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Land Suitability Mapping for Sustainable Agriculture in Egypt's Western Desert: A GIS–AHP Framework

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Abstract

This study presents a new way to combine the FAO land suitability framework with the Analytical Hierarchy Process (AHP) and Geographic Information System (GIS) tools to assess how suitable the land is for farming in Egypt's Western Desert, an important area that hasn't been thoroughly examined for its farming potential. Egypt faces increasing food security challenges due to limited arable land and rapid population growth, prompting the need to evaluate the feasibility of expanding cultivation into arid zones. The aim of this study is to assess land suitability across the Western Desert using a multi-criterion, spatially integrated model. Key input parameters include soil type, slope, evapotranspiration (ETo), precipitation, and land use/land cover (LULC). Datasets are sourced from SoilGrids250m, WorldClim, and remote sensing imagery. The AHP is used to assign weights based on expert evaluation, and a GIS-based weighted overlay analysis is applied to generate a suitability map. Results indicate that 20.74% of the area is highly suitable (S1), 41.56% moderately suitable (S2), and 37.36% marginally suitable (S3), with only 0.33% considered currently not suitable (N1). Notably, no areas fall under the permanently not suitable (N2) category, indicating strong potential for land reclamation if supported by appropriate interventions. These findings suggest that the Western Desert holds considerable agricultural promise, provided that challenges related to water availability, infrastructure, and sustainability are addressed. The study provides a transferable methodology to support evidence-based agricultural planning and national policy efforts aimed at land reclamation and food security enhancement.

1. Introduction

Egypt's fast-rising population has increased food demand and tested its limited arable land. Nearly 95% of Egypt's population lives near the Nile River and Delta, which cover just 5% of the country [1, 2]. Cairo, the capital, has 3820 inhabitants per square kilometer, one of the highest in the world [2]. Overreliance on the Nile Valley and Delta strains agriculture and emphasizes the need for population dispersion. Establishing more agricultural zones, particularly in the Western Desert, which covers two-thirds of Egypt, may reduce population pressures and increase food security.

Egypt has begun major Western Desert agricultural projects to expand arable land and food security. The Toshka Project, or New Valley Project, proposes canalizing Lake Nasser water to irrigate 540,000 acres of barren land. Established in the late 1990s, the effort attempts to reduce Nile Valley population density by creating new agricultural settlements. Despite early hurdles, the initiative has revived to enhance agricultural productivity.

Mustaqbal Misr (Egypt's Future) is crucial to the "New Delta" development. This effort, along the newly built Rod El Farag–El Dabaa axis, intends to recover 2 million acres (500,000 in the first phase) for agriculture [3]. The plan aims to boost agricultural production and create jobs for the economy. These programs demonstrate Egypt's commitment to managing land resources in the Western Desert and promoting sustainable agriculture. The study intends to simplify large-scale agricultural initiatives like Toshka and Mostakbal Misr using land suitability evaluations. The results will improve food security, land use, and Western

Desert agricultural expansion. While many existing studies focus on areas that are already cultivated or located in more favorable agro-climatic zones, there is a noticeable gap in suitability research for hyper-arid regions like the Western Desert, particularly using integrated multi-criteria approaches. This study addresses that gap by applying the FAO (Food and Agricultural Organization) framework, Analytical Hierarchy Process (AHP), and GIS-based spatial overlay in a context of national-scale land reclamation. The goal is not to compare different methodologies but to provide a practical and transferable assessment model tailored to environmentally and logistically complex regions

A regional land suitability study evaluates land's potential for agriculture. Scholarly efforts have focused on land suitability to meet expanding global food demand due to population growth. To ensure food security, the FAO predicts a 70% increase in food production by 2050 as the global population approaches 10 billion [4]. The dilemma is exacerbated by arable land shortages and soil degradation from overexploitation, urbanization, and climate change [5]. To boost output and sustainability, researchers have focused on finding suitable agricultural locations, particularly in neglected or marginal soils.

GIS and RS are essential for land suitability evaluations. GIS is important for accurate and efficient assessment of agricultural sites due to their spatial nature [6, 7]. Assessing agricultural land suitability requires several disciplines and criteria. It includes land topography, climate, irrigation water supply, soil qualities, and current management methods, including land usage and land cover. This complexity necessitates advanced decision-support tools like MCDM. MCDM excels in weighting land suitability parameters [8–10]. The AHP is a typical multi-criteria decision analysis (MCDA) approach for solving geographical issues like determining whether land is farmable. The Analytic Hierarchy Process (AHP) [11, 12] is widely used in planning, resource allocation, water resource management, and agricultural land suitability evaluation. Many worldwide case studies have employed the AHP approach and GIS application tools to assess land suitability. Pairwise comparisons and weighted multi-criteria analysis of biophysical and socioeconomic aspects are used. Similar methodologies have been successfully applied for site selection of solar energy plants, showcasing the versatility of the GIS-AHP approach [13].

The study of agricultural land suitability uses AHP and MCDA, two strong decision-making methods [14]. With GIS and AHP, one may layer quantitative and qualitative criteria on a single platform. This functionality aids agricultural management analysis [15–23]. In the AHP-GIS integrated approach, the study's goals must guide the purpose, criteria, and alternatives. Focus on assessment criteria that are relevant to decision-making and help achieve the goal.

This study evaluates and prioritizes land suitable for agricultural use in Egypt's Western Desert using AHP and MCDA methods [14]. The project intends to help decision-makers and land planners allocate agricultural land efficiently using evidence [24–26]. AHP and GIS are used to identify and outline agricultural growth areas, giving a reliable foundation for sustainable land use planning. To solve the food supply-demand gap, our study helps decision-makers identify the best agricultural areas. It will also help create new communities in these locations, lowering urban infrastructure strain and city population density.

Unlike many prior land suitability studies that focus on limited agricultural zones such as the Nile Delta or Upper Egypt, this research is among the first to apply a combined FAO–AHP–GIS approach across the extensive and arid Western Desert of Egypt. Globally, hyper-arid land suitability assessments using GIS and multi-criteria decision analysis have been successfully employed in regions such as Algeria—for durum wheat cultivation in the Mleta area [27], arid zones in eastern Iran using fuzzy logic approaches [28], and olive cultivation in Mersin, Turkey [29]. These works underscore the value of integrating climatic, edaphic, topographic, and infrastructural parameters. In contrast, previous studies in Egypt have largely targeted governorates in the Nile Delta or Upper Egypt [17, 30], with limited spatial scope. This study extends suitability mapping to a hyper-arid setting of large scale, integrating FAO-derived ETo with high-resolution DEM, SoilGrids, and LULC datasets, thereby offering a comprehensive, reproducible framework for reclamation planning in under-explored Egyptian desert regions. The novelty lies in the integration of multi-criteria geospatial analysis with a strategic focus on policy-driven agricultural expansion zones (e.g., Toshka and Mostakbal Misr), providing a replicable model for suitability evaluation in hyper-arid regions undergoing large-scale reclamation.

The anticipated outcomes of this study include the generation of an agricultural land suitability map based on FAO classifications, a quantitative ranking of key environmental factors through AHP, and spatially informed land management guidance to support sustainable agricultural development in this hyper-arid region.

In addition, the nation requires strategic planning to develop ways to meet its water demands for drinking, agriculture irrigation, and green spaces. It's important to think about long-term solutions that can reach the above goals, protect lives and property, and use that water for irrigation in gardens and green spaces instead of dumping it into sewage systems and having to be treated again. Numerous studies showed ways to treat and mitigate it [4]. Maintaining resources and components for future generations while solving the present issue is a key objective of sustainable development [31–33].

2. Material and Methods

To achieve the objectives outlined above, this section presents the datasets, criteria, and geospatial methodology used to assess agricultural land suitability in the Western Desert. This section describes Egypt's Western Desert's agricultural viability assessment methodology and methods. Section subsections describe the study area, datasets, and methodological framework, including the AHP. This section meticulously explains the data's origin, its processing, and the way AHP measures and combines land suitability criteria. The flow chart's methodological framework illustrates the stages from data preparation to creating an agricultural suitability map. **Figure 1** depicts the framework. All thematic maps and spatial analyses are conducted using ArcGIS Desktop 10.8 (ESRI), which served as the primary platform for map generation, reclassification, and weighted overlay analysis.

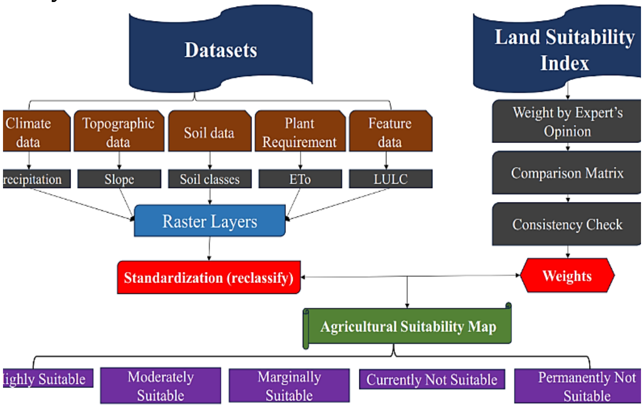

Figure 1. Methodological framework for agricultural land suitability assessment

2.1. Study area

Western Desert covers 680,650 square kilometers, or two-thirds of Egypt as shown in **Figure 2**. **Table *1*** indicates the research area's location using WGS84 coordinates. It has oases, plateaus, and depressions. The seven oases are Al-Karajah, Al-Dakhilah, Al-Farafirah, Al-Baḥriyyah, Paris, East of El-Oienat, and Siwa, the largest and most populated. The Western Desert extends from the Mediterranean Sea in the north to the Sudanese border in the south and from the Nile River in the east to the Libyan border in the west. Apart from the Great Sand Sea, it is largely a rocky desert.

Table 1. Coordinates of Study area boundaries Geodetic Coordinates (WGS84)

Point	Latitude	Longitude
1	31°39'58"	25°08'35"
2	22°00'52"	24°59'50"
3	22°00'22"	31°14'19"
4	30°50'12"	29°00'38"
5	28°02'59"	30°36'10"
6	24°45'50"	32°47'52"

Western Desert of Egypt depends on the Nubian Sandstone Aquifer System (NSAS) for water. This massive fossil aquifer in northern Africa provides freshwater for the area. NSAS groundwater supports household and agricultural activity in the Western Desert's oasis. Small seasonal rainfall in the northern Western Desert recharges shallow aquifers and sustains some vegetation. However, without irrigation, this rainfall is inadequate for viable cultivation. Egypt has built extensive infrastructure. Under construction: El-Hammam Agricultural Wastewater Treatment Plant. A 120-kilometer canal will transport treated water to irrigate 2 million acres in the Western Delta, converting dry territories into cultivable areas and improving food security. This study relies on strategic water resource availability and use throughout the Western Desert to promote sustainable agriculture and development.

Figure 2. Study area map for the Western desert of Egypt

2.2. Datasets used in Land Suitability

Egyptian Western Desert land must be assessed for agricultural viability using a variety of environmental and land-use considerations. There are five main types of information used to judge the study area: climate data (including rainfall and evapotranspiration (ETo), which shows how much water plants need); topographic data (including land slope); soil data (including soil classifications); and land use/cover (LULC). Considering natural restrictions and cultivation resources, each metric is significant for appraising the land's agricultural potential. These criteria identify physical and biological constraints for agriculture and help prioritize locations with the most agricultural potential for sustainable land-use planning and resource management. This section will carefully explore the five parameters and dataset sources utilized in this research.

2.2.1. Climate Data (Precipitation Depths in the Rainy Season)

As crops' main water source, precipitation affects agricultural productivity. In Egypt's parched Western Desert, rainfall amount and distribution during the rainy season (September–March) determine agricultural viability. Despite the region's low rainfall, precipitation depth may imply irrigation opportunities. The suitability model uses rainfall data to determine sites where rainwater may be utilized efficiently, reducing the requirement for groundwater and irrigation. The WorldClim Version 2 dataset [34], provides 1970–2000 monthly average climatic data. This study uses WorldClim Version 2 global climate layers with a 10-minute spatial resolution. Mean precipitation depths (mm/d) for the six rainy seasons are shown in **Figure 3**.

2.2.2. Climate Data (Evapotranspiration)

Evapotranspiration (ETo) includes evaporation and transpiration to calculate crop water needs. ETo is crucial for agricultural sustainability in water-scarce regions like the Western Desert. High ETo values imply increasing water demand, making locations unsuitable for cultivation without proper irrigation. ETo says integrating ETo into the suitability model helps us understand how much water plants require and locate spots where water consumption may be managed to assist farming. Egypt's ETo is calculated monthly using the FAO Penman-Monteith equation [35]. **Figure 4** illustrates the data's limitation to the research area and its yearly average (mm/d).

2.2.3. Topographic Data (Slope of the Land)

The viability of agricultural activities depends on slope. Steep inclines increase water flow and soil erosion, making agriculture difficult. Farms benefit from flat or moderately sloping terrains because they retain water, reduce erosion, and allow agricultural mechanization. Slope data (%) provides easier terrain more weight in suitability evaluations, making farming more effective and long-lasting **Figure 5**. The DEM, which depicts surface elevation topography, provides the land gradient of the study area [36]. Egypt's Western Desert DEM is geo-referenced to UTM WGS84 Zone 36 North and has a resolution of 1 arc-second (approximately 30 meters). As shown in **Figure 5**, the slope is created from this Digital Elevation Model (DEM) using ArcGIS and the Spatial Analyst Extension to gather data from the April 2018 ALOS World 3D - 30m (AW3D30) version 2.1. [37].

2.2.4. Soil Data (Soil Classes)

Land suitability for agriculture depends on soil texture, fertility, drainage, and salt. Soil classifications influence land suitability for varied crops [38, 39]. Sandy soils in the Western Desert may require fertilizers or irrigation for crop support, although clay-rich soils may waterlog. This study evaluates soil data—physical and chemical—to identify the best agricultural sites. **Figure *6*** shows soil data.

2.2.5. Land Use and Land Cover (LULC)

Land use and land cover (LULC) reveal the study area's land usage, including developed, urbanized, and environmentally protected areas. Such information is crucial for ensuring the appropriateness assessment matches land-use limits. The agricultural suitability evaluation encompasses urbanization, conservation, and other areas. LULC data is used to guarantee the final suitability map contains an area suitable for agricultural conversion. Land use and cover data come from the Environmental Systems Research Institute (ESRI) land cover map, a reliable GIS-based source. ESRI, a global GIS software pioneer, provides better spatial data for precise hydrological modeling [40]. The relationship between land use/land cover and land surface temperature is a critical factor in such studies, particularly in the Egyptian context, as demonstrated by research in the Dakahlia Governorate [41]. **Figure 7** shows land usage and cover in the research region.

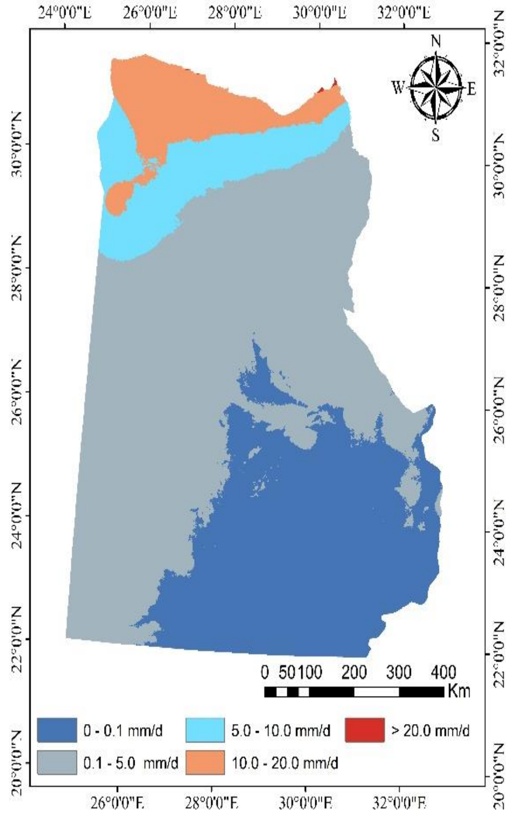

Figure 3. Map of Precipitation (mm/d) of Western Desert of Egypt

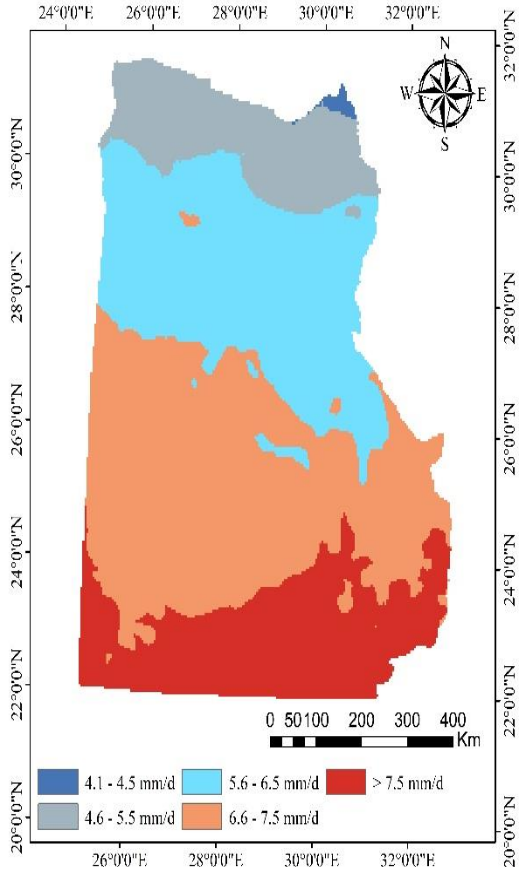

Figure 4. Map of ETo (mm/d) of Western Desert of Egypt

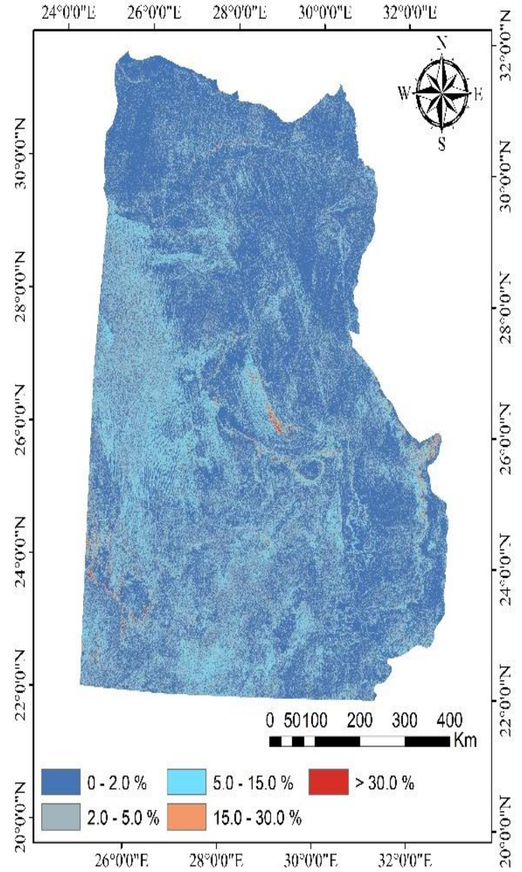

Figure 5. Map of Slope (%) of Western Desert of Egypt

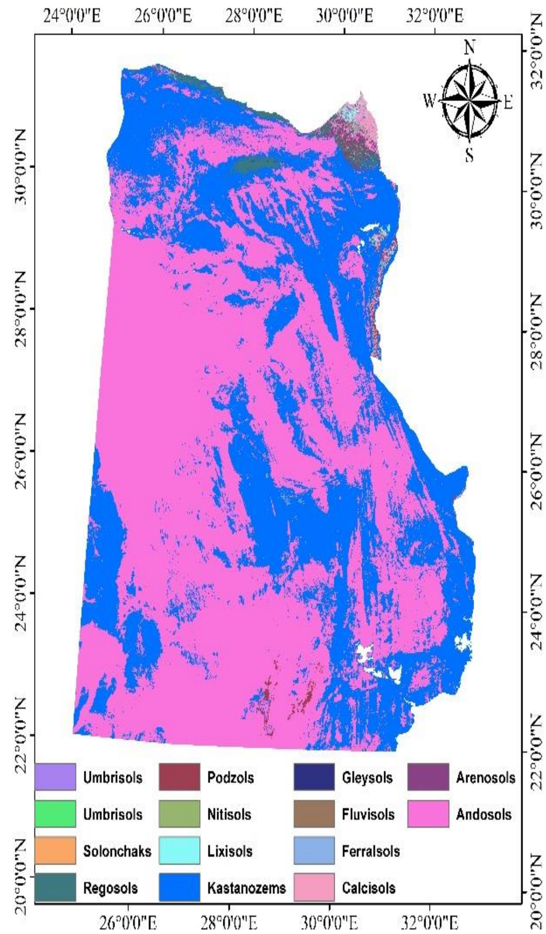

Figure 6. Map of Soil Type of Western Desert of Egypt

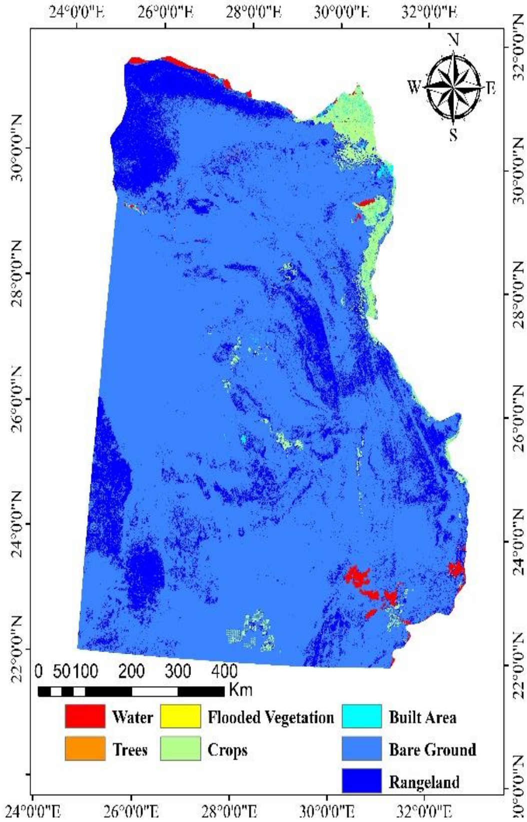

Figure 7. Map of LULC of Western Desert of Egypt

2.3. Analytical Hierarchy Process (AHP)

The AHP, introduced by Saaty [12], is an effective tool for structuring and prioritizing multiple decision criteria. In this study, AHP helps organize complex agricultural parameters into a comparative framework based on expert judgment. This technique incorporates various quantitative and qualitative factors into a unified framework that makes it easy to grasp their relative significance, making it effective for deciding whether land is suitable for agriculture. Analytic Hierarchy Process (AHP) is praised for its orderly approach to ranking criteria and identifying their relative significance via expert assessment, making it perfect for complicated agricultural decisions. It is used in environmental planning, resource management, and land-use appropriateness assessments because of its flexibility considering climate (rainfall and evaporation), topography (slope), soil qualities, and land use/land cover (LULC) when determining agricultural suitability. AHP makes it easy to determine how essential each criterion is and how it impacts a region's appropriateness by ranking them. By using AHP-derived weights, the final suitability map reflects the significance of each criterion in shaping the agricultural viability of the Western Desert, aligning with local environmental priorities. This improves analytical accuracy and utility. The weighted overlay analysis, which follows the AHP procedure, uses five parameters. This research weights these parameters based on expert judgments and literature reviews. Equations (1–5) assess normalized weight consistency using the Consistency Ratio (CR) [42].

2.3.1. Pairwise Comparison Matrix

A pairwise comparison matrix is constructed to quantify the relative importance of each criterion. The comparisons are based on a fundamental scale of 1 to 9, where:

- (1) indicates equal importance,
- (3) indicates moderate importance,
- (5) indicates strong importance,
- (7) indicates very strong importance, and
- (9) indicates extreme importance.

Intermediate values (2, 4, 6, 8) are used to refine judgments.

Preparation of pairwise judgment matrices as follows [21]:

$$\boldsymbol{M} = \begin{bmatrix} \boldsymbol{j_{11}} & \boldsymbol{j_{21}} & \cdots & \boldsymbol{j_{1n}} \\ \boldsymbol{j_{21}} & \boldsymbol{j_{22}} & \cdots & \boldsymbol{j_{2n}} \\ \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{j_{n1}} & \boldsymbol{j_{n2}} & \cdots & \boldsymbol{j_{nn}} \end{bmatrix} \qquad \textbf{Eq. 1.}$$

Where j_n represents the criteria with j_{nn} being the judgment matrix element, and n is the number of criteria.

2.3.2. Normalization of Weights

Once the pairwise comparison matrix is constructed, it is normalized to calculate the relative weights of each criterion [21]. The normalization is performed by dividing each matrix value by its respective column sum:

$$W_n = {GM_n}\Big/{\sum_{n=1}^{Nt} GM_n} \qquad \textbf{Eq. 2.}$$

Where N_t is the number of studying parameters [21], GM_n represents the geometric mean of the *i-th* row in the judgment matrix, calculated using the following equation:

$$GM_n = \sqrt[Nt]{j_{1n}\, j_{2n} \ldots j_{nNt}} \qquad \textbf{Eq. 3.}$$

2.3.3. Consistency Verification

To ensure the judgments in the pairwise comparison matrix is consistent, a Consistency Index (CI) is calculated [21]. A CR value of less than 0.1 indicates acceptable consistency in the judgment matrix. It can be calculated as follows:

$$CI = {\lambda_{max} - N_t}\Big/{(N_t - 1)} \qquad \textbf{Eq. 4.}$$

where λ_{max} is the largest eigenvalue of the matrix. The Consistency Ratio (CR) is then computed as follows:

$$CR = {CI}\big/{RCI} \qquad \textbf{Eq. 5.}$$

Where the value of RCI (random consistency index) is 1.12 in this study since the studying parameters are five according to standard table shown in [32].

The final weighted suitability map is classified according to the FAO land suitability system [S1 (Highly Suitable), S2 (Moderately Suitable), S3 (Marginally Suitable), N1 (Currently Not Suitable), and N2 (Permanently Not Suitable)], based on the reclassified input datasets and their AHP weights. The classification results for each parameter and the overall suitability map are presented in detail in the following Results section.

3. Results

Based on the multi-criteria methodology described above, the following section presents the spatial classification of suitability parameters and the resulting agricultural suitability map. This research uses a systematic approach to evaluate agricultural land suitability in Egypt's Western Desert. Climate (precipitation and evapotranspiration), topography (slope), soil (soil classes), and land use/land cover datasets are integrated. The FAO land suitability system [43], places land into five classes: S1 (Highly Suitable), S2 (Moderately Suitable), S3 (Marginally Suitable), N1 (Currently Not Suitable), and N2 (Permanently Not Suitable). The AHP uses expert judgment to weigh the reclassified datasets, creating a land suitability index.

This section presents the classification of datasets based on FAO suitability classes and the detailed calculation of the AHP method to determine the weight of each parameter. These steps are essential for generating the final agricultural suitability map and understanding the spatial distribution of suitability across the study area.

3.1. Dataset Classification

3.1.1. Precipitation Classification

Given the low precipitation typical of arid regions, the precipitation depths are classified to reflect the reliance on irrigation to supplement natural rainfall. Precipitation depths in the study area are ranged from 0.0 mm to 24 mm. Precipitation is categorized based on its adequacy for crop water needs using the following thresholds [44]

- S1: Precipitation >20 mm/d provides adequate natural water supply for crops, with minimal irrigation required.
- S2: Precipitation between 10–20 mm/d requires supplemental irrigation for optimal crop productivity.
- S3: Precipitation between 5–10 mm/d requires significant irrigation to meet crop water needs.
- N1: Precipitation between 1–5 mm/d makes the land unsuitable without high dependence on irrigation, which can be resource-intensive.
- N2: Precipitation 0 mm/d, where agriculture is not feasible without substantial irrigation.

3.1.2. Evapotranspiration Classification

Evapotranspiration (ETo) represents the water demand for crops, which is a key factor in determining agricultural suitability, especially in arid regions like Egypt. Higher ETo values indicate greater water loss, increasing the need for irrigation. The Eto ranges between 4.0 – 8.2 mm/d. The classification reflects the feasibility of sustaining crops under such conditions [45]:

- S1: Low ETo (4–4.5 mm/d), indicating manageable water loss and minimal irrigation requirements, suitable for a wide range of crops.
- S2: Moderate ETo (4.5–5.5 mm/d), requiring some irrigation but still manageable.
- S3: High ETo (5.5–6.5 mm/d), indicating significant irrigation needs, making the land marginally suitable.
- N1: Very high ETo (6.5–7.5 mm/d), where irrigation is costly and not feasible for most crops.
- N2: Excessive ETo (>7.5 mm/d), making agriculture unsustainable without advanced irrigation techniques.

3.1.3. Slope Classification

Slope affects the suitability of land for agriculture by influencing water retention, erosion risk, and mechanization. The land slope ranges between 0 – 85%. The FAO classifies land based on slope percentage, with steeper slopes posing greater challenges for farming [46]:

- S1: 0–2% slope (Flat or nearly flat) is ideal for agriculture, with no significant limitations for mechanization or erosion risk.
- S2: 2–5% slope (Gently sloping) has minor limitations, with minimal erosion risk and manageable for mechanization.
- S3: 5–15% slope (Moderately sloping) increases erosion risk and requires contour farming or soil conservation measures.
- N1: 15–30% slope (Steep slopes) poses a high erosion risk, limits mechanization feasibility, and requires significant land management.
- N2: >30% slope (Very steep) is permanently unsuitable for agriculture due to severe erosion risks and challenges with mechanization.

3.1.4. Soil Classes Classification

Soil quality is a critical factor in determining agricultural suitability. Soil types are classified based on the characterization guide for agricultural suitability by FAO [47]. The classification of soil types is based on their fertility, texture, drainage, and salinity. This classification assesses the ability of the soil to support agricultural activities [48]:

- S1 (Highly Suitable): Kastanozems, Andosols, and Nitisols. These soils are fertile, well-structured, and have good water-holding capacity, making them ideal for a wide variety of crops.
- S2 (Moderately Suitable): Lixisols, Fluvisols, and Umbrisols. These soils have moderate fertility and are suitable for agriculture with proper management, such as fertilization and drainage control.
- S3 (Marginally Suitable): Calcisols, Regosols, Arenosols, Gleysols, and Podzols. These soils are limited by issues such as low fertility, poor drainage, or sandy texture. They require significant management inputs, including irrigation and fertilization, to support agriculture.
- N1 (Currently Not Suitable): Solonchaks. These soils are characterized by high salinity, making them unsuitable for agriculture without extensive reclamation and management.
- N2 (Permanently Not Suitable): Ferralsols. Highly weathered and nutrient-depleted, these soils are not suitable for agriculture even with substantial interventions.

3.1.5. Land Use and Land Cover (LULC) Classification

Land Use and Land Cover (LULC) data is used to determine the feasibility of converting existing land into agricultural land. The classification reflects the land's current use and its potential for agricultural conversion [7]:

- S1: Crops, which are already under cultivation, are highly suitable for agriculture with existing practices.
- S2: Grasslands, rangelands, bare ground, and trees are moderately suitable, requiring some management to transition into productive agriculture.
- S3: Shrubs/scrub and flooded vegetation are marginally suitable, requiring significant clearing and infrastructure investment for conversion.
- N1: Built areas and water bodies are permanently unsuitable for traditional agriculture but may support aquaculture or other specialized activities.
- N2: Sensitive ecological areas (e.g., wetlands, protected forests) are permanently unsuitable due to environmental concerns.

Table *2* provides a summarized overview of the classification of all parameters based on the FAO land suitability framework.

Table 2. Summarized Classification of Parameters Based on the FAO Land Suitability Framework [48]

Param.	S1	S2	S3	N1	N2
ETo (mm/d)	4.0–4.5	4.5–5.5	5.5–6.5	6.5–7.5	>7.5
Soil Types	Kastanozems, Andosols, Nitisols	Lixisols, Fluvisols, Umbrisols	Calcisols, Regosols, Arenosols, Gleysols, Podzols	Solonchaks	Ferralsols
Prec. (mm/d)	>20	10–20	5–10	1–5	0
Slope (%)	0–2	2–5	5–15	15–30	>30
LULC	Crops	Grasslands, Rangeland, Bare Ground	Shrubs/Scrub, Flooded Vegetation	Built Areas	Water Bodies

3.2. AHP Method Calculation

Following the methodology outlined in the flowchart (**Figure 1**), the AHP method begins by assigning comparison weights for all parameters through the development of a pairwise comparison matrix. This is followed by applying the previously stated calculations to derive the weights for each parameter. Finally, the consistency of the pairwise comparisons is evaluated to ensure the reliability of the judgments.

The pairwise comparison matrix is developed to assign weights to the parameters using the AHP method, as shown in **Table 3**. The relative importance of the parameters in the matrix is determined based on the opinions of a panel of experts. The consistency ratio (CR) of the judgments in the pairwise comparison is calculated to be 0.033, indicating acceptable consistency. The Consistency Ratio (CR) is used to evaluate the logical coherence of the pairwise comparison matrix. A CR value ≤ 0.1 indicates acceptable consistency in expert judgments, ensuring that the weight assignment is reliable and not random [12, 49].

Table 3. Pairwise Comparison Matrix and Final Weights

	ETo	Slope	Precip.	Soil Classes	LULC	Weights
ETo	1	2	2	0.5	2	0.24
Slope	0.5	1	2	0.5	2	0.18
Precip.	0.5	0.5	1	0.5	2	0.14
Soil	2	2	2	1	3	0.34
LULC	0.5	0.5	0.5	0.33	1	0.10
λmax = 5.15, CI = 0.037, RI = 1.12, and CR = 0.033						

3.3. Agricultural Suitability Map

Following the methodology outlined in the flowchart, all datasets are reclassified according to the FAO framework for land suitability and weighted using the AHP. The calculated weights for each parameter are then applied in a weighted overlay analysis, carried out using ArcGIS software. This approach integrates the spatial data layers, ensuring that the relative importance of each parameter, as determined by the AHP method, is accurately reflected in the final agricultural suitability map.

The weighted overlay function in ArcGIS is a GIS-based tool designed for multi-criteria decision-making. It operates by combining multiple raster datasets, assigning relative importance to each dataset through weights. The function evaluates each cell of the input raster, calculates a weighted sum of values for each parameter, and produces an output raster that reflects the aggregated suitability score. In this study, the weighted overlay process assigned higher values to areas more suitable for agriculture (e.g., those with low slope, fertile soil, and adequate precipitation) while penalizing less suitable areas (e.g., those with low fertile soils, steep slopes, or low precipitation). This method ensures that the spatial variability of suitability factors is represented comprehensively in the analysis.

Through the weighted overlay process, an agricultural suitability map is generated, segmenting the Western Desert into classes based on cultivation potential. This visual output supports strategic planning for optimal land use and targeted agricultural development in the region.

4. Discussion

The discussion below interprets the key findings from the suitability analysis, highlighting their implications for agricultural development in arid regions. The agricultural suitability map generated for the Western Desert of Egypt provides a comprehensive spatial representation of the region's potential for agricultural development. By integrating key parameters, such as evapotranspiration, precipitation, soil types, slope, and land use/land cover (LULC), and applying the AHP, the analysis categorized the land into four suitability classes: Highly Suitable (S1), Moderately Suitable (S2), Marginally Suitable (S3), and Currently Not Suitable (N1). While category N2 (Permanently Not Suitable) disappeared in the analysis result. The results, as summarized in the suitability map (**Figure 8**) which reveals the spatial distribution of each suitability class. Also, **Figure 9** illustrates the area percentage of each class.

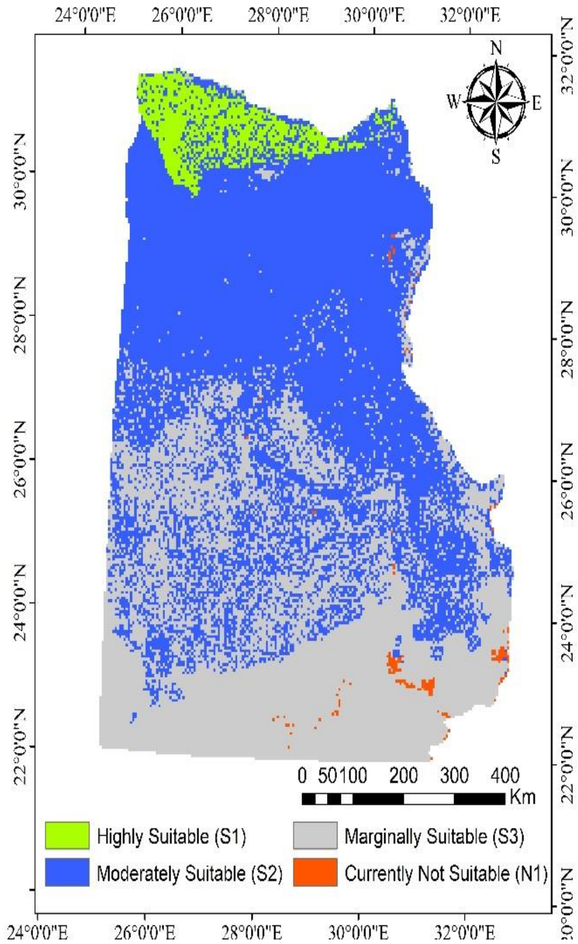

Figure 8. Agricultural suitability map for Western desert in Egypt

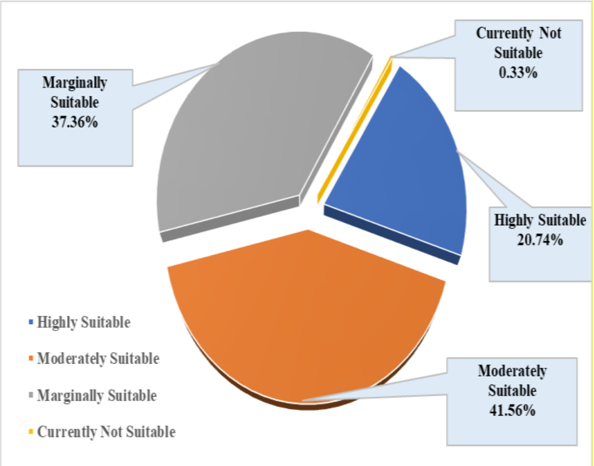

Figure 9. Area percentage of each suitability class

The analysis shows that 20.74% of the land is classified as Highly Suitable (S1), indicating areas with favorable conditions for agricultural activities, such as low plant water requirement, fertile soils, adequate water availability, minimal slope, and available land use/cover. These regions are critical for prioritizing agricultural expansion and sustainable land use planning. Additionally, 41.56% of the land falls under Moderately Suitable (S2), where moderate constraints such as higher plant water requirement, lower fertility or increased irrigation needs require targeted management strategies to optimize productivity.

A significant portion of the land, 37.36%, is categorized as Marginally Suitable (S3). These areas present considerable challenges, such as sandy or saline soils, steeper slopes, high evapotranspiration rates, or less water availability. While they can support limited agricultural activities, substantial investments in land management practices, irrigation systems, and soil improvements are necessary to enhance their agricultural potential. Lastly, a small fraction, 0.33%, is classified as Currently Not Suitable (N1), where severe constraints like high salinity or steep slopes render the land unsuitable for agricultural use without extensive intervention.

The findings of this study bring encouraging news, as they reveal the complete absence of the Permanently Not Suitable (N2) category in the generated agricultural suitability map. This indicates that, with appropriate management strategies and interventions, the entirety of the Western Desert exhibits some level of agricultural potential. The absence of N2-classified land in the map reflects the lack of extreme limiting conditions (e.g., highly sloped terrain, unsuitable soils, or non-agricultural LULC types) in the study area. While this outcome indicates that no land was permanently excluded under FAO criteria, the long-term feasibility of agricultural expansion remains constrained by groundwater availability and resource limitations.

Although precipitation is one of the parameters analyzed in this study, it is considered only a supplementary water source, as its contribution is limited to certain areas and seasons. The primary and more permanent water resources for agricultural activities in the Western Desert are groundwater aquifers, most notably the Nubian Sandstone Aquifer System (NSAS) and the Moghra Aquifer. The NSAS is one of the largest fossil aquifers worldwide, extending beneath Egypt, Libya, Sudan, and Chad, and providing a strategic but essentially non-renewable reserve that supports agricultural development in desert environments [50]. The Moghra Aquifer, underlying the Qattara Depression, is another important Miocene-aged reservoir, where recent studies have delineated its groundwater potentiality and highlighted its significance for regional agriculture [51]. These findings emphasize that, while groundwater availability currently enables agricultural expansion, long-term sustainability is constrained by depletion risks. Integrating suitability mapping with groundwater balance studies, efficient irrigation, and national water management strategies is therefore essential to ensure the viability of future reclamation projects.

The distribution of suitability classes underscores the importance of resource optimization in the Western Desert. The high percentage of moderately and marginally suitable areas highlights the need for tailored strategies, such as selecting drought-resistant crops, improving irrigation efficiency, and applying soil amendments, to maximize agricultural productivity. The suitability map serves as a decision-making tool for policymakers and stakeholders, enabling informed planning for sustainable agricultural development.

Furthermore, the methodology demonstrates the effectiveness of combining the FAO framework with AHP and GIS-based weighted overlay analysis to assess land suitability. The results align with the region's environmental characteristics, providing a scientific basis for addressing food security challenges and guiding future agricultural investments.

This study provides a novel application of this integrated method in Egypt's Western Desert, an area of national strategic importance, yet relatively underexamined in terms of comprehensive suitability mapping. The identification of no permanently unsuitable zones (N2) sets this work apart from many others and underscores the opportunity for informed reclamation, even in hyper-arid terrains, through optimized land and water resource planning.

5. Limitations and Challenges

Despite the utility of the presented model, several limitations related to data, methodology, and implementation context must be acknowledged and are discussed below. This study provides valuable insights into the agricultural suitability of the Western Desert of Egypt; however, several limitations and challenges are encountered during the analysis. A significant limitation lies in the availability and resolution of datasets. While global datasets such as WorldClim, Soil Grids, and ETo are used, their relatively coarse resolution may not fully capture localized variations in parameters like soil type and precipitation. This could affect the precision of suitability classifications for specific areas within the study region.

An additional challenge relates to the reliance on expert judgment in the AHP method, which introduces a degree of subjectivity. Although consistency check is performed to validate the pairwise comparisons, the subjective nature of weight assignment may still influence the final results. Furthermore, socio-economic factors, such as access to markets, transportation infrastructure, and labor availability, are not included in this analysis, even though they are critical for practical agricultural feasibility. The study also excluded certain environmental factors, such as biodiversity and ecosystem preservation, which are essential considerations for sustainable land-use planning.

While groundwater availability is a key strength of the Western Desert, certain critical aspects of groundwater resources are not addressed in this study. Parameters such as groundwater salinity and depth (unavailable data for this study area), which significantly influence irrigation quality and cost, are not analyzed. Salinity levels can restrict crop options and necessitate costly water treatment measures, while the depth of groundwater determines the energy and financial costs of extraction. Moreover, the sustainability of these aquifers, many of which are non-renewable fossil aquifers, is not studied. Without evaluating the longevity of groundwater resources, there is uncertainty regarding how long these water sources can sustain agricultural activities in the region, especially under increasing extraction demands.

Field validation (ground-truthing) of soil profiles and other land characteristics is not conducted in this study due to the vast spatial extent and inaccessibility of much of the Western Desert. Instead, the analysis relies on high-resolution, globally calibrated datasets such as SoilGrids250m, which integrates field observations with machine learning algorithms and is widely used in regional and global land suitability assessments. While this approach ensures consistency and reliability at broad scales, future work may incorporate targeted field sampling in select zones of interest to further validate and refine model outputs, particularly for localized implementation planning.

Finally, the long-term sustainability of land suitability under changing climatic conditions, including potential impacts on precipitation and evapotranspiration, is not explicitly analyzed. While the FAO framework provided a robust classification system, its rigid boundaries may oversimplify gradual transitions in land characteristics, potentially overlooking marginal variations in suitability.

These limitations highlight the need for improved data integration, expanded criteria inclusion, and further research to enhance the robustness and practical applicability of the agricultural suitability assessment.

While the GIS-based AHP method provides a robust framework for multi-criteria decision analysis, it is important to acknowledge the potential for enhancing accuracy and efficiency with more advanced techniques. Future research could explore the integration of machine learning and deep learning algorithms with remote sensing data to overcome some of the inherent limitations of traditional methods. Studies have shown that techniques like Random Forest (RF) and Support Vector Machines (SVM) are effective for agricultural crop type classification, offering improved accuracy in land suitability mapping. Furthermore, deep learning approaches, such as semantic segmentation using convolutional neural networks (CNNs), have demonstrated remarkable potential for tasks like automatic vineyard and greenhouse detection from very-high spatial resolution images, providing more detailed and precise insights for agricultural planning [52–54]. These advanced methods can help to refine the classification process and offer a more dynamic approach to evaluating land suitability in complex environments.

6. Conclusion

This study provides a detailed look at how suitable the land is for farming in Egypt's Western Desert by using a method that combines the FAO land classification system, AHP, and GIS-based weighted overlay analysis. The findings revealed that a substantial portion of the study area is classified as highly or moderately suitable for cultivation, with no regions falling under the "permanently not suitable" category. These results highlight the latent potential of the Western Desert to contribute to national agricultural expansion and food security goals.

However, practical implementation of these findings is not without challenges. The study relies on secondary data, and certain critical factors, such as groundwater salinity, extraction depth, and socio-economic variables, are excluded due to data limitations. Furthermore, while land suitability is promising, the availability and sustainability of irrigation water remain major constraints in this hyper-arid region, particularly given the reliance on fossil aquifers or expensive desalination.

Future research should aim to combine changing water resource models, analyze the costs and benefits of restoring land, and use up-to-date data to improve how we assess land suitability. Moreover, engaging with policymakers, local communities, and environmental stakeholders will be essential to design feasible and sustainable agricultural interventions. This study provides a foundational framework that can be expanded to guide evidence-based land use planning in arid environments.

Given the scale of agricultural initiatives underway in the Western Desert, the results of this study are particularly relevant for policymakers tasked with land resource allocation and national food security planning. The proposed framework supports the design of evidence-based, spatially informed policies that can enhance the viability and sustainability of future land reclamation efforts.

Author contributions

Hesham Ezz: Conceptualization, Methodology, Software, Field study, and Writing-Original draft preparation **Abdel-Wahab Amer:** Conceptualization, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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