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Feasibility Study of Agroclimatic Suitability for Jujube (*Ziziphus jujuba* L.) Cultivation Development in Sistan Region

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ABSTRACT

The Sistan region in southeastern Iran faces unprecedented agricultural challenges due to persistent severe droughts, limited water resources, and the 120-day winds. Introducing resilient and economically viable plant species is a critical strategy for ensuring sustainable production, conserving scarce water resources, and enhancing the resilience of local communities. This study aims to identify and assess the suitability of lands for jujube cultivation in the Sistan region using remote sensing (RS), geographic information systems (GIS), and geostatistical and analytical techniques. The research was conducted in five consecutive steps: 1) creating a database of climatic, land use, topographic, and soil characteristics of the Sistan region; 2) determining the agroclimatic characteristics and growth cycle patterns of jujube suitable for Sistan's conditions; 3) modeling and zoning the phenological stages of jujube; 4) calculating and analyzing spatial agroclimatic indices; and 5) integrating effective climatic and edaphic layers using the Analytic Hierarchy Process (AHP) in the ArcGIS environment. The results indicate that the jujube growth cycle in Sistan's climate is heavily influenced by high temperatures and moisture limitations. The base temperature for bud growth initiation is 7°C in this region, but the timing of phenological stages is significantly affected by early heat. Spatial analyses revealed that, due to harsh climatic conditions, only a small portion of the region's lands (approximately 5%) is highly suitable, a limited portion (approximately 15%) is moderately to well-suited, a significant portion (approximately 30%) has low suitability, and the majority (approximately 50%) is unsuitable for jujube cultivation aimed at producing high-yield and high-quality fruit. This protocol, emphasizing the need for accurate regional data collection, can serve as a technical guide for developing the cultivation of economically resilient species in extremely arid regions with multiple stresses, such as Sistan.

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1. Introduction

Agriculture serves as the backbone of livelihoods and economic development in many regions worldwide, particularly in developing countries. However, in recent decades, climate change, population growth, and overexploitation of natural resources have posed unprecedented challenges to this vital sector. Iran, with a significant portion of its landmass located in arid and semi-arid regions, has consistently faced challenges related to water scarcity and extreme rainfall variability (Asadi *et al*., 2020). Among these, the Sistan region, located in eastern Iran near the border with Afghanistan, stands out as a prime example of a climatically critical area. Persistent multi-decadal droughts, a drastic reduction in the inflow of the Helmand River (the region's primary water source) and the unique phenomenon of the 150-day winds (lasting from early June to mid-October), accompanied by severe dust storms, have created significant challenges for livelihoods, particularly in the agricultural sector (Amirizadeh *et al*., 2015). These harsh conditions have severely disrupted traditional and common cropping patterns, leading to a sharp decline in crop yield and quality, soil erosion, destruction of agricultural infrastructure, and ultimately, widespread population migration.

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Consequently, identifying and introducing new, economically viable plant species that exhibit exceptional adaptation to drought stress, soil salinity, and strong winds, while possessing significant economic production potential, is a top priority for promoting sustainable agricultural development, generating employment, conserving scarce water and soil resources, and enhancing the resilience of local communities (Forouzandeh *et al*., 2012; Rad *et al*., 2020).

Jujube (*Ziziphus jujuba* L.), as a native species of Central Asia, particularly in China, Iran, and the Indian subcontinent, has gained global attention in recent years due to its unique ecological, medicinal, and economic characteristics (Liu *et al*., 2020). This resilient tree possesses the ability to grow in adverse climatic and soil conditions and, owing to its high tolerance to environmental stresses, including drought, heat, salinity, and soil poverty, is utilized in arid and semi-arid regions. These attributes make it a highly suitable and strategic option for developing cultivation in marginal and low-water lands in the Sistan region (Zargari, 1991). This plant not only offers significant economic production potential, with its fruits possessing high nutritional and medicinal value (Agrawal *et al*., 2023), but can also play a crucial role in improving regional vegetation cover, which is vital for Sistan. Previous studies have also emphasized the importance of expanding production and developing jujube cultivation due to its unique features, such as economic value (in the food and pharmaceutical industries), nutritional value (rich in vitamins and antioxidants), medicinal value (improving sleep and boosting the immune system), environmental value (drought resistance and soil stabilization), and its ecological and cultural potential (Liu *et al*., 2020). Despite its considerable production potential, Iran's contribution to the global jujube supply remains relatively small, which underscores the increasing necessity for applied research to identify new suitable areas, particularly in regions facing severe climatic and environmental crises.

Agroclimatic assessment, as a scientific method for analyzing the suitability of crop cultivation under specific environmental conditions, has gained a prominent position in natural resources and agricultural research. This approach determines the suitability of a region for cultivating a specific crop by integrating meteorological data, thermal indices, plant phenological requirements, topography, and soil characteristics (van Wart *et al*., 2013). In Iran, successful studies based on this approach have been conducted for crops such as olive (Mohammadi *et al*., 2007), ruby grape (Amirizadeh *et al*., 2015), pomegranate (Ghamarnia and Nekokish, 2025), winter potato (Taei Semiromi *et al*., 2017), and wheat (Neamatollahi *et al*., 2012). Internationally, this method has been applied to analyze the ecological potential of olive orchards in Spain, date palms in North Africa, and vineyards in China, yielding results that have optimized regional cropping patterns (Anderegg *et al*., 2020). This study aims to assess the agroclimatic feasibility of developing jujube cultivation in the lands of the Sistan region, zone the specific ecological constraints of the Sistan plain, and propose a new cropping pattern based on low-input and stress-resilient agriculture. It also seeks to identify pilot areas for evaluating the adaptability of suitable jujube varieties to the harsh conditions of Sistan. The results of this research, as a comprehensive and georeferenced database, quantitatively and qualitatively elucidate the potential and limitations of the Sistan region for developing the cultivation of this valuable crop.

2. Materials and methods

Study Area: The study area encompasses the entire Sistan region, which is located in the northern part of Sistan and Baluchestan Province, lying approximately between 30° and 31.5° N latitude and 61° and 62° E longitude (Fig. 1). Due to its proximity to Iran's eastern border and neighboring Afghanistan, as well as the natural phenomenon known as the "120-day winds" that blow from late spring to early autumn, Sistan experiences an extremely arid to hyper-arid climate with very hot summers and relatively mild winters. The region's annual precipitation is extremely low, while potential evapotranspiration is very high, representing one of the primary limitations for agriculture. The soils in the region are predominantly light-textured, highly permeable, and saline-alkaline, which further pose challenges to agricultural development.

To establish the required meteorological database, long-term 25-year data (1996–2021) from synoptic and climatological stations covering the Sistan region, including Zabol and Zahak, as well as stations in neighboring provinces with similar climates to enhance

data interpolation accuracy, such as Nehbandan and Sarbisheh in South Khorasan, were utilized (Table 1). Daily data, including average, minimum, and maximum temperatures, precipitation, relative humidity, sunshine hours, wind speed, and evaporation, were collected for the specified period.

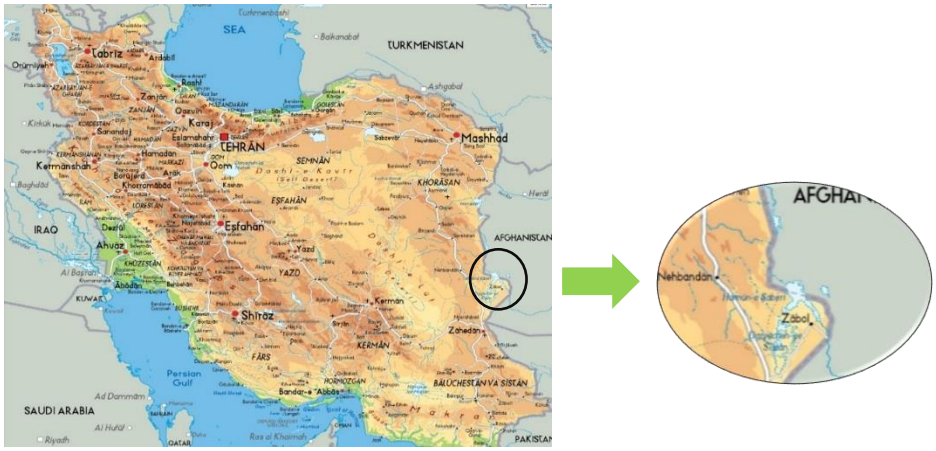


Figure 1. Geographical location of the study area

Table 1. Specifications of the meteorological database used (Jafari, 2000)

Station	Latitude	Longitude	Elevation (m)
Zabol	31°01'30" N	61°29'45" E	475
Zahak	30°89'44" N	61°70'67" E	496
Nehbandan	31°32'31" N	60°03'64" E	1192
Sarbisheh	32°34'25" N	59°47'48" E	1839

2.1. Determination of thermal stress indices

Cold Stress: To assess the risk of cold stress (temperatures below 7°C) and frost (temperatures below -2°C), the period of potential stress occurrence was determined based on jujube phenology. This period spans from the onset of growth to the beginning of dormancy. According to scientific reports, jujube can tolerate temperatures as low as -38°C during dormancy (Liu *et al*., 2020); thus, this period was excluded from cold stress risk calculations.

Heat Stress: The risk of heat stress was similarly calculated for a threshold temperature of 38°C. This threshold was established based on maintaining jujube yield and quality (Jiang *et al*., 2020). To measure heat stress intensity, indices such as the average daily maximum temperature during the flowering to ripening period and the Heat Stress Consistency (HSC) Index (Taei Semiromi *et al*., 2024) were used (Equation 1).

(1) HSC Index = [Number of days with P50 (daily Tmax > 38°C) / total period (day)] × 10

In this equation, the HSC Index represents the Heat Stress Consistency Index, where *Number of days with P50 (daily Tmax > 38°C)* is the number of days with a probability greater than 50% of daily maximum temperatures exceeding the flowering damage threshold, and *total period (day)* is the total number of days in the evaluated period.

Phenological Analysis of Jujube in the Sistan Region: Jujube flowering occurs provided the minimum thermal requirement (500–530 growing degree days) and chilling requirement are met. If the minimum daily temperature drops to -2°C during flowering, flowers sustain damage (Meir *et al*., 2016). For flowering initiation, the required growing degree days must be fulfilled. The fruit ripening period was estimated based on a threshold of 140 days after the onset of growth. The cumulative chilling requirement for jujube was calculated using the UTAH model (Richardson *et al*., 1974; Linvill, 1990). Studies indicate that the minimum chilling requirement for jujube is 240 hours (Liu *et al*., 2020). The cumulative thermal requirement (AHU) was calculated using the equation proposed by Tyldesley (1978).

In this study, the agroclimatic suitability assessment for jujube was conducted in four stages: initial field studies, data collection, calculation of agroclimatic suitability indices based on phenological stages and ecophysiological requirements of jujube, and phenological analysis of jujube under the diverse climatic conditions of the Sistan region, followed by zoning or determining the geographical distribution of calculated indices and their integration using the Analytic Hierarchy Process (AHP).

The geographical distribution analysis of thermal stresses was performed based on the correlation between station elevations and the probability of stress occurrence, using a digital elevation model (30-meter pixel resolution) in ArcGIS 10.8. Statistical calculations were conducted using Excel and SPSS version 17. For layer integration and weighting, the AHP method was employed. In this method, each layer was first classified into nine categories based on index values, with pixel values across all layers converted to a scale of 1 to 9 based on their initial values. Subsequently, optimal coefficients were calculated in three stages: creating a pairwise comparison matrix, calculating factor weights, and estimating the consistency ratio, using the AHP plugin in ArcGIS 10x.

Plant Database: This database includes comprehensive plant phenological data (precise timing of bud growth, flowering, fruit formation, ripening, and dormancy), fruit yield under various regional and climatic conditions, thresholds for thermal stress occurrence (low temperatures for frost and high temperatures for heat stress), salinity and drought stress tolerance thresholds, and models for predicting phenology and yield under different climatic conditions. These data were derived from recorded experiments on jujube in Iran (particularly at the Birjand research stations in South Khorasan Province, a primary jujube cultivation area with relatively similar climatic conditions) and other published scientific reports.

3. Results and discussion

Estimation of Jujube Growth Cycle Pattern: The temperature-limited growing period of jujube was analyzed based on its ecological tolerance range (7°C to 48°C) and thermal requirements in the Sistan region (Table 2). The jujube growth period begins when the average daily minimum temperature exceeds the threshold temperature (7°C), triggering the activation of lateral buds, and continues until the average daily maximum temperature exceeds the upper threshold (48°C) or falls *below the minimum threshold (*Allen *et al*., 1998). Using this approach, the growth cycle pattern was delineated. Given the extremely hot and arid climate of Sistan, the following outcomes are expected:

Early Onset of Growth Period: Due to the early rise in temperatures during late winter and early spring, the jujube growth period in Sistan begins significantly earlier than in more temperate regions.

Short and Intensive Growth Period: Due to extremely high temperatures during peak summer, the active growth period of the plant is shorter and more compressed.

Table 2. Zabol station phenology

Zabol Station	16 – 25 Feb	28 Feb – 6 Mar	10 – 15 Mar	15 – 26 Mar	10 – 15 Apr	15 – 29 Apr	29 Apr	14 Jun	30 Jun – 0 Jul	8 Sep	10 Dec
Bud Sprouting											
Leave development											
Shoot growth											
Inflorescence opening											
Flowering											
Fruiting											
Fruit attained 50% of its final dimension											
Change in fruit color: From dark green to light reddish brown											
Maturity											
Leaf dropping started											
Dropping of all leaves											

Heat Stress in Peak Summer: Although jujube is heat-tolerant, temperatures exceeding 40°C (particularly above 45°C) during the peak summer in Sistan can lead to physiological stress, reduced photosynthesis, and consequently negative impacts on fruit development, resulting in reduced quality and fruit shriveling. These temperatures may even induce temporary summer dormancy.

Based on the simulations, the onset of bud growth in Sistan can occur from mid to late February, significantly earlier than in colder or even more temperate regions (Table 2). Due to the high temperatures in this region, all phenological stages, particularly the onset of growth and flowering, occur markedly earlier than in more temperate areas. This provides an opportunity for early market supply of the

product but also presents challenges, such as the coincidence of fruit ripening with Sistan's intense 120-day winds and an increased risk of heat stress during critical stages of fruit formation and ripening.

Given the high temperatures in the Sistan region, jujube fruit ripening also occurs much earlier than in more temperate regions. This can provide the advantage of early product availability (e.g., in early summer), opening new market opportunities for producers. However, the risk of severe heat stress during the ripening period, which affects fruit quality (e.g., size, coloration, and shriveling), increases significantly. This necessitates precise management practices, including timely harvesting for fresh consumption, the use of natural or artificial windbreaks, and irrigation during this stage to maintain soil moisture and mitigate the impact of heat stress on fruit quality, which is critical.

The dormancy period of jujube in Sistan was calculated based on a temperature threshold of 7°C. Given the relatively mild and short winters in Sistan, the dormancy period for jujube is expected to be significantly shorter than in colder or even temperate regions. This means that jujube experiences a shorter dormancy period and enters the active growth phase earlier. This characteristic is highly significant for assessing the risk of cold stress and frost during sensitive stages (e.g., flowering), although the risk of cold stress in Sistan is generally lower than in colder regions of Iran. However, the short dormancy period may affect the fulfillment of chilling requirements for certain jujube cultivars. This situation can lead to phenomena such as uneven bud break, delayed flowering, or reduced flower numbers. Therefore, for successful jujube cultivation in Sistan, selecting cultivars with lower chilling requirements or employing specific management practices (e.g., foliar application of dormancy-breaking hormonal compounds) is of great importance (Meir *et al*., 2016).

3.1. Cold stress index

To assess the risk of cold stress, the probability of temperatures dropping below 7°C from the onset of the initial growth period in late February to fruit ripening in mid-April was calculated and analyzed. Regression models based on elevation, as used in this study, are widely employed for predicting cold stress risk in desert regions with high accuracy (R^2>0.90) (Bolstad *et al*., 1998; Kattel *et al*., 2022). The spatial distribution of the probability or risk of cold stress for jujube was calculated based on a significant linear relationship ($P \leq 0.001$) between the probability of cold stress risk at stations and elevation (coefficient of variation = 0.91). The classification of spatial distribution classes for cold stress risk during jujube flowering to ripening (Fig. 2a) indicated that the probability of temperatures falling below 7°C during the three months from February to April is approximately 20–25%. This risk is primarily concentrated in February and early March, particularly in the northeastern parts of the region, which experience lower temperatures. In the central and southern parts of the plain, this risk decreases to 15–20% and less than 10%, respectively, corresponding to approximately 5–10 days with temperatures below 7°C during this period, which is nearly negligible. Temperatures below 7°C during the early growth period of jujube can disrupt the flowering process and result in up to a 20% reduction in yield (Meng *et al*., 2020; Zhou *et al*., 2020).

3.2. Heat stress consistency index analysis

The Heat Stress Consistency Index (HSC Index) was calculated for the flowering and ripening periods of jujube due to its influence on the sustainability of flowering, pollination, yield, and fruit quality (Fig. 2b). This index incorporates both the risk of heat stress occurrence and the duration of temperatures exceeding the specified threshold, providing a quantitative assessment of heat stress persistence intensity in a region. Spatial distribution maps of the HSC Index were developed using a regression model fitted with a digital elevation model. The classification results for the HSC Index during the flowering to ripening period showed that 18.9% of the lands have an index value below 5, 22.3% fall within the 6–7 range, and 58.8% exceed 7. Studies indicate that heat stress consistency indices are crucial for predicting yield reductions in fruit-bearing crops like jujube, particularly in tropical regions, and are consistent with elevation-based models (Yang *et al*., 2024). Furthermore, recent research highlights that prolonged temperatures above the threshold can reduce pollination efficiency by up to 30%, underscoring the necessity of this index for orchard management (Jin *et al*., 2024). Importantly, jujube's pollination and flowering period do not align with the peak heat persistence period in the region.

However, due to the jujube's extended flowering period, where new flowers appear simultaneously with fruiting, the formation of new flowers faces a risk of sterility due to heat stress.

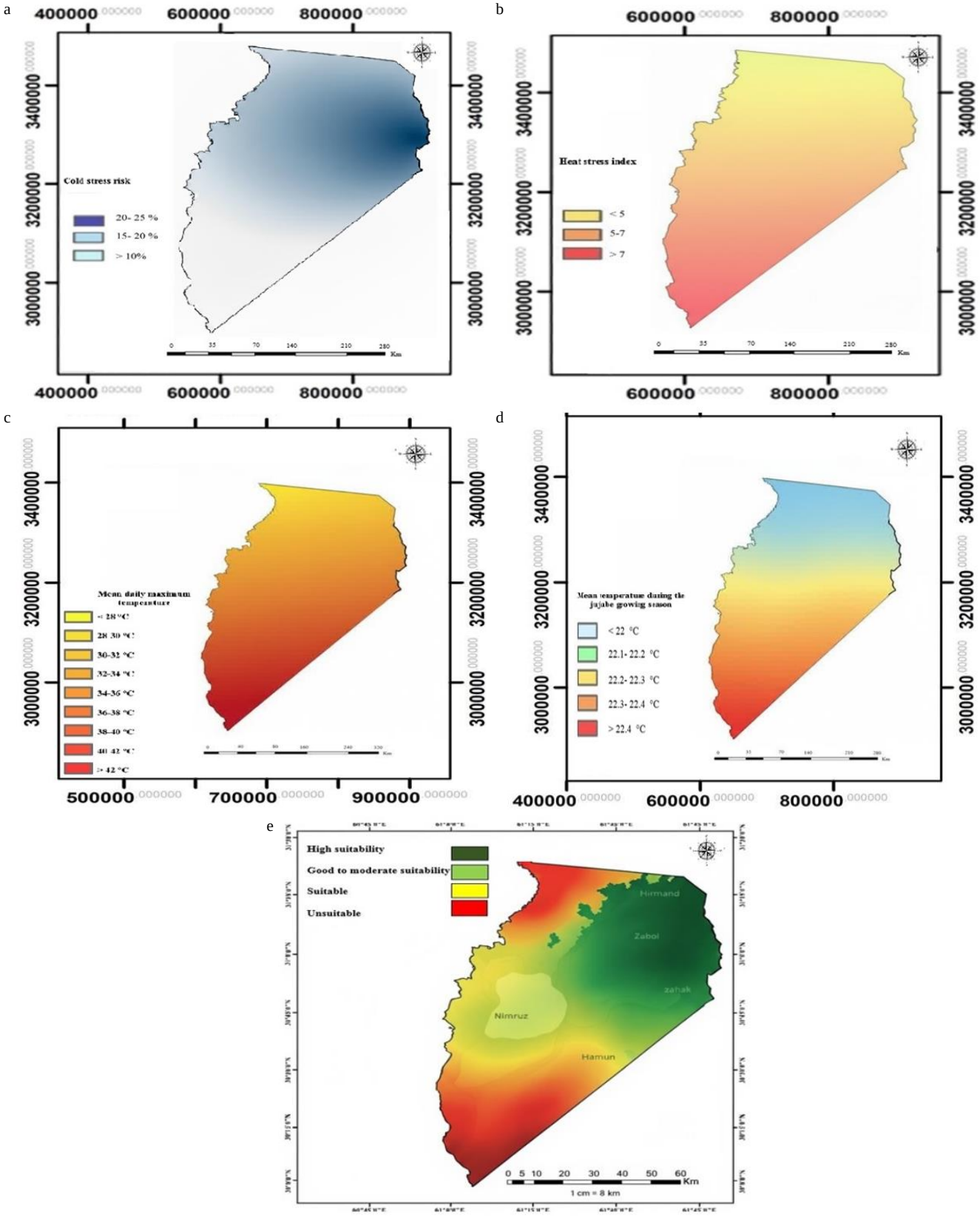


Figure 2. a) Risk of cold stress throughout the jujube growth period, b) Distribution of the heat stress index during the jujube growing season, c) Mean daily maximum temperature during the jujube growing season, d) Variability of mean daily temperature during the jujube growth cycle and e) The agro-climatic suitability of jujube cultivation in the Sistan plain.

3.3. Mean daily maximum temperature analysis

Spatial analyses were performed to examine the spatial distribution and zoning of the jujube flowering period pattern (stage 60, BBCH scale) (Sapkota *et al*., 2020). These analyses utilized a linear regression model fitted with flowering data from the studied stations and elevation (P≤0.001, coefficient of variation = 0.933). The results showed the mean daily maximum temperature during the flowering period distributed as follows: <28°C in 3% of the lands, 28–30°C in 6%, 30–32°C in 10%, 32–34°C in 12%, 34–36°C in 12.8%, 36–38°C in 15.2%, 38–40°C in 17.4%, 40–42°C in 15.6%, and >42°C in 8% of the lands (Fig. 2c).

The findings indicate that over 41% of the Sistan plain's lands face heat stress during the jujube fruit ripening stage. This heat stress, particularly in windy areas, results in smaller fruit, poor coloration, shriveling, and reduced marketability. Studies confirm that temperatures above 38°C during flowering and ripening disrupt photosynthesis and degrade product quality, consistent with this study's results (Khokhlov *et al*., 2022). Thus, a 38°C threshold was adopted as the stress-inducing limit for optimal product quality. For environmental and landscaping purposes, a temperature range of 45–48°C can be used. Recent studies highlight the role of heat stress management in windy regions through shading and optimized irrigation to improve jujube performance in the Sistan plain (Yang *et al*., 2024).

3.4. Mean daily temperature analysis

The mean daily temperature during the jujube growth period, from the onset of growth to the start of dormancy, was calculated. A spatial distribution map was created using a linear regression model fitted with elevation (P ≤ 0.001, coefficient of variation = 0.95) (Fig. 2d). The Sistan plain, with an average elevation of 475–500 meters above sea level, exhibits minimal temperature variation (less than 0.3°C across the region) due to a temperature lapse rate of approximately 0.6°C per 100 meters, resulting in a gentle gradient in the spatial distribution map. The classified zoning results showed that 10% of the lands had a mean growth period temperature below 22°C, 15% within 22–22.1°C, 25% within 22.2–22.3°C, 30% within 22.3–22.4°C, and 20% above 22.4°C.

Regression-based zoning analyses, as employed here, are extensively used for predicting climatic conditions and supporting sustainable agricultural management (Escandón-Panchana *et al*., 2025). Recent studies confirm that high temperatures during the jujube growth period, especially above 40°C, negatively affect fruit quality and yield (Duan *et al*., 2023). Elevation is a critical variable in temperature prediction models, significantly influencing the spatial distribution of mean temperatures, aligning with this study's findings (Yang *et al*., 2024). Given the relatively uniform elevation and temperature gradient in the Sistan region, the onset of the growth period is expected to be fairly consistent across the region.

3.5. Final agroclimatic suitability assessment and recommendations:

The classification of limitations for the studied indices was based on jujube cultivation for producing high-quality fruit with full coloration, free from shriveling and small size. For alternative purposes such as soil conservation, landscaping, timber, or secondary/medicinal products, the zoning results would differ, with reduced climatic limitations. The final agroclimatic suitability assessment for Sistan (Fig. 2e) shows:

- 5% very high suitability: Higher-elevation areas near Chah Nimeh reservoirs.
- 15% good to moderate suitability: Lands suitable with proper water and soil management (e.g., supplemental irrigation, soil amelioration).
- 30% low suitability: Areas with severe limitations, where cultivation is feasible only with significant investment and advanced techniques.
- 50% unsuitable: Desert areas, shifting sands, and highly saline-alkaline soils, where cultivation is not economically or sustainably viable.

4. Conclusion

This study comprehensively assessed the agroclimatic feasibility of jujube cultivation in Sistan, with key findings:

- Agroclimatic Classification: Sistan is hyper-arid with hot summers and mild winters, highlighting severe moisture and thermal limitations, necessitating resilient species and optimized resource management.
- Base Temperature and Phenological Modeling: A 7°C base temperature was accurately determined for jujube bud growth, valid for Sistan. Phenological

modeling showed earlier growth stages due to high temperatures.

- Dormancy and Chilling Requirements: Short dormancy and early active growth reduce frost risk.
- Flowering and Ripening Timing: Early flowering and ripening offer market opportunities but require heat stress management to maintain fruit quality. Harvesting before intense summer heat is recommended for fresh consumption.

Further research should focus on cultivar evaluation, water management, market development, and genetic improvement to enhance jujube production and stress adaptation.

- Research and Pilot Orchards: Establish orchards in suitable areas to test high-yielding cultivars for heat, drought, salinity, and wind tolerance, including nutrition, pest, and disease responses.
- Advanced Water Management: Explore rainfed cultivation with techniques like subsoil moisture barriers, mulching, or subsurface irrigation.
- Cultural and Market Development: Raise awareness of jujube's value for fresh/snack consumption and develop small-scale processing industries for value-added products.
- Genetic Improvement and Technology Transfer: Invest in developing high-yield, market-friendly cultivars with genetic resistance to environmental stresses.

Abbreviations

AHP: Analytic Hierarchy Process; GIS: Geographic Information Systems; HSC: Heat Stress Consistency; RS: Remote Sensing.

Conflict of interests

The authors declare no conflict of interest.

Ethics approval and consent to participate

No humans or animals were used in the present research. The authors have adhered to ethical standards, including avoiding plagiarism, data fabrication, and double publication.

Consent for publications

All authors have read and approved the final manuscript for publication.

Availability of data and material

All data analyzed in this study are embedded within the manuscript.

Authors' contributions

Mohamad Forouzandeh: Conception and design, acquisition of data, drafting of the manuscript, critical revision of the manuscript for important intellectual content, and administrative, technical, or material support; Javad Taei Semiromi: Analysis and interpretation of data, and obtaining funding; Fatemeh Bidarnamani: Statistical analysis, and supervision.

Informed consent

The authors declare not to use any patients in this research.

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Generative AI statement

The author declares that generative AI (artificial intelligence) tools, including Grammarly & QuillBot, were used to enhance the language & clarity of this work. The author takes full responsibility for the accuracy & integrity of the content.

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