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Research article

Geospatial Assessment of Geothermal Potential in the Jeffara Plain, Northwest Libya: A Weighted Overlay Analysis Approach

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Abstract
The Jeffara Plain in northwest Libya represents a critical frontier for low-enthalpy geothermal energy development within the transboundary Northwest Sahara Aquifer System (NWSAS). This study applies an integrated framework combining remote sensing, Geographic Information Systems (GIS), and Multi-Criteria Decision Analysis (MCDA) to delineate geothermal potential zones. Seven thematic layers, magnetic survey, gravity survey, transmissivity, geological setting, aquifer thickness, piezometric surface, and land use were standardized and weighted using the Analytical Hierarchy Process (AHP), then integrated through a Weighted Overlay Analysis (WOA) to derive a Geothermal Potential Index (GPI). The resulting map identifies the Az-Zahra region as the most favorable target, where the Al-Aziziyah geothermal aquifer exhibits temperatures on the order of 50–70 °C at depths of 200–350 m, suitable for direct-use applications such as desalination, greenhouse heating, and low-temperature industrial processes. The spatial correspondence between high-potential classes and existing thermal wells provides qualitative support for the validity of the proposed framework. Comparison with regional North African case studies further suggests that this workflow is transferable and can guide future, more quantitative validation efforts, such as Receiver Operating Characteristic Area Under the Curve (ROC–AUC) analysis for sustainable geothermal exploration in arid, data-scarce environments.
Keywords. Geothermal Energy, Jeffara Plain, Libya, NWSAS, Weighted Overlay Analysis.

Introduction

Libya's energy landscape is transitioning toward renewable sources to mitigate CO_2 emissions and ensure economic sustainability. Low-enthalpy geothermal resources in the Jeffara Plain offer a viable alternative for direct-use applications [1]. Recent research emphasizes that geothermal mapping in arid environments is critical for sustainable energy and water management [2,3]. While previous studies have touched upon these resources, this study provides a comprehensive, spatially explicit assessment integrating MCDA with a robust set of parameters. The main objective of this study is to develop a spatially explicit geothermal potential map for the Jeffara Plain in Northwest Libya using a GIS-based MCDA framework. Specifically, the study aims to: (i) compile and harmonize geophysical, hydrogeological, geological, and land-use datasets relevant to low-enthalpy geothermal exploration; (ii) derive a Geothermal Potential Index (GPI) through AHP-based weighting and Weighted Overlay Analysis; (iii) qualitatively assess the consistency of high-potential zones with available thermal well information; and (iv) identify priority areas, with a focus on the Az-Zahra region, for pilot-scale geothermal development and direct-use applications.

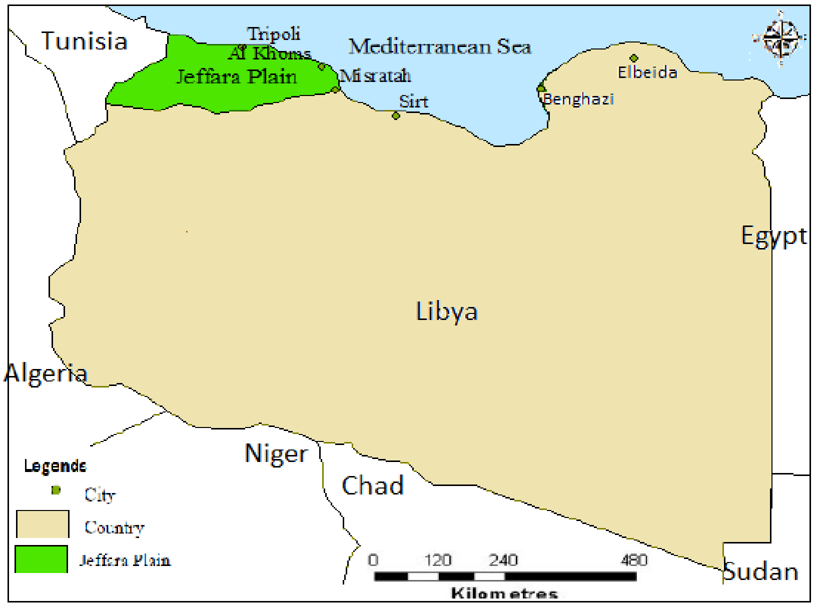

Figure 1. Location map of the Jeffara Plain.

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Regional Geology

The Jeffara Plain is a structural transition zone dominated by Triassic formations, specifically the Al-Aziziyah and Abu Shaybah formations. The structural framework, characterized by step faults, acts as a conduit for deep-seated thermal fluids [2,4,5]. The importance of lineament density as a structural control is highlighted in recent literature, as it directly influences fluid pathways and heat flow patterns [6,7].

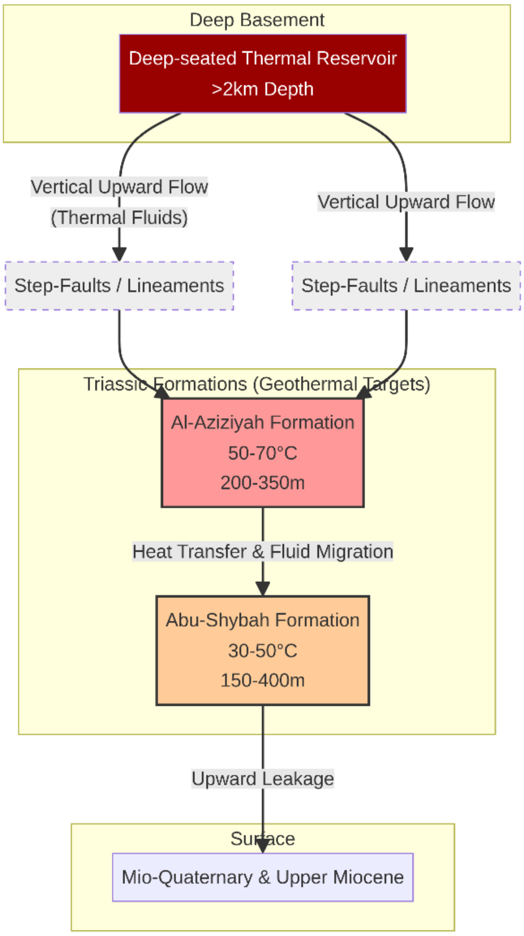

Figure 2. Conceptual model of the Jeffara Plain geothermal system, illustrating the structural control of step faults and lineaments on vertical groundwater flow. Deep-seated thermal fluids rising from basement levels (>2 km) are channeled into the Triassic aquifers, with the Al-Aziziyah formation (approximately 50–70 °C at 200–350 m depth) and the Abu Shaybah formation (approximately 30–50 °C at 150–400 m depth) representing the main low-enthalpy geothermal targets.

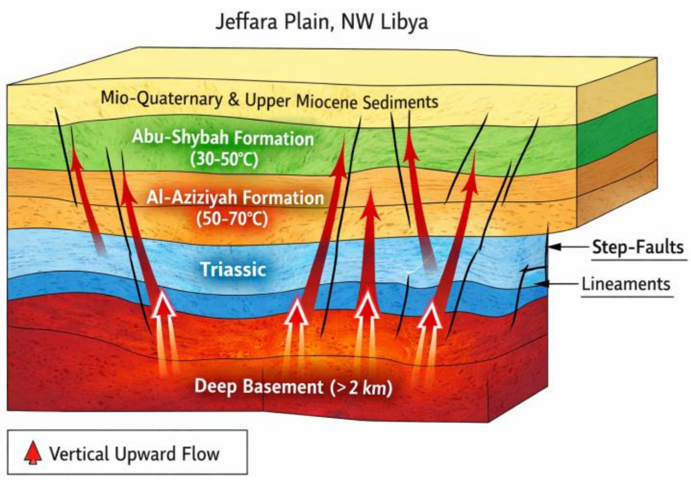

Figure 3. Detailed cross-section of the Jeffara Plain showing the stratigraphic sequence and upward thermal fluid flow via step faults.

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Hydrogeological Framework

The region is part of the transboundary Northwest Sahara Aquifer System (NWSAS). Hydrogeological dynamics are influenced by vertical upward groundwater flow [3,8]. The Al-Aziziyah aquifer (50–70 °C) and Abu Shaybah aquifer (30–50 °C) are the primary geothermal targets. Regional studies in Tunisia and Algeria show similar Na–Cl and Ca–SO_4 hydrochemical facies, with reservoir temperatures often estimated more reliably using silica geothermometers due to reduced sensitivity to water-rock interaction in arid systems [9].

Table 1. Hydrogeological properties of the main aquifers in the Jeffara Plain, including thickness, depth to water level, transmissivity, and salinity (TDS).

Aquifer	Thickness (m)	Water Level (m b.g.s.)	Transmissivity (m^2/day)	Salinity (TDS) (g/L)
Mio-Quaternary	10 – 90	10 – 80	103.68 – 8640	0.5 – 1
Upper Miocene	100 – 200	35 – 90	43.2 – 604.8	3 – 4
Abu Shaybah	150 – 400	10 – 145	2.2464 – 864	1 – 2
Al-Aziziyah	200 – 350	165 – 176	604.8 – 1728	1.5 – 2

Methods

Data Acquisition and Processing

Authoritative local data from the General Water Authority (2006), including magnetic, gravity, transmissivity, and piezometric surface surveys, as well as aquifer thickness data, were integrated with geological settings and land use maps to identify areas with high potential for geothermal energy extraction [10,11].

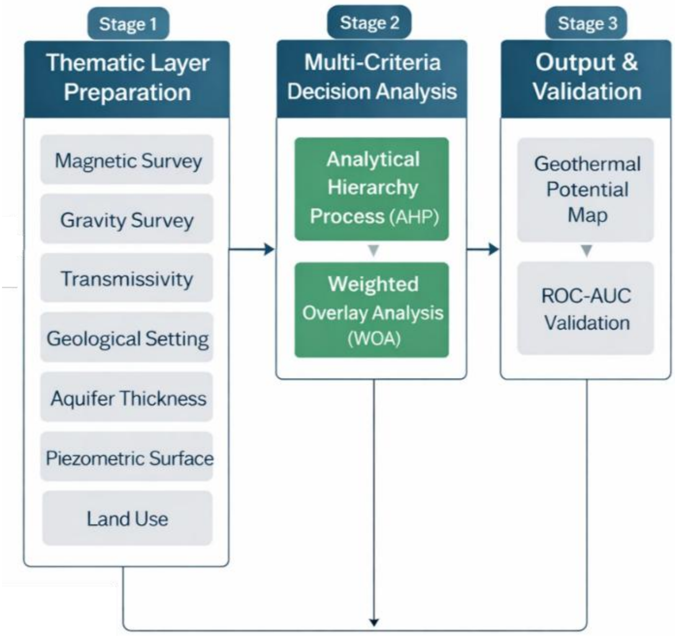

Figure 4. Flowchart of the study methodology model

Multi-Criteria Decision Analysis (MCDA)

The Analytical Hierarchy Process (AHP) was applied to derive relative weights for the seven thematic factors: magnetic survey, gravity survey, transmissivity, geological setting, aquifer thickness, piezometric surface, and land use. A pairwise comparison matrix was constructed based on expert judgement and supported by previous geothermal and hydrogeological studies in the region. The principal eigenvector of this matrix was used to obtain the normalized weights. In standard AHP applications, the Consistency Ratio (CR) is calculated to check whether the pairwise judgments satisfy the commonly accepted consistency threshold ($CR < 0.10$); this step is recommended as an additional refinement in future work. The resulting weights in this study emphasize the dominant role of structural controls and aquifer properties in governing geothermal potential, with higher importance assigned to the magnetic survey, transmissivity, and gravity survey criteria.

Recent studies have demonstrated that hybrid MCDA frameworks, such as AHP–TOPSIS and AHP combined with fuzzy logic, can further reduce subjectivity and better capture uncertainty in spatial decision-making [12-14]. Although these methods are not implemented in the present work, they are recommended as promising extensions for future geothermal potential assessments in similarly data-scarce environments.

Weighted Overlay Analysis (WOA)

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The final Geothermal Potential Index (GPI) was computed using a Weighted Overlay Analysis (WOA) within a GIS environment [15,16]. Each thematic layer was first converted to a raster dataset and reclassified into a common suitability scale to allow combination. Reclassification thresholds were defined based on the physical meaning of each criterion and informed by regional studies and expert knowledge.
For the magnetic survey, classes were defined to distinguish zones associated with deep-seated structural features, with higher reclassified values assigned to anomalies interpreted as favorable conduits for upward fluid migration. To increase sensitivity to structural effects, this layer was reclassified on a 2–10 scale, where 2 represents the least favorable and 10 the most favorable magnetic conditions. The remaining thematic layers, gravity survey, transmissivity, geological setting, aquifer thickness, piezometric surface, and land use were reclassified on a 1–5 scale, where 1 denotes very low suitability, and 5 denotes very high suitability. For hydrogeological parameters (transmissivity, aquifer thickness, piezometric surface), higher classes correspond to conditions that enhance storage capacity and vertical or lateral flow of thermal waters, whereas for land use, higher classes indicate areas with better accessibility and lower environmental or socio-economic constraints for geothermal development.
The standardized layers were then combined using a linear weighted sum:

$$GPI = \sum_{i=1}^{n}(Wi * Ri)$$

where Wi is the normalized weight of criterion ii derived from AHP, and Ri is the reclassified rank of that criterion [17,18].

Table 2. Criteria used in the MCDA–WOA framework, original map value ranges, reclassification scales, physical justification, and assigned AHP weights for geothermal potential mapping in the Jeffara Plain.

Criteria	Map Value	Reclassification Scale	Justification	Weight
Magnetic Survey	-40 to 210 nT	2, 4, 6, 8, 10	Detects deep-seated structural conduits (faults).	0.25
Gravity Survey	-65 to 25 mGal	1, 2, 3, 4, 5	Identifies density variations related to basement depth.	0.15
Transmissivity	5 to 4000 m^2/day	1, 2, 3, 4, 5	Assesses ease of geothermal fluid movement.	0.20
Geological Setting	N/A	1, 2, 3, 4, 5	Differentiates favorable Triassic formations.	0.10
Aquifer Thickness	30–45 meters	1, 2, 3, 4, 5	Influences total volume of the geothermal reservoir.	0.10
Piezometric Surface	350–1000 meters	1, 2, 3, 4, 5	Indicates hydraulic pressure and upward flow.	0.10
Land Use	N/A	1, 2, 3, 4, 5	Assesses accessibility and feasibility.	0.10

Validation Strategy

To provide an initial assessment of the reliability of the geothermal potential map, the spatial distribution of high-GPI classes was compared qualitatively with available thermal well data in the Az-Zahra region. Zones classified as high and very high potential coincide with wells where measured temperatures indicate the presence of low-enthalpy geothermal resources, supporting the physical plausibility of the derived Geothermal Potential Index. Although a full statistical evaluation was not carried out in this study, Receiver Operating Characteristic–Area Under the Curve (ROC–AUC) analysis is recommended as a rigorous next step. Such an approach would treat thermally productive wells as “presence” points and a set of background locations as “absence” points, and would quantify how effectively the GPI discriminates between these two groups [7,8].

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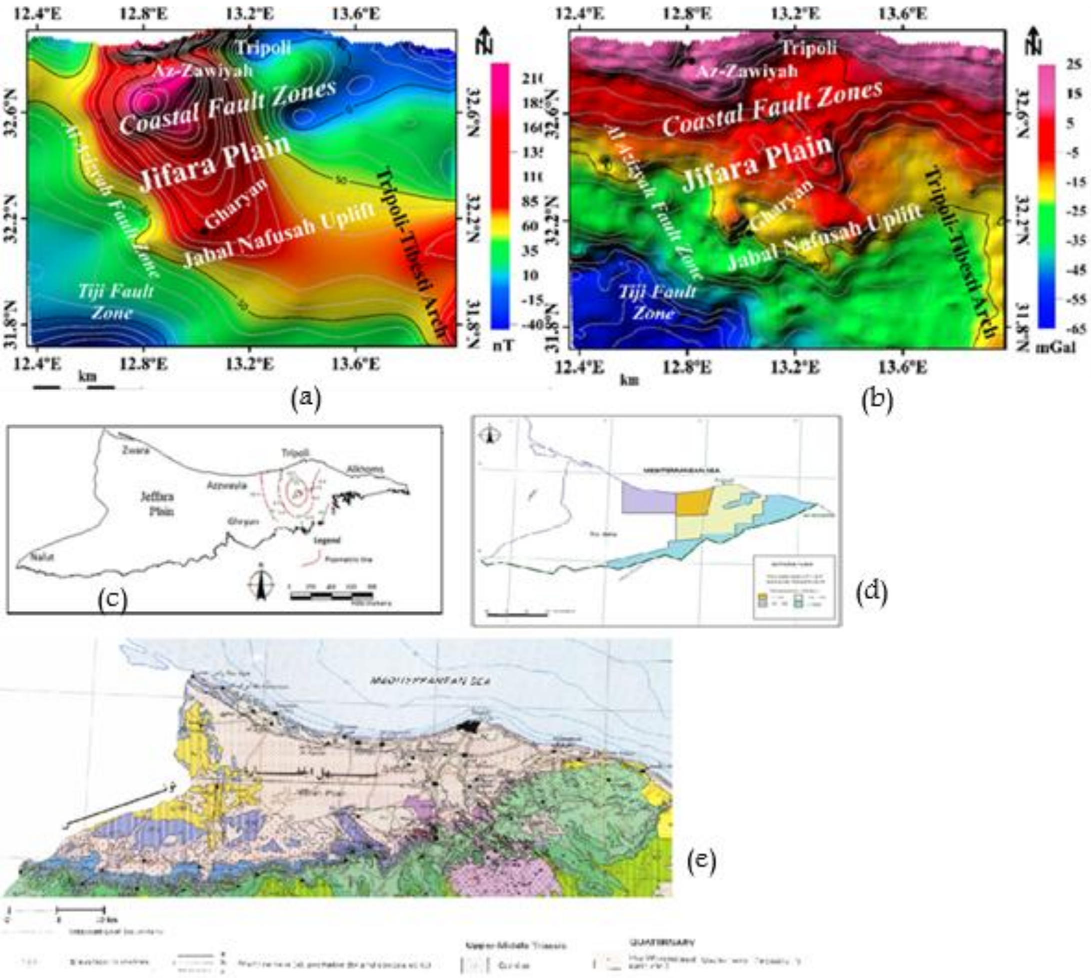

Figure 5. Layers of the WOA analysis: (a) Magnetic survey map; (b) Gravity survey map; (c) Piezometric map; (d) Transmissivity map; (e) Geological map of the study area.

Results

Geothermal Potential Zonation

The Weighted Overlay Analysis (WOA) identified five geothermal potential classes across the Jeffara Plain: very low, low, moderate, high, and very high. The resulting Geothermal Potential Index (GPI) map shows a clear spatial clustering of high and very high potential zones in the central and southwestern parts of the study area.

The Az-Zahra region emerges as the most promising area, with extensive coverage by the high and very high GPI classes. In this region, existing geothermal wells report temperatures exceeding 65 °C, consistent with the expected range of approximately 50–70 °C in the Al-Aziziyah formation. This thermal regime reflects circulation depths on the order of several kilometres, in agreement with regional NWSAS observations, where flow paths often extend to depths greater than 2 km [1,19]. The spatial distribution of the Geothermal Potential Index (GPI) is shown in (Figure 6).

Geophysical and Structural Controls

The spatial distribution of high GPI values in the Az-Zahra region shows a strong correspondence with characteristic geophysical anomalies. High-potential zones coincide with pronounced magnetic lows and gravity anomalies, which are interpreted as signatures of deep-seated basement faults and structural discontinuities. These features are consistent with the conceptual model and cross-section presented for the Jeffara Plain, where step faults and lineaments act as vertical conduits for upward migration of thermal fluids from deeper reservoirs into the Triassic aquifers.

The alignment between high GPI classes, magnetic lows, and gravity anomalies indicates that structural controls play a dominant role in shaping the geothermal system. In particular, the overlap between these geophysical indicators and the mapped extents of the Al-Aziziyah and Abu Shaybah formations supports the interpretation

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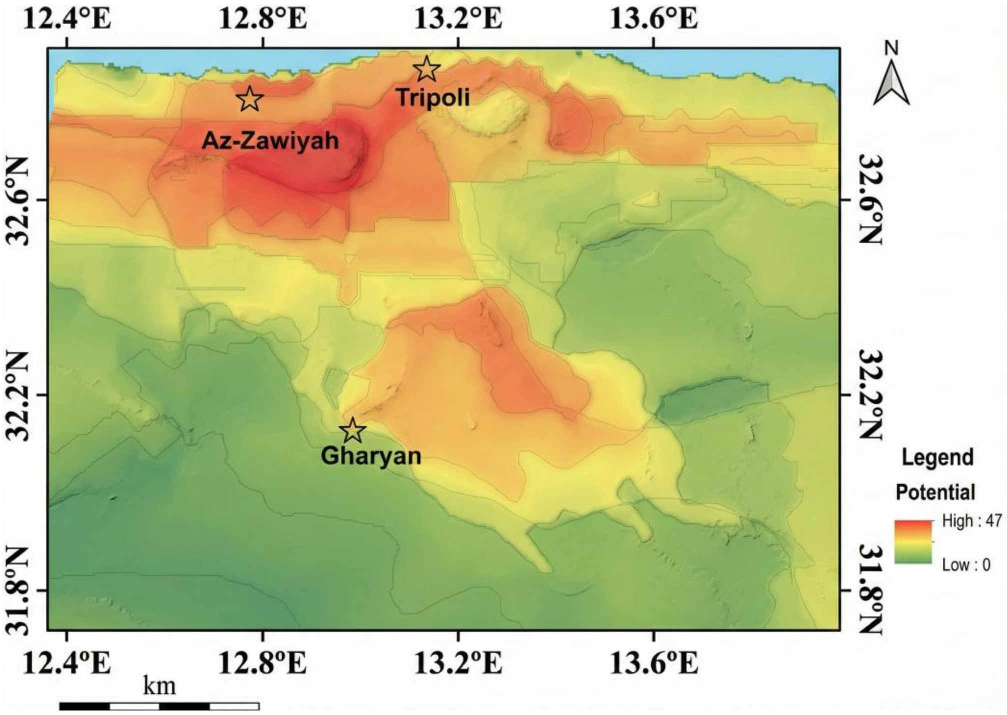

Figure 6. Geothermal potential map of the Jeffara Plain derived from the Weighted Overlay Analysis of seven thematic layers. The map shows five classes of the Geothermal Potential Index (GPI) from very low to very high potential. The most favorable zones are concentrated in the Az-Zahra region, where the high-potential class coincides with known thermal wells and a structurally controlled Triassic aquifer.

that these Triassic aquifers are the primary low-enthalpy geothermal targets within the study area.

Hydrothermal Characteristics and Environmental Conditions

Hydrothermal conditions inferred for the Az-Zahra region and surrounding areas are consistent with the conceptual understanding of the Northwest Sahara Aquifer System (NWSAS). The Al-Aziziyah aquifer exhibits temperatures of approximately 50–70 °C at depths of 200–350 m, while the Abu Shaybah aquifer displays temperatures of approximately 30–50 °C at depths of 150–400 m. These temperature ranges are in line with geothermal gradients reported in the eastern extension of the Jeffara Plain in southeastern Tunisia, for example, in the Medenine region.

High salinities, locally reaching up to about 3 g/L total dissolved solids, are observed in the geothermal waters. This elevated salinity suggests prolonged water–rock interaction and deep circulation pathways, and has direct implications for the selection of appropriate utilization technologies. In addition, transmissivity and aquifer thickness patterns within the Triassic formations confirm that the most favorable geothermal zones coincide with areas where storage capacity and hydraulic connectivity are enhanced.

Discussion

Implications for Geothermal Development in the Jeffara Plain

The results demonstrate that the Az-Zahra region constitutes the most favorable low-enthalpy geothermal prospect within the Jeffara Plain. The concentration of high and very high GPI classes, combined with documented aquifer temperatures of approximately 50–70 °C in the Al-Aziziyah formation, indicates strong potential for direct-use applications. These include thermal desalination to alleviate regional water scarcity, greenhouse heating to support agricultural production around Az-Zahra and Az-Zawiyah, and low-temperature industrial processes requiring a stable heat supply.

From a planning perspective, the delineated high-potential zones can serve as a first-order screening tool to prioritize locations for more detailed geophysical surveys, test drilling, and pilot-scale projects. By focusing initial investment on the most promising areas, decision makers can reduce exploration risk and accelerate the deployment of geothermal energy within the broader renewable energy portfolio of northwest Libya.

Regional Context within the NWSAS

The geothermal characteristics identified in the Jeffara Plain are consistent with observations from the wider Northwest Sahara Aquifer System in Tunisia and Algeria. Similar Na–Cl and Ca–SO_4 hydrochemical facies and comparable temperature ranges have been reported in transboundary segments of the NWSAS, particularly in southeastern Tunisia. The alignment of high-potential zones in the Az-Zahra region with known geothermal manifestations to the east underscores the transboundary nature of the system and suggests that the Jeffara Plain forms part of a broader regional geothermal province.

This regional context implies that the geospatial framework developed in this study may be transferable,

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with appropriate adjustments, to other parts of the NWSAS. Applying a similar MCDA–WOA approach in adjacent areas could support coordinated, cross-border strategies for geothermal resource assessment and utilization, especially in water-stressed environments where coupled water energy planning is a priority.

Environmental and Technical Considerations

The relatively high salinity of the geothermal waters (up to approximately 3 g/L) imposes specific technical constraints on utilization strategies. Open-loop systems that directly discharge geothermal fluids may pose risks of scaling, corrosion, and contamination. As a result, binary-cycle (closed-loop) systems are more appropriate for electricity generation or combined heat-and-power applications, as they minimize direct contact between geothermal fluids and surface infrastructure [5]. For direct-use applications, pretreatment or blending strategies may be required to manage salinity and protect equipment.

Economic feasibility is influenced by the balance between high initial drilling and infrastructure costs and lower long-term operational costs compared to fossil fuel-based systems. In this context, low-enthalpy geothermal development in the Jeffara Plain is especially attractive for decentralized, small- to medium-scale projects that can directly serve local communities, agricultural enterprises, and industrial facilities. Integrating geothermal deployment with existing water and energy infrastructure would further enhance overall system efficiency.

Methodological Limitations and Future Improvements

While the AHP–WOA framework provides a coherent basis for geothermal potential mapping in data-scarce environments, several limitations should be acknowledged. First, the present analysis relies on qualitative validation through spatial comparison of high GPI classes with existing thermal wells in the Az-Zahra region. Although this correspondence supports the physical plausibility of the results, it does not yet provide a quantitative measure of predictive performance. Future work should therefore implement formal statistical validation, for example, using ROC–AUC analysis based on thermal well data and representative background locations. Second, the AHP weights are derived from expert judgement and literature, and the Consistency Ratio (CR) was not computed in this study. Explicit calculation of the CR in subsequent applications would help assess the internal coherence of the pairwise comparisons and improve confidence in the resulting weights. Third, uncertainties associated with data quality, interpolation methods, and reclassification thresholds were not explicitly quantified. Incorporating uncertainty analysis, including Monte Carlo simulations or fuzzy logic representations, would provide more robust decision support.

Finally, the MCDA approach adopted here assumes predominantly linear relationships between criteria and geothermal potential. Interactions among geological, geophysical, and hydrogeological parameters may be highly non-linear. Hybrid MCDA–Machine Learning frameworks, trained on expanded well datasets and high-resolution geophysical information, represent a promising avenue to capture these relationships and refine geothermal prospectivity mapping in the Jeffara Plain and across the NWSAS.

Conclusion and Recommendations

Overall, the integrated GIS–MCDA framework highlights the Az-Zahra region as the primary low-enthalpy geothermal prospect within the Jeffara Plain. The highest GPI classes occupy a limited but strategically important portion of the study area and correspond to aquifer temperatures of approximately 50–70 °C in the Al-Aziziyah formation. These conditions are well suited for direct-use applications such as desalination, greenhouse heating, and low-temperature industrial processes, offering a realistic pathway to diversify the regional energy mix and enhance water–energy security in northwest Libya.

Key recommendations for future work are as follows. First, geothermometric calibration should be standardized for arid hydrogeochemical conditions in the NWSAS to better constrain reservoir temperatures and fluid–rock interactions. Second, deep borehole data and long-term monitoring of temperature, pressure, and water chemistry should be integrated to refine the conceptual model and improve understanding of subsurface flow regimes. Third, the geothermal potential map should be subjected to formal statistical validation, for example, through ROC–AUC analysis based on thermal well data, to quantitatively assess its predictive performance. Finally, future applications of this framework would benefit from explicit computation of the AHP Consistency Ratio (CR) to evaluate the reliability of expert judgements used to derive the criterion weights, and from the exploration of hybrid MCDA–Machine Learning approaches to capture non-linear relationships among geological, geophysical, and hydrogeological parameters.

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Conflicts of Interest

The authors declare no conflicts of interest.

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