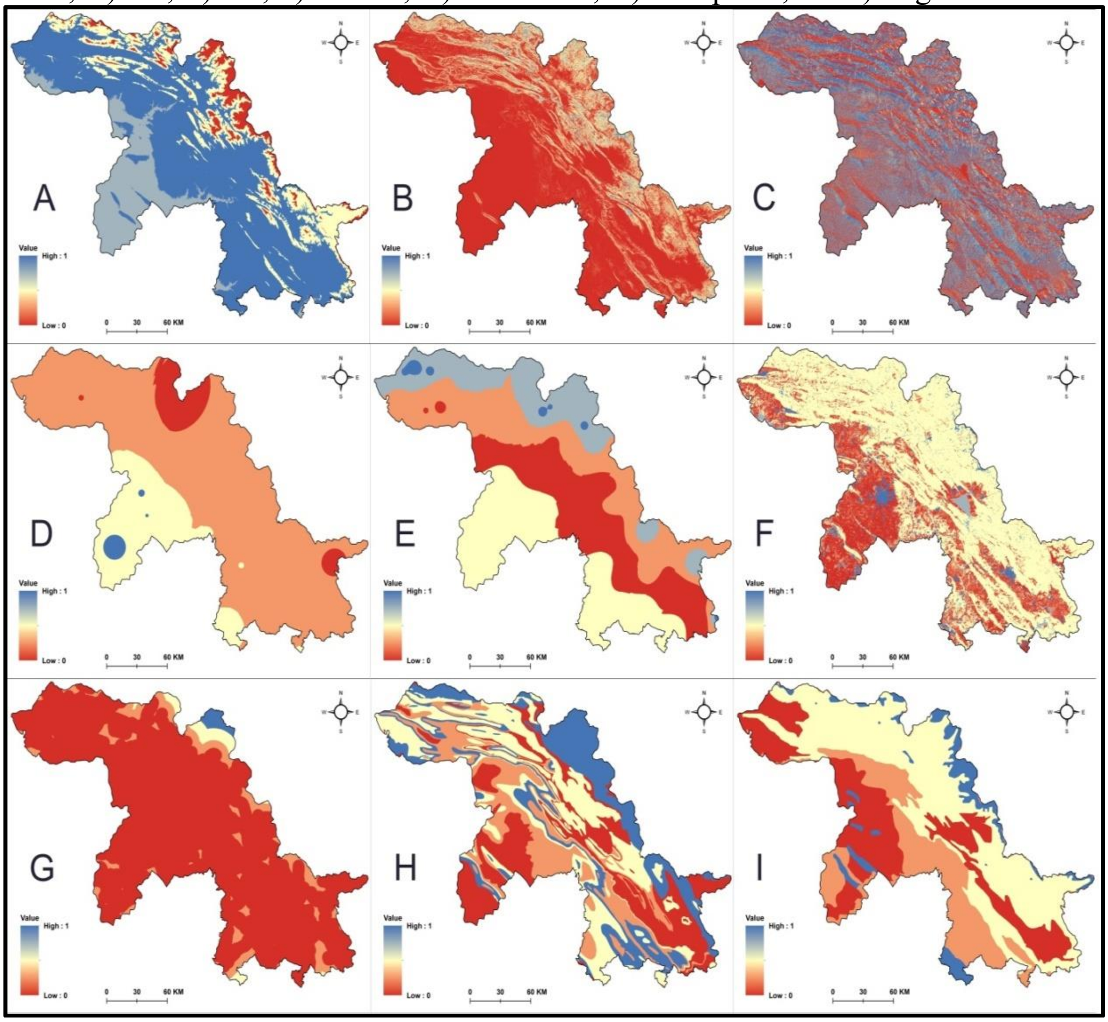

Figure 7: Spatial distribution of fuzzy values of land capability factors: A) Elevation, B) Slope, C) Slope Aspect, D) Precipitation, E) Temperature, F) LULC Classes, G) Roads, H) Geological Formation, and I) Soil Types.

2.5. Weighting Factors and Alternatives

2.5.1. AHP Weighting

As was previously said, AHP is one of the most trustworthy techniques and is regarded as a suitable mathematical technique when analyzing complex decision-making issues [54]. Within GIS-MCDA, the AHP approach can be applied in two different ways, including as a way to generate criterion weights and as a way to overlay data [55]. The AHP was used in land capability assessment to choose between alternatives or establish priorities. To create criteria, a group of factor maps or event control is analyzed and weighted [49]. Criterion weights represent each criterion's relative importance or priority in a decision problem. Several specialists from various fields were interviewed in this study to analyze the significance of the factors and to identify which factors (and to what extent or weight) impact the appraisal of land for food production. These assessments of a criterion's priority were transformed into criterion weights (Wi) using analytical hierarchical process approaches according to Eq. (1) [12].

$$w_i = (\lambda_i / \Sigma\lambda_j) \quad (1)$$

In this equation:

- wi represents the weight for the i-th criterion.
- λi represents the eigenvalue associated with the i-th criterion. The eigenvalue represents the extent to which the i-th criterion is prioritized relative to the others.
- Σλj represents the sum of all eigenvalues.

After that, for each sample point, each index's (Xi) value (Score for each criterion) is calculated based on Eq. (2).

Score for Criterion Xi = Σ (Xi * Wi) (2)

In this equation:

- Xi represents the value or performance of the criterion.
- Wi represents the weight or relative importance assigned to the criterion.

The equation sums up the product of each criterion's value (Xi) and its corresponding weight (Wi). The weights are typically obtained through the eigenvector method by analyzing the pairwise comparison matrix.

In order to obtain the weight of factors and compare the pairs of criteria, sub-criteria pairs, and alternative pairs, the Pair Wise Comparison Matrix technique was used, which is based on the [56] measurement ratio and uses a nine- ratio scale (1 = same importance, 3 = weekly more important, 5 = moderately more important, 7 = strongly more important, 9 = absolutely more important, and 2, 4, 6, 8 = intermediate values) to express individual preferences or judgments. In The pairwise comparison matrix technique, the matrix A, denoted as A=(a_ij), is an (n * n) matrix where n represents the number of criteria being compared. Each element a_ij in the matrix represents the relative importance or preference of criterion i compared to criterion j. [45]. As mentioned, Saaty's scaling ratios, which are numerical numbers that describe the strength of preference or importance, are commonly used to obtain the components of matrix A.

For example, if you have three criteria (n=3), the matrix A would be defined as:

A = | a_11 a_12 a_13 |
| a_21 a_22 a_23 |
| a_31 a_32 a_33 |

Each element a_ij in the matrix A represents the preference or importance of criterion i compared to criterion j. The diagonal elements (a_ii) are usually set to 1 since a criterion is considered equally important to itself. However, Table 1, 2, 3, 4, 5, 6, and 7 display the produced hybrid pairwise comparison matrices for evaluating land capability in the case study area, and

Table 8 lists specifics of the weights applied to the evaluation criteria.

Table 1: Paired comparison of main factors in land capability assessment of the KRI.

Main Factors	(1)	(2)	(3)	(4)	(5)	(6)	Normalized Weight
(1) Topography	1	0.33	0.5	0.5	2	0.5	0.095
(2) Climate Element	3	1	2	2	5	2	0.319
(3) Water resources	2	0.5	1	2	3	0.5	0.175
(4) Land use/ Land cover	2	0.5	0.5	1	2	0.5	0.13
(5) Geology	0.5	0.2	0.33	0.5	1	0.3	0.06
(6) Soil characteristics	2	0.5	2	2	3	1	0.222
CR	0.02279						

Table 2: Paired comparison of Topography Sub-Factors in land capability assessment of the KRI.

Sub-Factors	Elevation	Slope	Slope Aspect	Normalized weight
Elevation	1	0.33	3	0.258
Slope	3.00	1	5	0.637
Slope Aspect	0.33	0.2	1	0.105
CR	0.03703			

Table 3: Paired comparison of Climate elements Sub-Factors in land capability assessment of the KRI.

Sub-Factors	Precipitation	Temperature	Normalized weight
Precipitation	1	4	0.8
Temperature	0.25	1	0.2
CR	0.00000		

Table 4: Paired comparison of Water Resources Sub-Factors in land capability assessment of the KRI.

Sub-Factors	Distance from river	Distance from Springs	Distance from Lakes	Normalized weight
Distance from river	1	2	3.00	0.54
Distance from Springs	0.5	1	2	0.297
Distance from Lakes	0.33	0.5	1	0.163
CR	0.00885			

Table 5: Paired comparison of LULCs Sub-Factors in land capability assessment of the KRI.

Sub-Factors	LULC categories	Distance from roads	Normalized weight
LULC categories	1	5	0.83
Distance from roads	0.2	1	0.16
CR	0.00000		

Table 6: Paired comparison of Geology Sub-Factors in land capability assessment of the KRI.

Sub-Factors	Geological formations	Soil Types	Normalized weight
Geological formations	1	0.2	0.16
Soil Types	5	1	0.83
CR	0.00000		

Table 7: Paired comparison of Soil Characteristics Sub-Factors in land capability assessment of the KRI.

Sub-Factors	EC	PH	Nitrate	Phosphate	Potassium	Organic Matter	Normalized weight
EC	1	0.5	0.25	0.33	0.25	0.22	0.0511
PH	2	1	0.4	0.5	0.4	0.33	0.086
Nitrate	4	2.5	1	2	1.5	0.5	0.2196
Phosphate	3	2	0.5	1	0.66	0.33	0.1308
Potassium	4	2.5	0.66	1.5	1	0.5	0.182
Organic Matter	4.5	3	2	3	2	1	0.3304
CR	0.01537						

2.5.2. ANP Weighting

ANP, a prominent MCDA-GIS technique, is crucial in determining the value and weight of various aspects in different scenarios, influencing decision-making in the real world [31, 57]. The ANP weighing process involves pairwise comparisons, akin to hierarchical analysis, to quantify values and relative importance [58]. Decision-makers construct a network connecting variables (criteria and alternatives) and assign numerical values to depict the strength of these connections [59]. The network's clusters capture cause-and-effect interactions, feedback loops, and dependencies in the decision problem [60]. The ANP methodology for weighting comprises several steps [31, 57]:

- Constructing an analytical model (network): Describe the problem, identify contributing variables, provide alternatives, and involve specialists in relevant sectors to construct a representative network.
- Pairwise comparison matrices and calculation of factor weights: Considering the higher network level and internal communication, creating matrices for criterion and sub-criterion influence, using a numerical scale (e.g., 1 to 9) to express relative preferences. This phase, crucial in ANP, involves comparing the relevance and impact of primary and auxiliary components through a network representation of direct and indirect linkages, requiring accurate collaboration with experts.
- Supermatrix construction: Combining local priorities and dependencies between components at various levels to create the supermatrix, illustrating how factors at one level affect those at another. The supermatrix for each level combines the weights of lower-level elements connected to higher-level elements. For obtaining global weights in a system with interdependent influences, ANP employs three matrix analyses: the supermatrix, the weighted supermatrix, and the limit (unweighted) matrix.

However, priority weight was determined using the pairwise comparison matrix as follows: Combine the local priority matrix P (obtained from pairwise comparisons within the current level) with the dependence matrix D (representing the interdependencies between elements from different levels) to form the supermatrix A Eq. (3):

$$A= (1-W)\,I+W.P.\,D \tag{3}$$

Where: W is a constant representing the dependence matrix's influence level. I is the identity matrix.

Then, the formula for calculating the eigenvector V is given by Eq. (4):

$$A\cdot V=\lambda\cdot V \tag{4}$$

Where: A is the supermatrix. V is the eigenvector (column vector) containing the relative priorities. λ is the corresponding eigenvalue. (Table 8) displays the final normal ANP weights for each criterion.

2.6. Verifying the accuracy of the final pairwise comparison judgment matrix

Both AHP and ANP approaches use the Consistency Ratio (CR) as a metric to evaluate the consistency of the pairwise comparison matrix. It is helpful to assess the accuracy and internal coherence of the judgments made in the matrix [61]. The eigenvector method is a mathematical technique used by the AHP and ANP methodologies to guarantee assessment consistency. The relative weights of the criteria or alternatives are represented by the matrix's primary eigenvector, which is calculated [62]. The consistency of the matrix is then compared to a randomly produced matrix of the same size to determine the consistency ratio (CR) [63]. It was calculated by dividing the random index (RI) value by the consistency index (CI) value [31]. The following formula is used to get the CR Eq. (5):

$$CR = CI / RI \tag{5}$$

The consistency index (CI), which measures the inconsistency of the matrix, is determined using the formula below Eq. (6):

$$CI = (\lambda\_max - n) / (n - 1) \quad (6)$$

The symbol λ_max in the formula denotes the matrix's most significant eigenvalue, while the matrix's order (the number of comparison criteria or alternatives) is denoted by n. On the other hand, the random index (RI) is a pre-determined value based on the matrix's size and is used as a reference for determining the acceptability of the consistency ratio.

A CR of 0.10 or less indicates a satisfactory level of consistency. If the CR is less than 0.10, it was determined that the weight values are accurate and reliable and that the pairwise comparison matrix has adequate consistency. Besides, if the CR is greater than 0.10, the pairwise comparisons are inconsistent, and the matrix should be changed along with the element values [31].

2.7. GIS Based Sustainable Land Capability Mapping

In GIS, overlaying map layers involves merging spatial datasets to make informed decisions with diverse criteria [64]. Integrating MCDM approaches with GIS has advanced land capability evaluations beyond traditional map overlay methods [45]. Weighted overlay integrates various input data by applying a common scale of values [65]. The 18 factors listed above in this research categorize land's SFP capability. These factors underwent processes including transformation into layer classes, standardization through fuzzification, and utilization in establishing eucalyptus suitability using GIS tools. After determining factor weights with ANP and AHP, standardized and weighted criteria were combined via the weighted overlay approach to map land capability separately for AHP and ANP methods, based on Eq. (7) below.

$$\boldsymbol{A = \sum_{i=n}^{n} (Wi\, Xi)} \quad (7)$$

Where A is the Capability, Wi is the weight of factor i, and Xi is the criterion score of factor i.

While the outcomes of the two approaches in this investigation show minimal differences, each MCDA method has drawbacks and may be susceptible to certain uncertainties and confusion related to judges' decisions, method complexity, incomplete or subjective data, ambiguity, predictability, or diverse perspectives [66]. This study combined the two methodologies to achieve a more acceptable outcome. The map algebra function in the GIS environment was used to aggregate the average results of the two maps, Figure 9 andFigure 11, into a layer. This process resulted in the final classification map of land capability for SFP, presented in Figure 12. The land capability maps for the study area were classified into five categories: competent land, moderately capable land, low capable land, limited capable land, and negligible capable land.

3. Results

3.1. Weights and Priorities of Criteria

Table 8 presents a comprehensive overview of rankings and weights derived from F-ANP and F-AHP analyses. The AHP technique prioritizes climatic elements as the most crucial factor (weight of 0.318) in assessing the land's sustainable capability across all six main datasets. Additionally, soil characteristics, water resources, land use, and topography carry weights of 0.2215, 0.175, 0.1299, and 0.0952, respectively, with geology considered the least influential (weight of 0.06). Within the Topography criteria, based on previous AHP partial weights in Table 1, 2, 3, 4, 5, 6, and 7, slope emerges as the most critical sub-criterion (weight of 0.637).

In the current study, the ANP weighting method was employed to validate AHP weights, resulting in minor differences in the weights of main and sub-factors while maintaining consistent priority orders. Notably, the weights of factors underwent substantial changes, as illustrated in Figure 8, with precipitation ranking highest (0.19929) and slope aspect ranking lowest (0.00381) in weight.

To ensure the reliability of our evaluations, the consistency index (CI) and consistency ratio (CR) equations were utilized. All main factors and sub-factors exhibited consistency ratios well below 0.1, indicating high consistency in the pairwise comparisons and the appropriateness of relative weights for assessing land capability.

Table 8: Final rankings and weights for the factors of the assessment of the capability of the land to produce food were determined through a pairwise comparison of experts using the ANP and AHP methods.

Main groups of data	Sub-Factors	Reclassified factors	Ranks of Reclassified Factors *	Fuzzy membership Values	AHP overall weights	ANP Weights	CR
Topography	Elevation (m)	< 400	4	0.6 - 0.8	0.03013	0.03568	0.01756
		400 – 800	5	0.8 - 1			
		800 – 1200	3	0.4 - 0.6			
		1200 – 1800	2	0.2 - 0.4			
		>1800	1	0 - 0.2			
	Slope (°)	< 7	5	0.8 - 1	0.08496	0.06583	0.03703
		7 – 15	4	0.6 - 0.8			
		15 – 25	3	0.4 - 0.6			
		25 – 40	2	0.2 - 0.4			
		>40	1	0 - 0.2			
	Slope Aspect	F	5	0.8 - 1	0.01126	0.00381	0.0781
		N, NE, NW	4	0.6 - 0.8			
		E	3	0.4 - 0.6			
		S, SE, SW	1	0 - 0.2			
		W	2	0.2 - 0.4			
Climate Element	Precipitation (mm)	< 250	1	0 - 0.2	0.18096	0.19929	0.00355
		250 – 400	2	0.2 - 0.4			
		400 – 700	3	0.4 - 0.6			
		700 - 1000	4	0.6 - 0.8			
		>1000	5	0.8 - 1			
	Temperature (°)	< 14	2	0.2 - 0.4	0.05406	0.06594	0.01759
		14 – 16	5	0.8 - 1			
		16 – 18	4	0.6 - 0.8			
		18 – 20	3	0.4 - 0.6			
		>20	1	0 - 0.2			
Water resources	Distance from the river (km)	< 2	5	0.8 - 1	0.07975	0.0873	0.00911
		2_4	4	0.6 - 0.8			

* Detailed weights for ranges of criteria between 1–5 (5 equal to very important and 1 equal to less important for Land capability assessment)

		2_6	3	0.4 - 0.6			
		6_10	2	0.2 - 0.4			
		>10	1	0 - 0.2			
	Distance from Springs (km)	< 1	5	0.8 - 1	0.04458	0.06768	0.02312
		1_2	4	0.6 - 0.8			
		2_3	3	0.4 - 0.6			
		3_4	2	0.2 - 0.4			
		>4	1	0 - 0.2			
	Distance from Lakes (km)	< 10	5	0.8 - 1	0.04902	0.07151	0.00691
		10_20	4	0.6 - 0.8			
		20_30	3	0.4 - 0.6			
		30_40	2	0.2 - 0.4			
		> 40	1	0 - 0.2			
Land use/ Land cover	LULC categories	Waterbodies	2	0.2 - 0.4	0.09262	0.09876	0.02135
		Built-up/Bare land	1	0 - 0.2			
		Dense Forest/Open Forest/Rangeland	3	0.4 - 0.6			
		Orchard/Irrigated Farm/Harvested Farm	5	0.8 - 1			
		Dry Farm	4	0.6 - 0.8			
	Distance from the Roads	< 1	5	0.8 - 1	0.0187	0.03285	0.06337
		1_2	4	0.6 - 0.8			
		2_3	3	0.4 - 0.6			
		3_4	2	0.2 - 0.4			
		> 4	1	0 - 0.2			
Geology	Geological formations	Baluti Fn, Avroman Fn, Kurra China Fn/Chia Zairi Fn/Harur Fn Ora Fn, Kaista Fn/Katarash Series/Khabour Fn/Lower Fars fn/Naopurdan Series, Walash Series/Upper Fars Fn	1	0 - 0.2	0.01418	0.01989	0.0651
		Bekhma Fn , Aqra Fn, Qamchuga Fn, Sarmord Fn/Chiagara Fn ,Naokelekan Fn ,Basarin ,Sargalu Fn/Khurmala Fn, Sinjar Fn , Kolosh Fn/Ophiolite/Red Bed Series, Govenda Fn/	2	0.2 - 0.4			
		Kometan Fn, Gulneri Fn ,Dokan Fn , Garagu Fn/Lower Bakhtiari Fn/Pilaspi Fn , Gercus Fn/Qandil Series/Upper Bakhtiari Fn	3	0.4 - 0.6			
		Recent alluvial, flood plain, delluvial deposits/Tanjero Fn , Shiranish Fn/Balambo Fn	4	0.6 - 0.8			
		River terraces/Sehkanian Fn, Sarki Fn/Shilair series	5	0.8 - 1			
	Soil Class	Reddish brown soil, medium phase/Deeply Erosion Phase soil/Rough Mountainous land/Lithosolic soils stand stone and gypsum/Lithosolic soils in limestone	1	0 - 0.2	0.05614	0.04631	0.03473
		Brown soils, medium and shallow phase over Bakhtiary gravel	3	0.4 - 0.6			
		Brown Soils, Deep Phase	4	0.6 - 0.8			
		Chestnut soils, Shallow, Stony, and sloping phase/Chestnut soils, deep	5	0.8 - 1			

		phase Rough, Broken, and stony land	2	0.2 - 0.4			
Soil characteristics (Soil Physical and chemical characteristics)	EC (mho\cm)	< 0.15	5	0.8 - 1	0.0195	0.01247	0.03946
		0.15 - 0.2	4	0.6 - 0.8			
		0.2 - 0.3	3	0.4 - 0.6			
		0.3 - 0.4	2	0.2 - 0.4			
		> 0.4	1	0 - 0.2			
	PH	< 7	5	0.8 - 1	0.02892	0.01656	0.04217
		7 - 7.2	4	0.6 - 0.8			
		7.2 - 7.4	3	0.4 - 0.6			
		7.4 - 7.6	2	0.2 - 0.4			
		> 7.6	1	0 - 0.2			
	Nitrate (ppm)	< 0.15	1	0 - 0.2	0.05741	0.05229	0.01469
		0.15 - 0.2	2	0.2 - 0.4			
		0.2 - 0.3	3	0.4 - 0.6			
		0.3 - 0..4	4	0.6 - 0.8			
		> 0.4	5	0.8 - 1			
	Phosphate (ppm)	< 5	1	0 - 0.2	0.04658	0.02518	0.02078
		4_6	2	0.2 - 0.4			
		6_8	3	0.4 - 0.6			
		8_10	4	0.6 - 0.8			
		> 10	5	0.8 - 1			
	Potassium K+ (ppm)	< 50	1	0 - 0.2	0.05224	0.03504	0.05388
		50 - 70	2	0.2 - 0.4			
		70 - 90	3	0.4 - 0.6			
		90 - 110	4	0.6 - 0.8			
		110	5	0.8 - 1			
	Organic Matter (gr\kg.)	< 15	1	0 - 0.2	0.07899	0.06361	0.0331
		15 - 18	2	0.2 - 0.4			
		18 - 21	3	0.4 - 0.6			
		21 - 21	4	0.6 - 0.8			
		> 24	5	0.8 - 1			

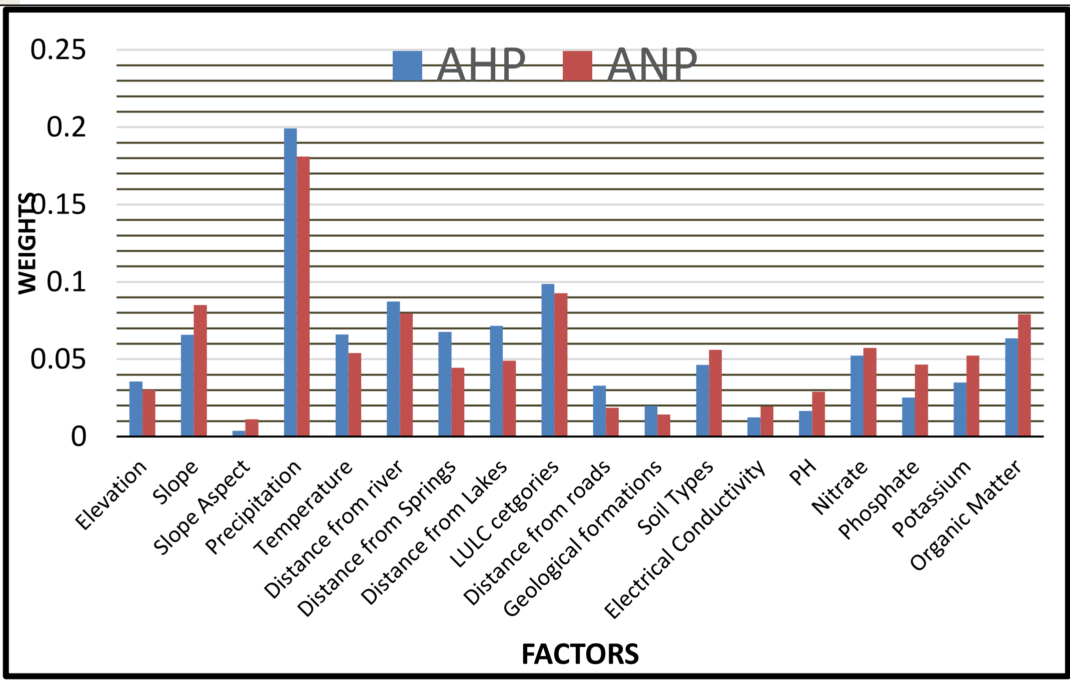

Figure 8: Comparison of factor weights based on the findings of the AHP and ANP weighing Process.

3.2. Land Capability Analysis for SFP of KRI

Final maps illustrating the potential for sustainable food production in the Kurdistan Region of Iraq (KRI) were developed at a scale of 1:20,000. These maps were generated using the Fuzzy Analytic Hierarchy Process (F-AHP) and Fuzzy Analytic Network Process (F-ANP) methodologies for criterion weighting, complemented by the fuzzy overlay method (gamma function) to cluster criteria. The outcome is a raster layer where each pixel is assigned a value indicating ground capacity for sustainable food production (SFP), ranging from low (0.16441) to high (0.88) for F-AHP, low (0.185878) to high (0.900355) for F-ANP, and low (0.175344) to high (0.890178) for the integrated F-AHP and F-ANP methodologies. Higher values signify greater SFP potential, while lower values denote lower capacity levels. Subsequently, the results were classified into five land potential zones, with values and areas measured in square kilometers and analyzed across the provinces of the Kurdistan Region.

The distribution map of land capacity for sustainable food production in the Kurdistan Region, based on the fuzzy-AHP hybrid model, is illustrated in Figure **9**, complemented by Table 9, which showcases the spatial distribution across the region and its three provinces in terms of area and percentage. According to this analysis, approximately 3121.7 km² (7.883%) of the Kurdistan Region's land area is currently considered negligible for food production potential, while 6945.9 km² (17.54%) was classified as limited for food production. The largest portion of the region, encompassing 14363 km² (36.27%), exhibits low capability for SFP, with the second-largest area (11048 km², 27.9%) demonstrating a moderate capability. However, only 4123 km², representing 10.41% of the region's total land area, possesses a high potential for sustainable food production.

Table 9: Spatial Distribution of Land Capability class for SFP based on the result of AHP

Land Capability Levels	KRI provinces						KRI	
	Erbil		Sulaimani		Duhok			
	Area km^2	%	Area km^2	%	Area km^2	%	Area km^2	%
Highly capable land	519.9	3.548	2847.545	19.019	755.594	7.5742	4123	10.41
Moderately capable land	2817.88	19.23	4704.292	31.421	3526.21	35.347	11048	27.9
Low capable land	5052.99	34.48	5082.963	33.95	4226.68	42.369	14363	36.27
Limited capable land	3734.64	25.49	1761.587	11.766	1449.63	14.531	6945.9	17.54
Negligible capable land	2528.54	17.25	575.3675	3.843	17.8198	0.1786	3121.7	7.883
Total	14654	100	14971.75	100	9975.94	100	39602	100

A fuzzy-ANP analysis was conducted to compare and validate the F-AHP results in land capacity evaluation. The outcomes of this methodology are detailed in Figure 10 and Table 10. The analysis reveals significant differences between limited and low-capacity land, with limited-capacity areas expanding from 17.54% to 19.51% compared to the AHP Hybrid method, while low-capacity land decreases from 36.27% to 33.9%. However, minimal variation is observed in other land potential categories.

While the Analytic Network Process (ANP) is often praised for its effectiveness, its complexity can introduce uncertainty. Therefore, this study adopts a combined approach, utilizing ANP and AHP methods. The averaged results, informed by expert weighting and pairwise comparison matrix processing, are the final analysis of land capability for sustainable food production in the Kurdistan Region. The resulting land capability distribution map, derived from integrating the fuzzy-AHP hybrid and fuzzy-ANP models, is presented in Figure 12, accompanied by Table 11, illustrating the spatial distribution across the Kurdistan Region and its provinces in terms of area and percentage. According to the final study outcomes, the classification of land capability for SFP estimates that 3295.4 km² (8.321%) of the Kurdistan Region's land is currently negligible for food production, while 7168 km² (18.1%) is limited. The largest area of the region (13534 km², 34.18%) demonstrates low potential for SFP, with the second-largest area (11358 km², 28.68%) showcasing moderately capable land. However, only 4245.7 km², equivalent to 10.72% of the region's total land area, exhibits high potential for producing sustainable food for future generations. This study combined the two methodologies to achieve a more acceptable outcome. The map algebra function in the GIS environment was used to aggregate the average results of the two maps, Figure 9 and Figure 11, into a layer. This process resulted in the final classification map of land capability for SFP, presented in Figure 12. The land capability maps for the study area were classified into five categories: competent land, moderately capable land, low capable land, limited capable land, and negligible capable land.

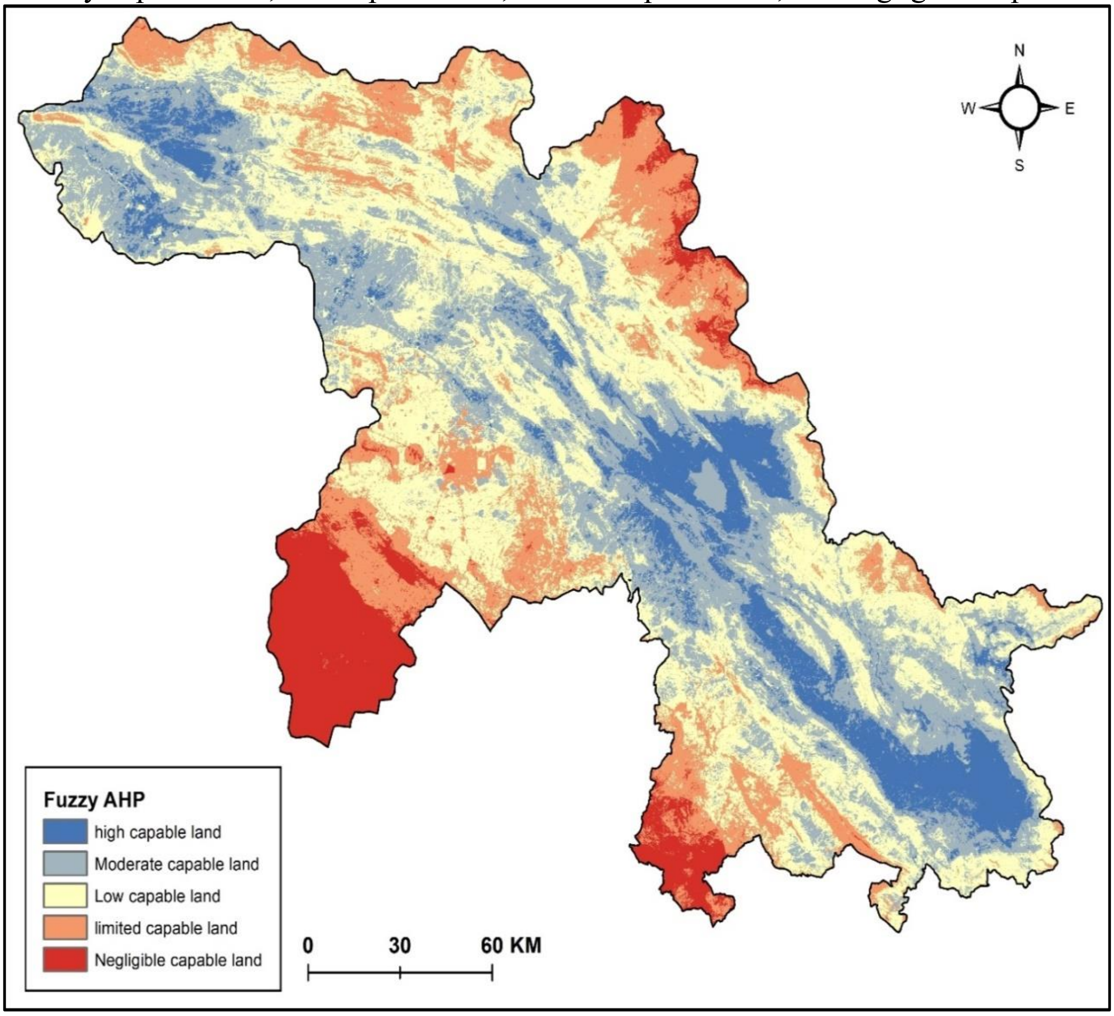

Figure 9: The outcome of the F-AHP method-based land capability map for SFP in the study area.

Spatial analysis by provinces within the Kurdistan Region highlights Sulaymaniyah as having the highest concentration of high and moderate productive land, accounting for 19.69% (2947.86 km²) and 32.15% (4813.59 km²) of the total area, respectively. In contrast, Erbil province exhibits smaller potential for SFP, with only 3.85% and 20.04% of the county's area classified as high and moderate capable, respectively. Duhok, the smallest province in the northwest, primarily consists of land with moderate or low capability for SFP, representing 36.17% and 39.43% of the total area, respectively. Despite its smaller size (733.26 km²), Duhok demonstrates a significant proportion (7.35%) of high-capability land for sustainable food production.

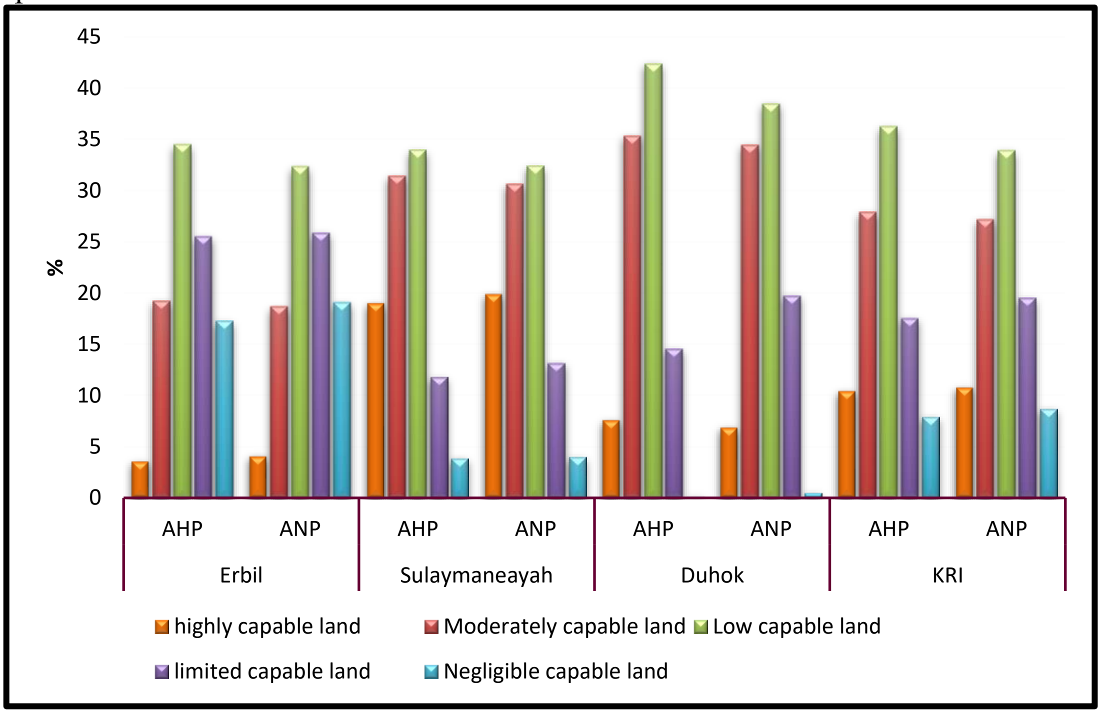

Figure 10: Land capability classes at the regional and provincial levels based on the findings of the FAHP and FANP methodologies.

Table 10: Spatial Distribution of Land Capability class for SFP based on the result of ANP

Land Capability Levels	**KRI provinces**						**KRI**	
	Erbil		**Sulaimani**		**Duhok**			
	Area km2	**%**	**Area km2**	**%**	**Area km2**	**%**	**Area km2**	**%**
Highly capable land	595.548	4.064	2979.296	19.899	683.74	6.8539	4258.6	10.75
Moderately capable land	2735.7	18.67	4584.266	30.619	3438.44	34.467	10758	27.17
Low capable land	4737.15	32.33	4849.334	32.39	3838.22	38.475	13425	33.9
Limited capable land	3791.22	25.87	1966.384	13.134	1967.9	19.727	7725.5	19.51
Negligible capable land	2794.33	19.07	592.4854	3.9573	47.6371	0.4775	3434.5	8.672
Total	14654	100	14971.77	100	9975.95	100	39602	100

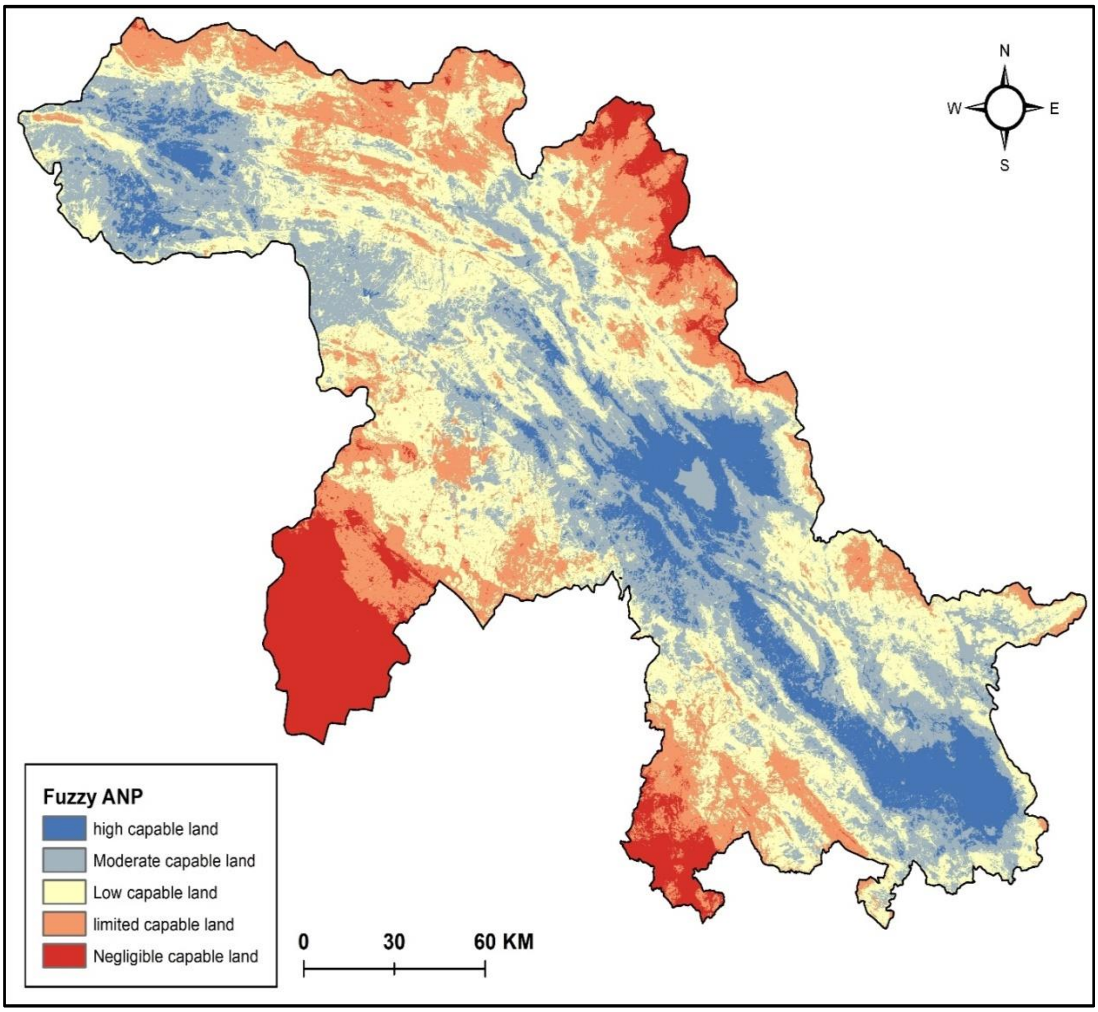

Figure 11: The outcome of the FANP method-based land capability map for SFP in the study area.

4. Discussion

Assessing land capability for sustainable food production is critical, particularly in the Kurdistan Region of Iraq, where environmental and geographical factors significantly impact agricultural potential. This study employed weighted overlay techniques based on MCDM using GIS methods, generating three land suitability maps through a hybrid model integrating Fuzzy-AHP and Fuzzy-ANP methodologies. Rankings and weights for various land capability factors were analyzed.

The findings highlight the critical role of climatic factors, assigned the highest priority in the AHP weighting (0.318), while geology was the least influential (0.06). Compared to previous studies, slope was identified as a significant factor, aligning with findings from [12, 14]. The analysis underscores the interplay of soil characteristics, water resources, land use, and topography, each contributing distinct weights to land capability. The slope criterion emerged as crucial, as slopes exceeding 10-12% hinder mechanical cultivation and contribute to soil erosion, reducing food production potential [67]. Precipitation was the most significant climate sub-criterion (0.80), given the reliance on rain-fed irrigation [68]. Among water resources, rivers were the most critical sub-factor (0.539), emphasizing their role in irrigation during dry seasons [69, 70]. Other influential factors included LULC categories, soil types, and organic matter, with weights of 0.833, 0.833, and 0.33, respectively.

AHP overall weights ranked precipitation highest (0.181), followed by LULC categories (0.093) and slope (0.085). In contrast, the slope aspect was the least relevant (0.011). A comparison with previous studies [45] confirmed precipitation and fertility as dominant criteria. The integration of fuzzy-ANP provided further validation, revealing shifts in sub-factor prioritization and emphasizing evolving methodologies in land capability assessments.

Figure 12 illustrates declining land capability in southern and southwestern Kurdistan, mainly due to reduced rainfall, climate change, and drought [42]. In the north and northeast, rising topographical barriers and soil degradation contribute to reduced food production [71]. Conversely, highly and moderately capable lands are concentrated in central plains, lower elevations, and areas benefiting from guaranteed rainfall [72, 73]. Spatial distribution analysis indicates that Sulaimani province has a higher concentration of suitable lands, attributed to its productive plains and reliable rainfall [43, 74]. Erbil province faces challenges despite major dams due to uncertain rainfall and complex topography zones [42, 43, 75].

In conclusion, this study comprehensively assesses land capability in the Kurdistan Region, highlighting the challenges and opportunities for sustainable food production. By integrating diverse methodologies and interdisciplinary insights, these findings support informed policy and land management decisions to enhance agricultural resilience and productivity.

Table 11: Spatial Distribution of Land Capability Class for SFP Based on Aggregation of F-AHP and F-ANP

Land Capability Levels	KRI provinces						KRI	
	Erbil		Sulaimani		Duhok			
	Area km2	%	Area km2	%	Area km2	%	Area km2	%
Highly capable land	564.525	3.852	2947.861	19.689	733.267	7.3504	4245.7	10.72
Moderately capable land	2935.99	20.04	4813.593	32.151	3608.62	36.173	11358	28.68
Low capable land	4804.45	32.79	4795.76	32.032	3934.14	39.436	13534	34.18
Limited capable land	3670.34	25.05	1824.922	12.189	1672.74	16.768	7168	18.1
Negligible capable land	2678.68	18.28	589.6236	3.9382	27.0891	0.2715	3295.4	8.321
Total	14654	100	14971.76	100	9975.85	100	39602	100

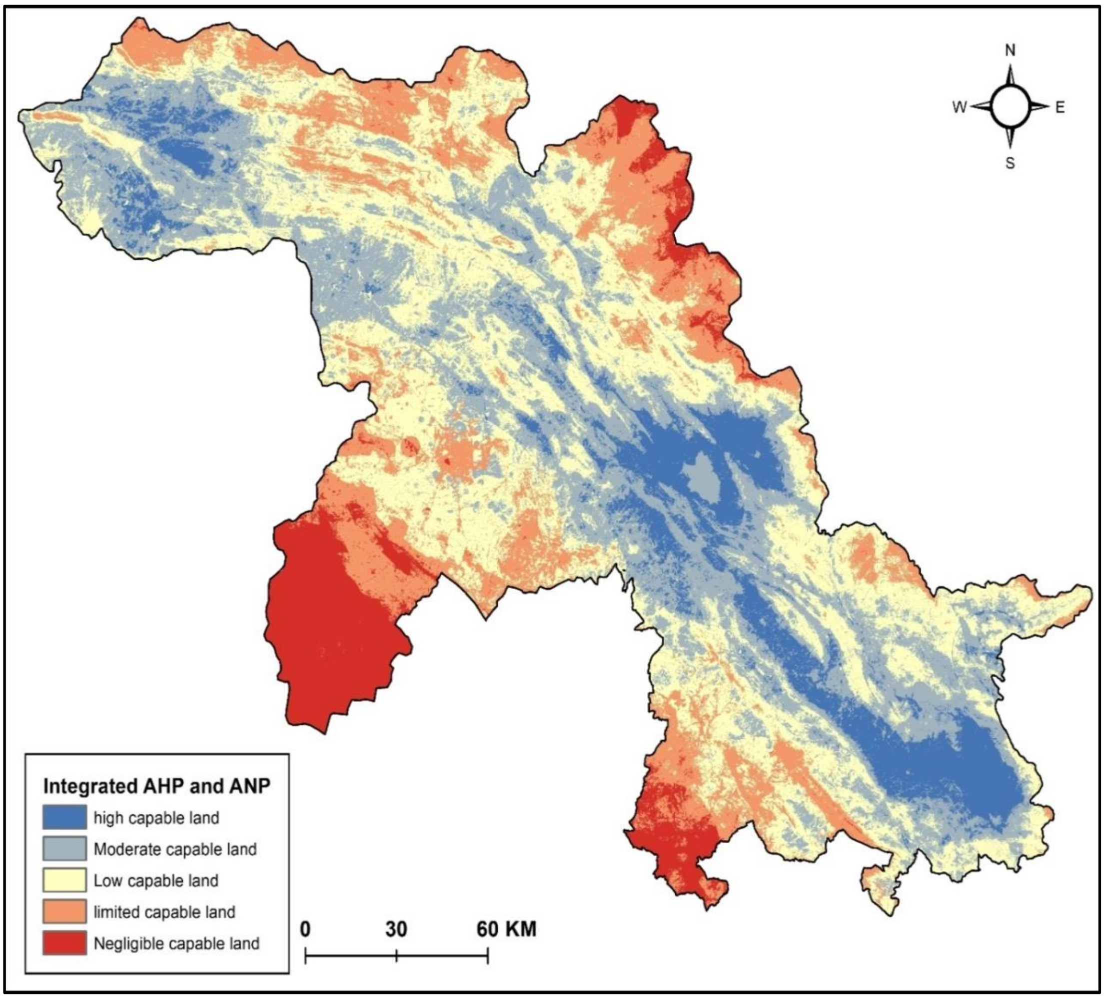

Figure 12: The outcome of land capability mapping for SFP in the study area, based on integrated F-AHP and F-AHP methodologies.

5. Conclusion and Future Work

Evaluating the land's capability and proficiency for SFP is essential for planning for future sustainable land resources and formulating an appropriate long-term food security strategy. While the Kurdistan Region is currently a significant source of food production in Iraq, it is critical to monitor and evaluate the capability of the land for SFP in order to create effective plans for SFP, guarantee long-term food security, and ensure that future generations receive their fair share of natural resources. Therefore, to determine the capability land for SFP in KRI, this study used multiple GIS-MCDA approaches. According to the study, only 10.72 percent of Kurdistan's land is highly capable of food production. A large portion of its land (%34.18) has a low capability for food production. This means that several kinds of climatic, water, LULC, and topographical obstacles to food production are present in the majority of the agricultural land in the Kurdistan Region, and it is anticipated that these obstacles will deteriorate over time as a result of challenges like population growth, unplanned urbanization at the expense of agricultural land, the growth of wasteland, and degradation of agricultural land, the effects of land use change, etc., that are noticeable and are anticipated to get worse. Therefore, future work may be conducted to extend this methodology to examine how future difficulties will affect land's capability for food production. This is done by setting several scenarios of future land use change and climate challenges and integrating them with the MCDA methodology. However, the current study can strongly recommend that the pertinent parties take a position on the findings and create plans to address the difficulties in creating long-term strategies to maintain food security in the Kurdistan Region, utilizing GIS tools and taking into account data on land use, including the outcomes of the MCDA model. On the other hand, the findings of this study may be helpful to other researchers who may use them for various studies. In conclusion, the results of this study suggest that decision-makers can benefit greatly from a database and lead map created using GIS and the application of multi-criteria assessment (F-AHP and F-ANP).

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Data availability: All data generated or analyzed during this study are included in this manuscript.

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