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Geospatial modeling for optimal site selection of *Artemisia judaica* cultivation using remote sensing and GIS

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Abstract

Spatial modeling is an important aspect of biodiversity conservation, as many wild plant species are threatened by anthropogenic pressure and climate change. Remote sensing and GIS can be used to monitor medicinal plants, assess habitat suitability and support sustainable cultivation to reduce pressure on wild populations. This study developed a geospatial model to identify suitable areas for sustainable cultivation and in situ conservation of *Artemisia judaica* in Egyptian arid coastal environments. The model integrated multiple environmental variables, including soil properties (pH, texture, and $CaCO_3$), climatic factors (temperature, rainfall, and relative humidity), land use/land cover, and remotely sensed vegetation indices (NDVI and NDWI), derived from satellite data and field observations. The proposed framework aimed to support the efficient use of underutilized and degraded lands within a broader sustainable land management perspective. The resulting suitability map classified the study area into different suitability classes and provided a spatial decision-support tool for prioritizing locations for *A. judaica* cultivation. This approach contributes to biodiversity conservation, improves natural resource use efficiency, and supports long-term ecological sustainability in arid regions. The findings demonstrate the value of integrating remote sensing and GIS techniques in medicinal plant cultivation planning and conservation. Future studies may further strengthen the model by incorporating socio-economic factors and climate change scenarios.

Key words: Site selection, medicinal plants, modeling, *Artemisia judaica,* remote sensing.

Introduction

A. judaica, commonly known as the "Judean wormwood" is a valuable medicinal plant found in Egypt. It is a fragrant shrub that grows widely in the Arabian region (Acheuk *et al.,* 2017). This species is traditionally prepared as a tea and consumed by people in Sinai and Saudi Arabia, where it holds an important place in traditional Arabic medicine. It is used to treat cardiovascular health issues and various other diseases (Abu-Darwish *et al.,* 2016; Acheuk *et al.,* 2017).

Secondary plant metabolites found in *A. judaica* serve as active chemical defenses against pathogens and play a vital role in protecting the plant from herbivory and other interspecies interactions (Qanash *et al.,* 2023; Al-Ismail *et al.,* 2007; Boham and Kocipai, 1974; Calliste *et al.,* 2001; Boulos, 2002). Previous phytochemical analyses by several authors have revealed its antioxidant activity, anti-malarial, antibacterial, anti-inflammatory properties, and its potential as a biopesticide (Chiang *et al.,* 2004; Djeridane *et al*., 2006; Eberlein *et al.,* 2008; El-Masry *et al.,* 2002; El-Sayed *et al.,* 2013; Erol-Dayi *et al.,* 2011; Essiett and Akpan, 2013). Studies on wild and cultivated plant species have also highlighted the importance of evaluating protein quality and antinutritional factors when assessing their nutritional potential (Carnovale *et al*., 1991).

A. judaica has received considerable attention in the context of the COVID-19 pandemic, as it belongs to Artemisia—one of the most diverse and widespread genera in the *Asteraceae* (Compositae) family (Boukhalfa *et al.,* 2023; Koul *et al.,* 2018; Mishra *et al.,* 2013).

Optimal site selection plays a crucial role in the successful cultivation of medicinal plants. With advances in remote sensing technologies and the development of Geographic Information Systems (GIS), it is now possible to use these tools for precise and efficient site selection. For Egyptian medicinal plants such as *A. judaica,* which are important for their therapeutic properties, integrating geospatial tools can support informed decisions on identifying ecologically suitable cultivationareas.

Identifying highly suitable cultivation zones may reduce harvesting pressure on natural populations and contribute to the conservation of *A. judaica*. Similar conservation efforts have highlighted the importance of maintaining suitable environmental conditions for the survival of threatened plant species (Bhutia *et al.,* 2023). Recent studies have demonstrated that GIS-based multi-criteria approaches integrating soil, climatic, and landscape variables are effective for identifying suitable agricultural zones and supporting sustainable land-use planning (Widiatmaka, 2016). Advances in data-driven suitability assessment further highlight the importance of integrating soil health indicators and environmental datasets for improving crop suitability predictions (Agrawal and Goyal, 2025).

Remote sensing and GIS have been successfully applied to map plant species distribution, environmental conditions, and landscape characteristics (Stow *et al.,* 1993). In a study by Coudun *et al.* (2006), it was revealed that the impact of various climatic factors on plant distribution is less pronounced than the substantial influence of soil pH. This finding underscores the potential benefits of incorporating soil nutrient variables into regional or national models for predicting plant species distribution. Consequently, this integration significantly improves prediction accuracy for these species, facilitating the identification

of areas where plants are present or absent within the study region. This enhanced modeling accuracy plays a critical role in guiding effective conservation strategies and spatial planning efforts. (Khdery *et al*., 2026; Wang *et al*., 2025; Araújo and Rahbek, 2006; Cabeza *et al*., 2004; Margules and Stein, 1989; Polasky *et al*., 2000; Williams *et al*., 2005).

Several studies have successfully applied remote sensing and GIS techniques to determine optimal site selection for various crops and medicinal plants worldwide. For example, Hailu *et al.* (2020) and Khdery *et al.* (2025) used remote sensing data and GIS tools to identify suitable areas for cultivating medicinal plants in Ethiopia.

However, limited research has been conducted on *A. judaica* in Egypt. Therefore, this study aims to fill this research gap by employing remote sensing data and GIS tools to identify the optimal sites for *A. judaica* cultivation in Egypt. The outcomes of this research are expected to support sustainable cultivation efforts and contribute to the long-term conservation of this valuable medicinal species.

This study focuses on identifying ecologically optimal cultivation zones for *A. judaica,* aiming to enhance its sustainable use and conservation. The anticipated outcomes support both medicinal applications and broader public health efforts.

Materials and methods

Study area: Two distinct study areas were selected to develop the proposed model. The first study site, Wadi Hagul, represented the original location of the plant species under investigation. The second study site encompassed the Northwestern coast of Egypt, which served as the proposed site for *A. judaica*. Plant and soil samples were collected from both Wadi Hagul and the Northwestern coast of Egypt to support comprehensive analysis and inform model development (Fig. 1).

Wadi Hagul: Wadi Hagul, located in the Suez region of Egypt, is a hydrographic valley characterized by distinctive geographical attributes. It is situated within the northern section of the Eastern Desert of Egypt, in the Cairo-Suez vicinity, encompassing the geographic coordinates of approximately 32° 08′ 32″ E longitude and 29° 41′ 30″ N latitude, as illustrated in Fig. 1. The valley is flanked by notable landmarks: Ataqa Mountain to the north, Wadi Bada'a to the south, the Gulf of Suez to the east, and Gebel El-Kahaliya to the west. Wadi Hagul holds a strategic position at the crossroads of three major routes leading to Suez in the north, Cairo in the northwest, and Hurghada in the south, as indicated in Fig. 1.

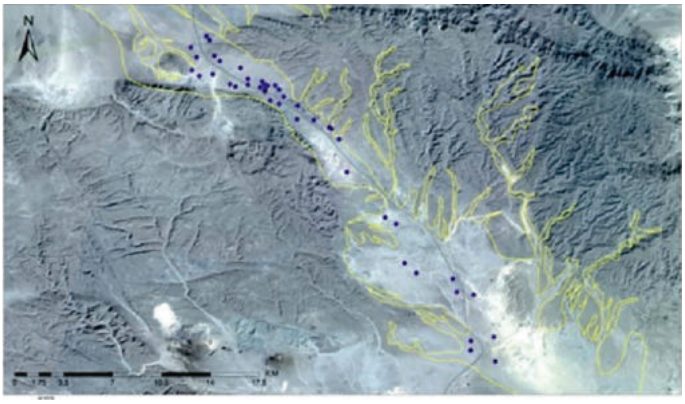


Fig. 1. Surveyed locations in Wadi Hagul. Blue dots are sampling sites

Northwestern coast of Egypt: The second study site encompasses the northwestern coast of Egypt, which is the designated area for the modeling efforts. As illustrated in Fig. 2, this coastal region extends from approximately 29.88° N to 31.21° N in latitude and from 25.01° E to 31.62° E in longitude. The study area has a semi-arid Mediterranean climate. In December, the average air temperature is around 15°C, accompanied by an average wind speed of about 19 km/h. During this winter month, the average monthly rainfall is approximately 11.42 mm, with the highest daily recorded rainfall reaching about 7.1 mm. In April, the climate transitions as the average temperature rises to approximately 20°C, the average wind speed drops slightly to around 17 km/h, and the average monthly rainfall decreases to about 1.27 mm, with a maximum daily rainfall typically reaching 1 mm.

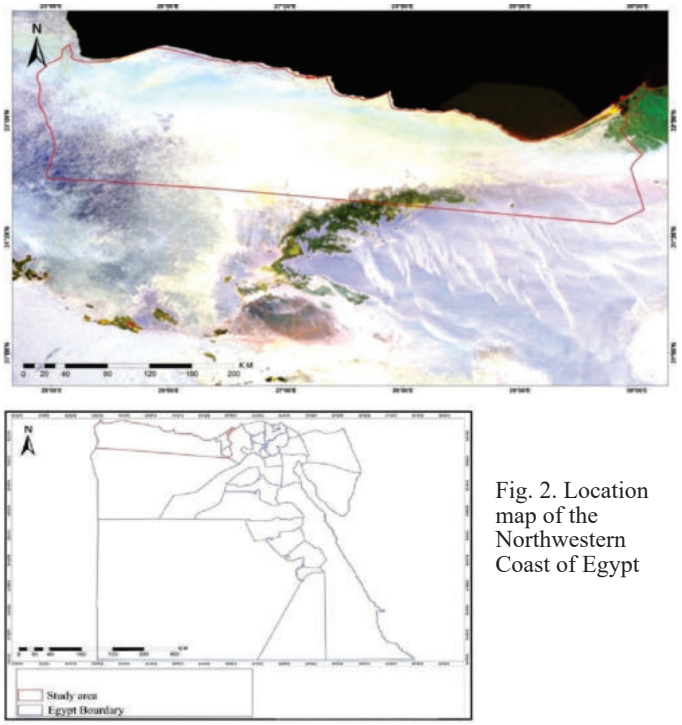


Fig. 2. Location map of the Northwestern Coast of Egypt

Data source

Satellite images: The satellite data utilized in this research comprised imagery from the Sentinel-2 constellation. The Multispectral Instrument (MSI) aboard Sentinel-2 provides data at varying spatial resolutions (10 m, 20 m and 60 m) depending on the specific spectral band. Each satellite has a temporal resolution of approximately 10 days, which improves to a 5-day combined revisit frequency when both satellites in the constellation are used.

Climate Data: Historical climate data spanning from 2000 to 2020—including precipitation, temperature, and relative humidity—were acquired from four meteorological stations distributed across the study area: Alexandria, El Dabaa, Marsa Matrouh, and Salloum. The analysis focused specifically on the winter season, encompassing December, January, and February. To generate a continuous and comprehensive climate surface across the entire study region, the Inverse Distance Weighted (IDW) interpolation technique was implemented. The resulting climatic variations and spatial distributions are illustrated in Fig. 3, 4, and 5.

Soil analyses: During field observations, soil samples were collected from the study sites and analyzed in the laboratory.

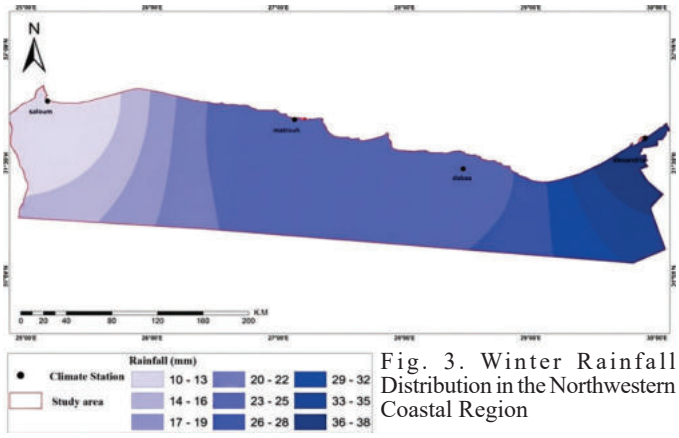


Fig. 3. Winter Rainfall Distribution in the Northwestern Coastal Region

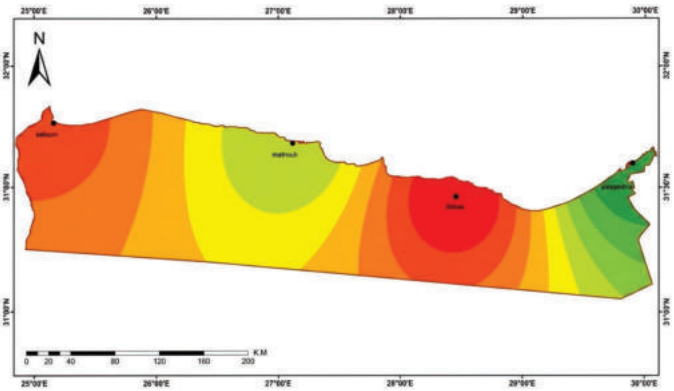


Fig. 4. Spatial distribution of winter temperature in the northwestern coastal region

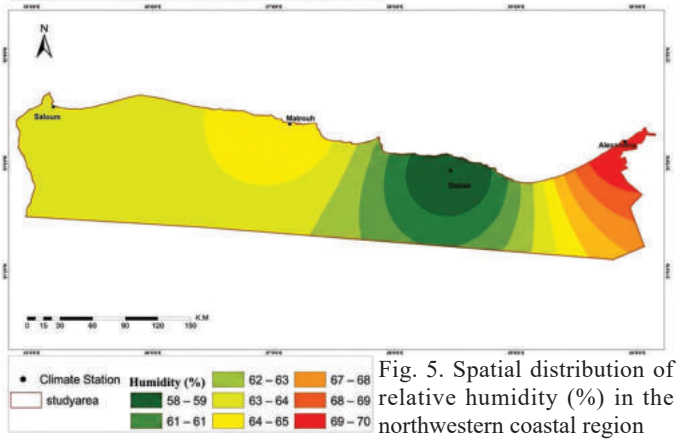


Fig. 5. Spatial distribution of relative humidity (%) in the northwestern coastal region

The measured soil parameters included pH, calcium carbonate ($CaCO_3$) content, electrical conductivity (EC), silt and clay content, coarse sand, and medium sand. The IDW interpolation technique was subsequently used to generate spatial maps of these soil characteristics (Figs. 6 -10).

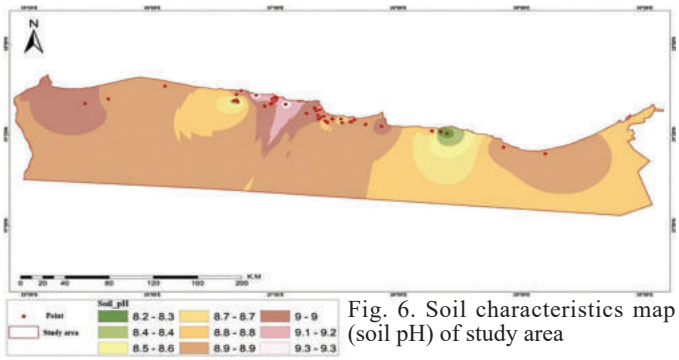


Fig. 6. Soil characteristics map (soil pH) of study area

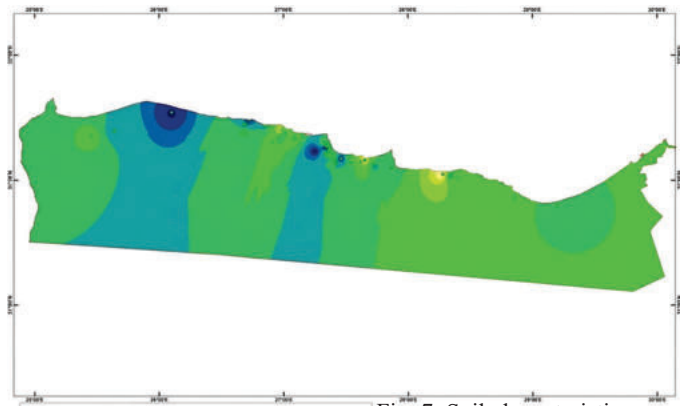


Fig. 7. Soil characteristics map of calcium carbonate content ($CaCO_3$) in the study area

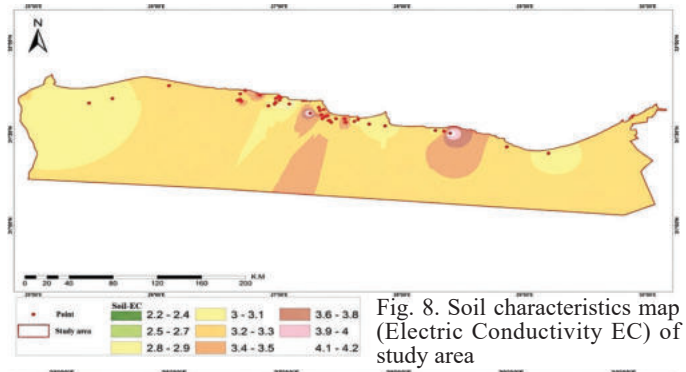


Fig. 8. Soil characteristics map (Electric Conductivity EC) of study area

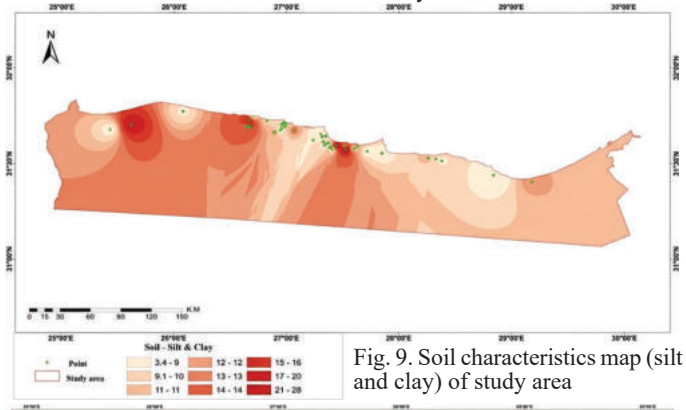


Fig. 9. Soil characteristics map (silt and clay) of study area

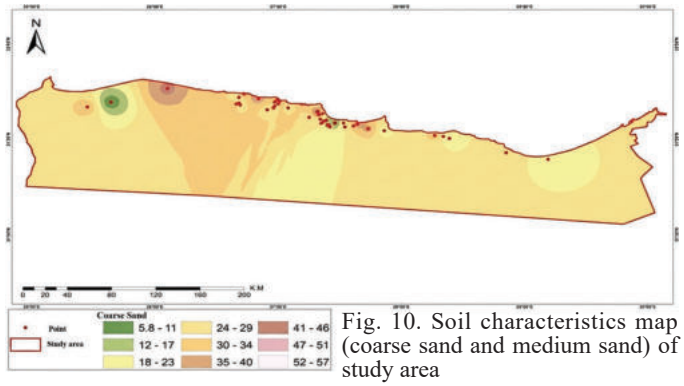


Fig. 10. Soil characteristics map (coarse sand and medium sand) of study area

Land cover: According to Fig. 11, the land cover map for the study area was generated using the (FAO - LCCS) methodology. Additionally, Table 1 presents comprehensive details regarding the total area and specific descriptions of each land cover type.

DEM analysis: A 30-m resolution digital elevation model (DEM) derived from SRTM data was used for the topographic analysis, as shown in Fig. 12 .

Table 1. Land cover areas (km²), description, and land cover classes

Land cover classes	Land cover areas (km^2)	Description
Desert	22369.68	Desert
Agriculture	5246.253	Vegetation Cover
Urban	3520.253	Urban Area(s)
Water body	114.9413	Water body
Roads	374.339	Road(s)

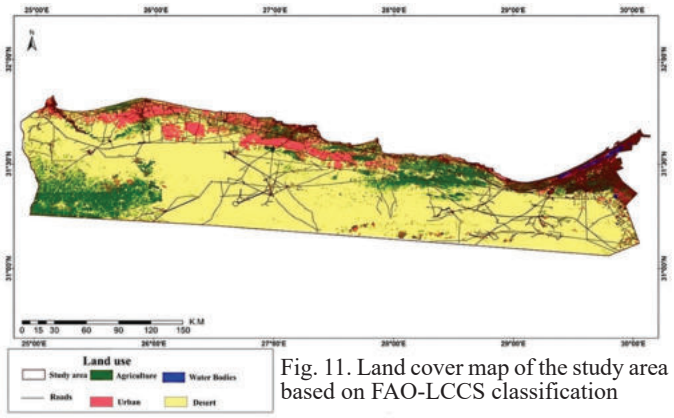


Fig. 11. Land cover map of the study area based on FAO-LCCS classification

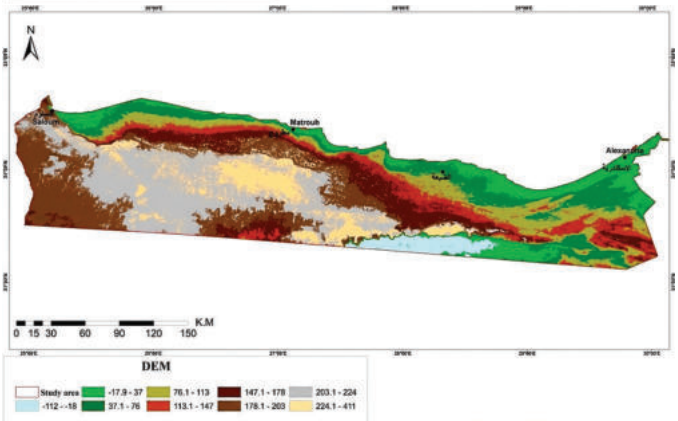


Fig. 12. Digital elevation model (DEM) of the study area

Normalized difference vegetation index (NDVI): Sentinel-2 imagery was downloaded from the USGS EarthExplorer platform and extracted from their compressed format. Subsequently, they were stacked together using image processing software for further analysis (Fig.13). The red (R) and near-infrared (NIR) measurements obtained from the images allow for the calculation of the Normalized Difference Vegetation Index (NDVI) using the formula:

NDVI = (NIR - Red) / (NIR + Red)

Normalized difference water index (NDWI): NDWI = (NIR - SWIR) / (NIR + SWIR)

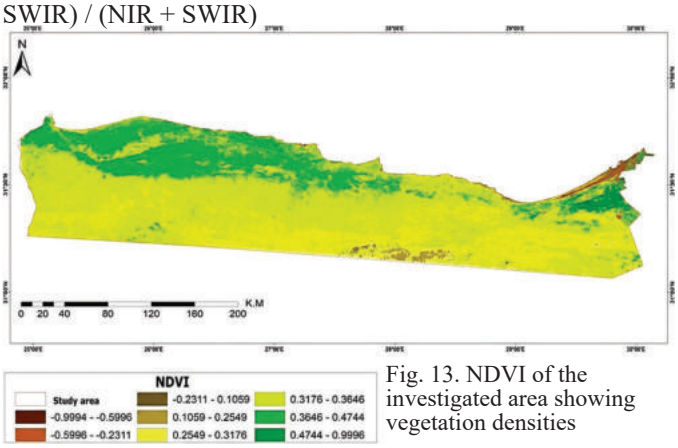


Fig. 13. NDVI of the investigated area showing vegetation densities

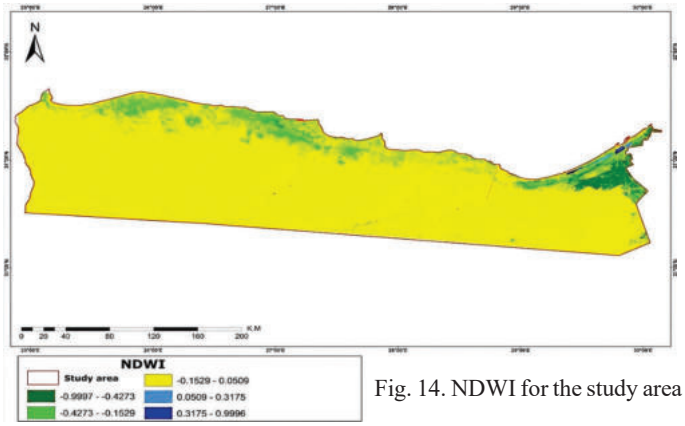


Fig. 14. NDWI for the study area

The NDWI was calculated following the method proposed by Gao (1996) for estimating vegetation water content using near-infrared and shortwave infrared bands.

Sentinel-2 Band 8 (NIR) and Band 12 (SWIR) were used to calculate NDWI. This vegetation index is sensitive to vegetation water content and complements NDVI, with higher NDWI values generally indicating greater vegetation water content (Fig. 14). This study employed a combination of desktop computer analyses and field observations to assess the suitability of the study area for *A. judaica* cultivation. Various research parameters were considered, including bare land, temperature, rainfall, relative humidity, soil type, land surface elevation, and slope. To gather data, Sentinel-2 satellite images with a spatial resolution of 10 meters were downloaded from the Earth Explorer website. Additionally, SRTM 30-meter DEM tiles were acquired for deriving slopes. Soil samples were collected and measured at the Institute of Land, Water, and Environmental Research.

Climate data, spanning from 2000 to 2020, including precipitation, temperature, and relative humidity, were obtained from four climatic stations in and around the study area (Alexandria, Dabaa, Matrouh, and Saloum). Inverse Distance Weighted (IDW) interpolation technique, using the ArcMap IDW tool, was applied to interpolate the climate data. A land cover map of the study area was produced based on the Food and Agriculture Organization's Land Cover Classification System (FAO-LCCS). Normalized Difference Vegetation Index (NDVI) and NDWI from Sentinel-2 images were calculated using their respective equations.

After preprocessing, the layers were masked, reclassified, and resampled to a 30-meter spatial resolution for weighted overlay analysis. Weighted overlay analysis is a GIS-based technique that combines multiple datasets to generate a new layer based on predefined criteria. The relative importance of the environmental variables used in the weighted overlay analysis was determined based on expert knowledge and previous studies addressing habitat suitability and medicinal plant cultivation in arid environments. Each environmental factor was assigned a weight according to its influence on the growth requirements and ecological distribution of *A. judaica*. Climatic parameters (temperature, rainfall, and relative humidity), soil properties (pH, texture, $CaCO_3$, and EC), topographic factors (elevation and slope), land use/land cover, and vegetation indices (NDVI and NDWI) were evaluated and weighted to reflect their relative contribution to plant establishment and survival. The weights were normalized to ensure that the total contribution of all criteria equaled 100%. This weighting scheme allowed the integration of multiple environmental datasets into a single suitability index

using the GIS weighted overlay approach. The suitability criteria for all study parameters were defined based on their relative influence on the ecological requirements of *A. judaica*.. The weighted overlay analysis resulted in the development of the final suitability map, outlining the optimal areas for *A. Judaica* cultivation. Detailed steps for this process are illustrated in Fig. 15 . Overall, the methodology employed a combination of remote sensing data, GIS analysis, field measurements, and stakeholder engagement to evaluate the suitability of the study area for *A. judaica* cultivation.

Results and discussion

Model for site selection: The GIS-based suitability model classified the northwestern coastal region of Egypt into two main suitability classes for *A. judaica* cultivation: suitable and non-suitable areas. The classification was derived from the integration of multiple environmental layers, including climatic parameters (temperature, rainfall, and relative humidity), soil characteristics (pH, $CaCO_3$ content, soil texture, and electrical conductivity), topographic conditions, land use/land cover, and remotely sensed vegetation indices (NDVI and NDWI). The final suitability map indicated that 89,233 pixels of the total analyzed area fall within the suitable category, while 33,004 pixels were classified as non-suitable for *A. judaica* cultivation. This spatial distribution suggests that a considerable portion of the northwestern coastal region provides favorable environmental conditions for establishing and sustainably cultivating this medicinal plant. The spatial pattern of the suitability map reveals that the suitable areas are mainly associated with zones characterized by moderate climatic conditions, relatively suitable soil properties, and favorable vegetation indices. Areas with appropriate soil pH and texture, combined with moderate rainfall and temperature regimes, showed higher suitability for *A. judaica* cultivation.

In contrast, unsuitable zones were mainly related to unfavorable soil conditions, extreme climatic variability, or land cover types not suitable for plant establishment. Integrating vegetation indices derived from Sentinel-2 imagery further supported the identification of suitable locations. NDVI values helped identify areas with existing vegetation conditions that may support plant establishment, while NDWI provided additional information on vegetation water content and environmental moisture conditions within the study area. The resulting suitability map represents an important spatial decision-support tool for identifying optimal cultivation zones for *A. judaica*. It highlights the potential of geospatial techniques to support sustainable land management and medicinal plant cultivation planning in arid and semi-arid environments. Model reliability was assessed by comparing the predicted suitability classes with field observations from locations where *A. judaica* naturally occurs. Approximately 80% of the observation points fell within predicted suitable zones, demonstrating good spatial agreement between modeled suitability and observed field conditions. The correspondence between the predicted suitable areas and the observed distribution of *A. judaica* confirms the applicability of the integrated geospatial approach for identifying ecologically suitable cultivation zones for this species. Fig. 16 presents the final suitability model showing the spatial distribution of suitable and non-suitable areas for *A. judaica* cultivation in the northwestern coastal region of Egypt.

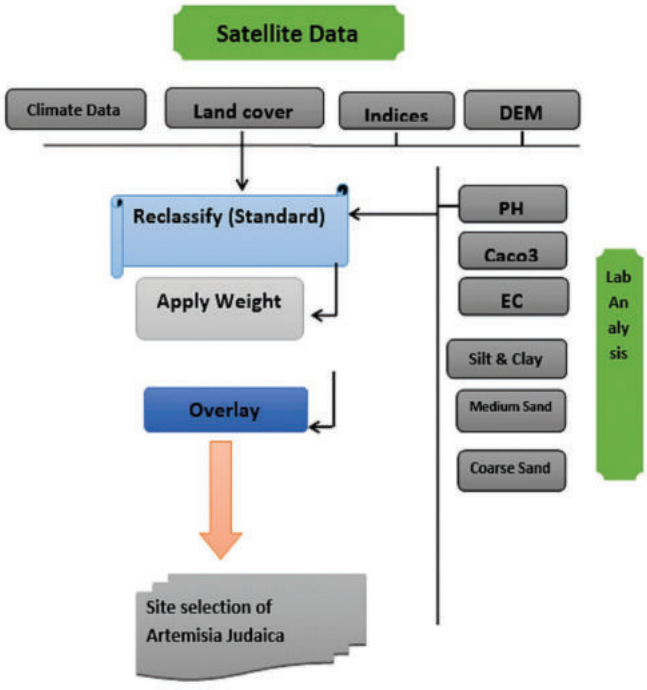


Fig. 15. Geospatial workflow for site selection of *Artemisia judaica*

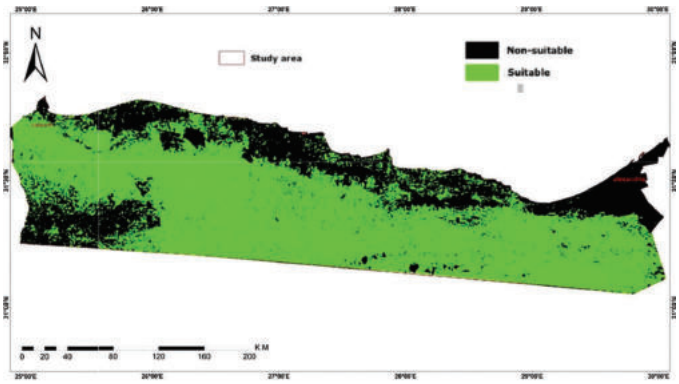


Fig. 16. Site suitability model of *Artemisia judaica*

The developed geospatial model delineated the northwestern coastal region into suitable and non-suitable zones for *A. judaica* cultivation based on climatic, edaphic, topographic, land-cover, and vegetation-index criteria. The resulting suitability map provides a spatial decision-support tool for prioritizing cultivation areas and allocating resources. Previous studies have emphasized the value of spatial modeling in supporting sustainable agriculture and biodiversity conservation, especially for medicinal plant species under climate stress (Qanash *et al.,* 2023; Wang *et al.,* 2025). The environmental sensitivity of *A. judaica,* particularly to soil pH, precipitation, and temperature, aligns with findings from recent geospatial habitat modeling efforts that stress the importance of integrating both climatic and edaphic variables (Dastres *et al.,* 2025; Boukhalfa *et al.,* 2023). The current model confirms that variations in these parameters play a pivotal role in determining the plant's spatial distribution. From a horticultural perspective, soil pH is not merely a mapping variable, but a direct regulator of nutrient availability and root uptake efficiency. Soil pH controls the chemical forms and solubility of essential nutrients, particularly phosphorus and several micronutrients, and therefore affects plant establishment, vegetative growth, and biomass accumulation. Under highly alkaline or highly acidic conditions, nutrient availability declines, which can reduce plant vigor even when other environmental conditions appear suitable. This physiological role is especially important when

evaluating the cultivation potential of medicinal plants in arid and calcareous landscapes (Khdery *et al.,* 2025; Penn and Camberato, 2019). In addition, environmental conditions strongly influence secondary metabolite production in medicinal plants. Reviews on medicinal plant metabolism show that temperature regimes, water availability, and related stress conditions can alter the synthesis and accumulation of terpenoids, phenolics, and other bioactive compounds. Therefore, the climatic suitability identified by the GIS model is biologically meaningful not only for plant survival and growth, but also for the medicinal quality of the crop. This interpretation is particularly relevant for Artemisia species, which are widely recognized for their rich phytochemical composition and pharmacological importance (Pant *et al.,* 2021; Qaderi *et al.,* 2023; Koul *et al.,* 2018; Khdery *et al.,* 2021).

Historical references such as Sunderland and Samu (2000) and Cammell and Knight (1992) further support the discussion of model validation. The "greenhouse effect" and its impact on global mean temperature, precipitation patterns, and weather conditions can significantly influence the distribution and abundance of plants and ecosystems. Climatic factors, especially temperature, play a direct role in evaluating anticipated alterations in species distribution and present a challenge when relying on empirical data due to the prolonged timescales involved, spanning decades to centuries (Lang, 1994; Bradshaw and Lindbladh, 2005; Araújo and Rahbek, 2006; Gamal *et al*., 2020; Khdery, 2020).

The current modeling framework builds on previous GIS-based conservation work in similar arid environments, particularly the study by Gamal *et al.* (2020), which used multi-criteria evaluation and spatial analysis to prioritize suitable habitats for endangered plant species. That study demonstrated the effectiveness of integrating topographic, soil, and climate data in predicting species distribution in marginal landscapes. Similarly, the present model leverages remote sensing-derived indices and environmental datasets to guide the sustainable cultivation of *A. judaica*. The consistency of methodological performance across distinct ecological zones further validates the robustness and transferability of GIS-based site suitability modeling in arid and semi-arid regions.

Vegetation indices also add horticultural value to suitability interpretation because they are linked to canopy vigor, chlorophyll status, and photosynthetic activity. In particular, NDVI is widely used as an indicator of vegetation greenness and productivity, which makes it useful for distinguishing environmentally favorable zones from areas with limited plant performance. Thus, integrating vegetation indices with soil and climatic variables strengthens the ecological and agronomic interpretation of the suitability model rather than serving as a purely spatial overlay step (Khdery *et al.,* 2023; Xue and Su, 2017). More broadly, plant secondary metabolites are part of plants' adaptive response to environmental conditions, and their accumulation is closely associated with stress physiology and plant–environment interactions. This supports the interpretation that the "suitable" zones identified in the present study are not only locations where *A. judaica* may survive, but also areas where its physiological performance and medicinally important biochemical traits are more likely to be maintained under arid-land cultivation conditions (Bourgaud *et al.,* 2001; Pant *et al.,* 2021).

The successful development and validation of the geospatial model for *A. judaica* site selection have significant implications for plant conservation and sustainable agricultural development. By identifying suitable areas for the cultivation, this research can support the cultivation and sustainable harvesting of the valuable medicinal plant. Moreover, the model can help conserve *A. judaica's* natural habitat, enabling more effective conservation and restoration efforts.

In conclusion, the results presented in the paper showcase the successful development and validation of a geospatial model for *A. judaica* site selection on the Northwestern coast of Egypt. The model's accuracy and effectiveness were confirmed through field observations, ensuring that it aligns with real-world conditions. The research highlights the significance of remote sensing and GIS technologies in addressing plant conservation and sustainable agricultural development challenges. The identified suitable areas for planting *A. judaica* can have positive implications for the herbal and pharmaceutical industries, public health, and overall population well-being. The study's use of remote sensing technology and Geographic Information Systems (GIS) underscores the importance of these advanced tools in site selection and biodiversity management. Remote sensing data, such as satellite imagery from the Sentinel-2 instrument, enabled analysis of various environmental parameters, including land cover, climate data, and vegetation indices like NDVI and NDWI.

Competing interests: The authors declare that they have no conflict of interest in the publication.

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