Climate resilience of traditional olive-growing systems: an ethnobotanical and agro-ecological study in Khenchela, Algeria

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Research

Abstract

Background: Climate change poses significant threats to Mediterranean olive-growing systems, primarily through rising temperatures, precipitation variability, and water scarcity. The Wilaya of Khenchela in northeastern Algeria, with pronounced agroclimatic heterogeneity (annual rainfall ranging from ~60 to 431 mm), offers an ideal context to assess olive system resilience under contrasting environmental constraints. Despite Algeria being the ninth largest global olive producer, systematic assessments of how genetic diversity, morphometric traits, and socio-economic factors interact to confer adaptive capacity remain scarce.

Methods: A cross-sectional survey was conducted among 286 olive growers across five municipalities representing North Khenchela (NKh) and South Khenchela (SKh) agroclimatic zones. Data collection combined semi-structured questionnaires, morphometric analyses of 29 cultivar-district combinations, and historical production records (2017–2021). Sixteen composite indices were developed to capture genetic diversity (Shannon-Weaver Index), productive potential, hydric vulnerability (Water Dependence and Stress Indices), economic performance, and ecological resilience. These were integrated into a novel Composite Climate Stress Impact Index (CSII) that combines system-level resilience metrics with CMIP6-derived climate projections for 2041–2070 under SSP245 and SSP585 scenarios.

Results: Analysis of 29 cultivar-district combinations revealed significant spatial differentiation. Northern Khenchela exhibited higher varietal diversity (Varietal Diversity Index: 2.639 vs 0.693), superior oil conversion efficiency (0.782 vs 0.624), and greater ecological resilience (0.412 vs 0.248) than the southern zone. Cultivars Aberkane, Aimel, and Khadraia achieved the highest resilience scores (85.9–87.4%). Water stress indices were substantially higher in SKh (0.85–0.92 vs 0.52–0.68), correlating with greater production instability (coefficient of variation: 0.25 vs 0.14). CSII results highlighted that northern systems possess superior adaptive capacity under projected climate stress (+1.8 °C NKh vs +2.5 °C SKh).

Conclusions: Olive system resilience in Khenchela is multi-dimensional, relying on genetic diversity, water resource management, and cultivar morphometric efficiency. Priority interventions include varietal diversification in SKh, adoption of water-efficient irrigation practices, and conservation of high-resilience cultivars. The CSII framework provides a transferable tool for assessing and prioritizing adaptation strategies in Mediterranean olive agroecosystems under climate change.

Keywords: Climate resilience; Olive diversity; Composite indices; Water stress; North Africa; Adaptive capacity; CSII

Background

Climate change poses unprecedented challenges to Mediterranean agricultural systems, with olive cultivation particularly vulnerable to rising temperatures, precipitation variability, and water scarcity (Mairech *et al.* 2020; Fraga *et al.* 2024). The Mediterranean Basin, recognized as a climate change "hotspot" (Giorgi, 2006; IPCC, 2023), is projected to experience substantial warming (1.5–2 °C by mid-century) alongside a 15–25% reduction in precipitation across North Africa (Tanasijevic *et al.* 2014; Tramblay *et al.* 2023). These climatic shifts are already resulting in significant disruptions: global olive oil production dropped from 3.42 Mt in 2021–22 to 2.41 Mt in 2023–24, a 26% decrease largely driven by recurrent droughts and heatwaves in Mediterranean producing regions (Kaniewski *et al.* 2023; Statista, 2024). In North Africa, where olive cultivation has underpinned rural livelihoods for millennia, these pressures threaten both productive stability and the socio-economic resilience of farming communities (Benítez-Cabello *et al.* 2023). Consequently, understanding the adaptive capacity of traditional olive-growing systems under climate stress has become a critical research priority.

Olive trees (*Olea europaea* L.) exhibit remarkable ecological plasticity, growing under annual precipitation regimes ranging from 200 to 800 mm (Boulal, 2013). However, they remain sensitive to extreme temperatures and frost events, which can cause severe damage. The Mediterranean Basin accounts for over 95% of global olive production (COI, 2012; Benítez-Cabello *et al.* 2023), covering 10.8 Mha across 58 countries and generating employment for 35 million people worldwide (Benítez-Cabello *et al.* 2023). Algeria ranks ninth globally, producing approximately 915,000 tons of olive oil in 2023/24 from 431,506 hectares (COI, 2012; Algerian Ministry of Agriculture, 2021). Nevertheless, the country experiences high production volatility: after producing only 30,000 tons in 2022/23 the lowest harvest in 30 years due to adverse weather and wildfires—production in 2023/24 remained 40–50% below expectations (Rives, cited in Olive Oil Times, 2024). Despite its substantial production potential, Algeria's olive sector is primarily oriented toward domestic consumption, with per capita consumption (1.5 kg/person/year) far below Mediterranean standards, such as Greece (16.3 kg/person/year) (Chikhi, 2022). This productivity gap reflects multiple constraints, including limited institutional support, climatic variability particularly recurring droughts and wildfires that destroy large olive growing areas and limited integration into international export markets (Chikhi, 2022; Raseef22, 2023), despite the recognized quality of Algerian olive oils, which can reach extra virgin grade (Djelili-Mamou, 2018).

The Wilaya of Khenchela in northeastern Algeria provides a particularly relevant context for studying olive system resilience. The region is characterized by high environmental heterogeneity, with marked altitude gradients, topographic contrasts, and substantial spatial variation in annual rainfall (ranging from 60 mm in the arid southern zones to over 400 mm in the northern semi-arid areas). Two distinct agroclimatic zones coexist: North Khenchela (NKh), influenced by Mediterranean climate regimes from the Tellian Atlas, offers relatively favorable conditions for olive cultivation, with an average annual rainfall of approximately 431 mm and elevations ranging from below 800 m to over 1,600 m. In contrast, South Khenchela (SKh) experiences a transitional climate between Mediterranean and Saharan influences, with reduced rainfall (60–200 mm/year) and higher exposure to desertification. This spatial heterogeneity provides a natural laboratory for comparative analysis of olive system resilience under different climatic constraints.

Previous studies in Khenchela have explored the molecular diversity of olive germplasm (Boukhari, 2020; Falek, 2022; Kadi, 2023), fruit morphology (Gueboudji, 2021; Mekersi, 2021), and the physicochemical properties of olive oil and its by-products. However, systematic assessment of interactions between genetic diversity, agro-ecological conditions, productive performance, and socio economic vulnerability remains limited. Moreover, existing research has not explicitly integrated climate projections into vulnerability assessments, nor developed composite indices capable of synthesizing the multiple dimensions of system resilience. Conserving and utilizing genetic diversity has emerged as a key adaptation strategy: more than 2,600 olive cultivars exist worldwide (Fraga *et al.* 2020), representing a millennia-old heritage and a fundamental resource for climate adaptation (Hannachi *et al.* 2009; Barazani *et al.* 2023). Recent studies have shown that wild populations (*O. europaea* var. *sylvestris*) harbor unique stress-adaptive traits (Belaj *et al.* 2011; León *et al.* 2018; Tadić *et al.* 2024) and that cultivar-specific responses to water and salinity stress are genetically mediated (Calvo-Polanco *et al.* 2019; Al-Kilani *et al.* 2024). Nevertheless, systematically quantifying the interaction between genetic diversity and agroclimatic conditions to enhance system-level resilience remains largely unexplored in North African olive agroecosystems.

This study adopts an integrated approach combining ethnobotanical surveys, morphometric characterization, and multidimensional resilience modeling. Sixteen composite indices were used to assess genetic diversity (Varietal Diversity Index, Shannon-Weaver), productive potential (Varietal Productive Potential Index, Oil Conversion Efficiency), hydric vulnerability (Water Dependence Index, Water Stress Index according to FAO Penman-Monteith; Allen *et al.* 1998), economic performance (Climate Economic Vulnerability, Global Economic Productivity), ecological resilience (incorporating efficiency, diversity, input pressure, and stress; Holling, 1973; Walker *et al.* 2004), and temporal stability (Temporal Stability Index; Tilman, 1999). These indices were calibrated using primary data collected from 286 farmers across five municipalities spanning the full agroclimatic gradient of the wilaya, combined with morphometric analyses of fruits and leaves from 29 cultivar-district combinations.

A Composite Climate Stress Impact Index (CSII) was employed to explicitly integrate genetic diversity, morphometric efficiency, ecological resilience, economic vulnerability, and projected climate stress (temperature increase and hydric stress intensity), based on CMIP6 multi-model ensembles reported in the IPCC AR6 (IPCC, 2022, 2023). Climate projections for Mediterranean North Africa indicate temperature increases of +1.5 to +3.0 °C by 2041–2070 under intermediate to high emission scenarios (IPCC, 2022, 2023), with irrigation requirements rising by 18.5% (70 ± 28 mm/season), potentially reaching 140 mm in southern Spain, Algeria, and Morocco (Tanasijevic *et al.* 2014). Low-density rainfed orchards, which dominate traditional systems, are expected to experience yield reductions of up to 28% and a 20% increase in interannual variability, particularly in the Iberian Peninsula (Mairech *et al.* 2020). Eight-thousand-year pollen analyses have identified photosynthetic activity as a key determinant of olive productivity, threatened by increasing water stress and potential reductions in solar radiation during the 21st century (Communications Earth & Environment, 2025). The CSII thus enables a comprehensive assessment of olive agroecosystem vulnerability under climate scenarios, facilitating identification of districts and cultivar assemblages with high adaptive capacity or heightened vulnerability (Urruty *et al.* 2023; Moriondo *et al.* 2021).

The objectives of this study are: (1) to characterize and compare the morpho-agronomic diversity of olive cultivars across contrasting agroclimatic zones of Khenchela, based on genetic variability and phenotypic traits in Mediterranean germplasm (Hannachi *et al.* 2021; Rallo *et al.* 2024; Rodríguez *et al.* 2018; Mousavi *et al.* 2020); (2) to evaluate multiple dimensions of system resilience—genetic, productive, hydric, economic, and ecological—using a comprehensive set of composite indicators widely applied in agricultural resilience assessment (Gomez & Ricketts, 2013; Li & Lupi, 2014; Balodis *et al.* 2019; FAO, 2021); and (3) to assess the differentiated vulnerability of northern and southern olive-growing systems to projected climate impacts, considering both adaptation strategies (deficit irrigation, cultivar selection, cover cropping) and mitigation potential (carbon sequestration by olive systems; Proietti *et al.* 2014; Brilli *et al.* 2016; Mairech *et al.* 2020). By providing a multi-scale, multidimensional assessment at the cultivar, farm, and district levels, this study aims to develop effective adaptation strategies to ensure sustainable olive production in Mediterranean environments under climate stress, while addressing adaptation barriers identified by the IPCC (2023).

Materials and Methods

Study area and study period

The present study was conducted between September 2021 and January 2022 in the wilaya of Khenchela, covering an area of approximately 9,811 km² and ranking 40th in the national administrative division. The region is characterized by pronounced environmental and climatic heterogeneity resulting from marked contrasts in altitude, topography, and the spatial distribution of annual rainfall, making it particularly relevant for investigating the resilience of olive-growing systems under climatic constraints. The general climate is Mediterranean, with hot, dry summers and cold, wet winters; however, a notable spatial differentiation exists, including very harsh winters and moderate summers in the central mountainous areas, moderate winters and hot, dry summers in the southern Saharan steppes, and very cold winters with dry summers in the northern high steppes. Mean annual precipitation across the wilaya is approximately 446 mm, although strong gradients are observed between the northern and southern zones (Mariama 2022). The study period focused on the collection of primary data through field surveys with olive growers, as well as the sampling and morphometric analysis of olive fruits. Historical climatic and production data, covering the last five years (2017-2021), were also gathered to enable the calculation of interannual variability indices (Figure 1).

The study area was subdivided into two main agroclimatic regions, namely North Khenchela (NKh) and South Khenchela (SKh), in order to better assess the effects of contrasting environmental conditions on olive cultivation. The North Khenchela sites, administratively associated with the municipalities of Taouziant, Chelia, Kais, and Baghai, are located between 35°40′16″ N and 35°21′37″ N in the northern Aurès piedmont, within the Atlas Mountains. This area is influenced by the

Mediterranean climate of the Tellian Atlas, with precipitation mainly concentrated between November and April and an annual average of about 431 mm. Altitudes range from less than 800 m in the central plains, particularly around Taouziant, to more than 1,600 m at the summit of Djebel Chelia, generating a diversity of microclimates favorable to arboriculture. The landscape is dominated by agricultural plains representing more than 80% of the surface area, interspersed with forest formations such as the Beni Imloul massif, and characterized by soils derived from sandstone and limestone. This region is considered one of the most productive agricultural zones of the wilaya, where olive growing represents an important activity, mainly practiced in small-scale farms (Bouzekri 2017, Belhouchet 2024).

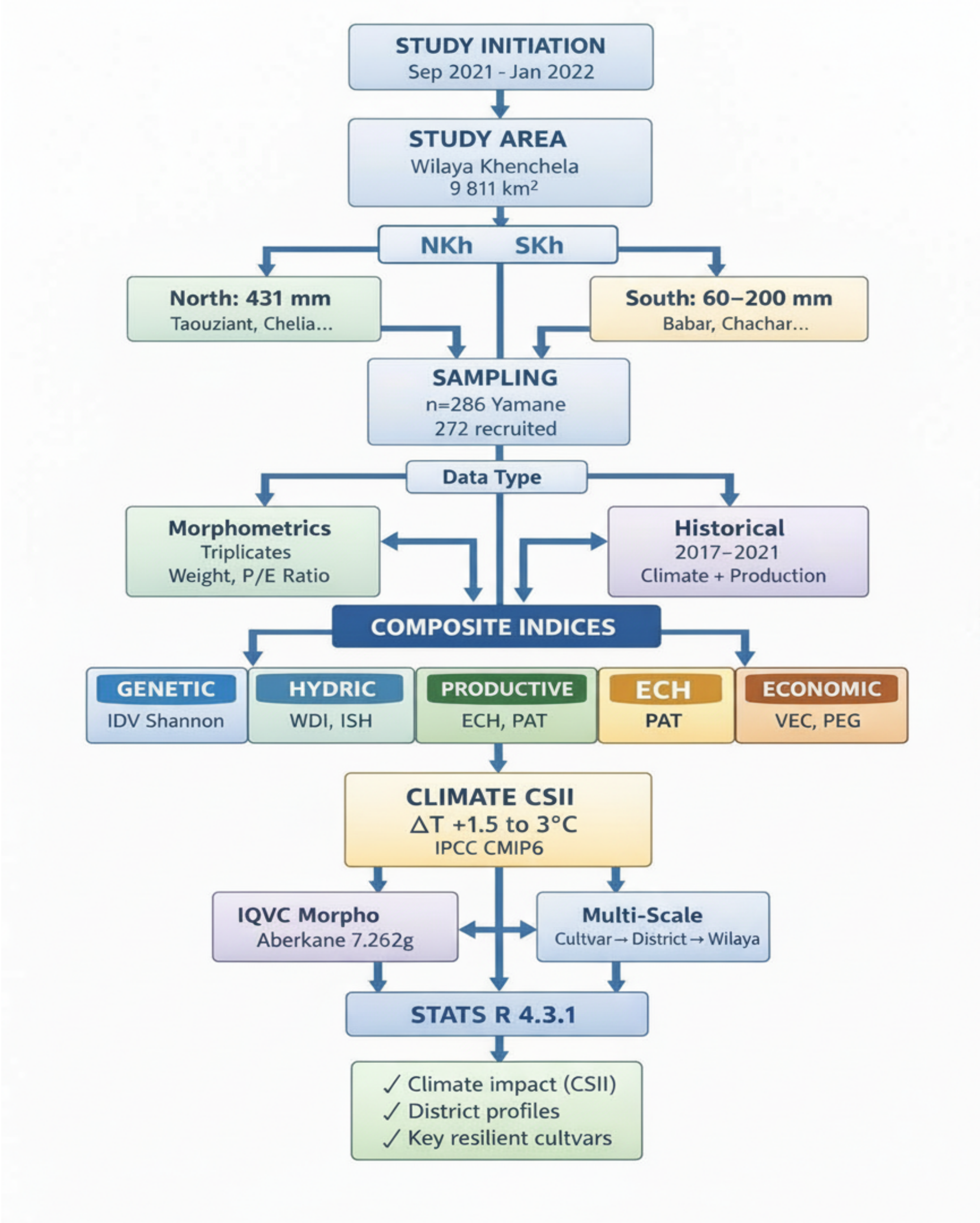

Figure 1. Study Design, Composite Indices, and Climate-Resilience Analysis Workflow

The South Khenchela sites, encompassing the municipalities of Babar, Chachar, and Khirane, are located between 35°15’14” N and 34°09’35” N, and 07°10’00” E and 07°55’00” E, within a transitional zone marked by the interaction between Mediterranean influences from the Tellian Atlas in the north and Saharan influences from the Saharan Atlas in the south. This region is characterized by a gradual transition from a semi-arid to an arid climate, with maximum temperatures recorded between May and October, winter temperatures that may drop to 5 °C, and an average annual temperature of approximately 22 °C. Mean annual precipitation varies considerably with latitude, reaching about 200 mm in the northern semi-arid zones and decreasing to nearly 60 mm in the southern arid zones. The landscape is predominantly steppe-like, dominated by plant formations such as alfa grass (*Stipa tenacissima*) and wormwood (*Artemisia herba-alba*), evolving toward pre-Saharan landscapes in the south, which confers an agro-sylvo-pastoral vocation to the region. Soils are also of sandstone and limestone origin, and the area is highly exposed to desertification processes, increasing the vulnerability of agricultural systems to climate change (Bouzekri 2017, Sedrati 2017, Mariama 2022).

Within this context, the study sites included the municipalities of Bouhmama, Kais, Chachar, Babar, Taouziant, Chelia, and Khirane, covering the main olive-producing areas of the wilaya and representing a diversity of environmental and socio-economic settings. All research activities were carried out in consultation with the Directorate of Agricultural Services of the wilaya of Khenchela and several of its local subdivisions, in order to ensure data consistency and the representativeness of the selected sites. Field surveys were conducted among olive growers in both regions, including five producers in the northern zone and five in the southern zone, selected based on their long-term experience in olive cultivation and their willingness to provide detailed historical data. These ten producers served as key informants to complement the broader quantitative survey. This integrated spatial and temporal approach made it possible to comparatively analyze the dynamics of olive-growing systems under contrasting agroclimatic conditions, while addressing key issues related to resilience and sustainability of olive cultivation in the wilaya of Khenchela.

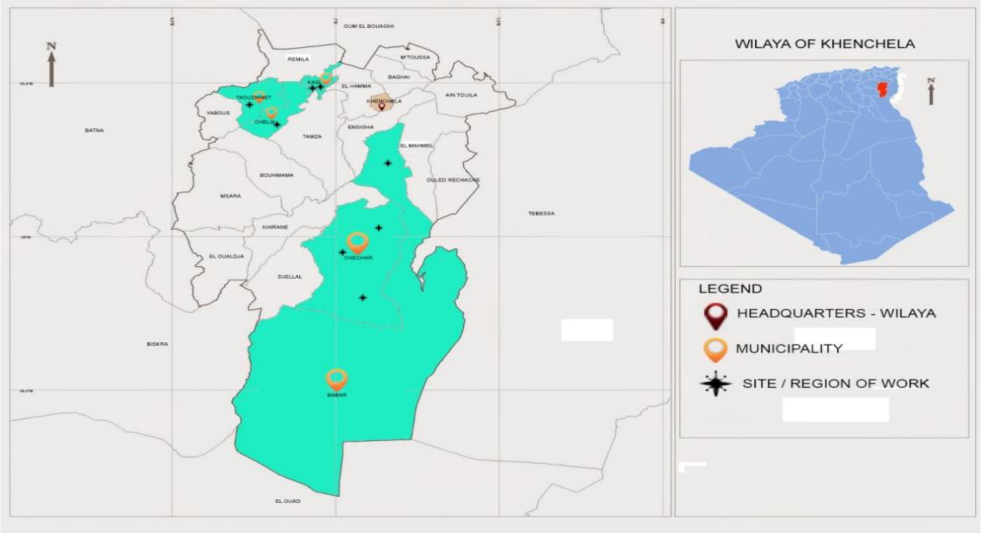

Figure 2. Geographic location and agroclimatic zones of the study area in Khenchela, northeastern Algeria.

Population and sampling

The target population of this study consisted of all olive growers registered in the Wilaya of Khenchela, totaling 1,000 farmers. To ensure the statistical robustness of the results and the representativeness of the sample, its size was determined using Yamane's formula (1967) with a 95% confidence level and a 5% margin of error:

$$n = N / [1 + N(e^2)] \qquad (1)$$

Where n represents the sample size, N the total population (1,000 olive growers), and e the tolerated margin of error (0.05). Applying this formula led to an optimal sample size of 286 farmers, ensuring an appropriate balance between statistical precision and practical feasibility in the field.To account for the structural and socio-economic diversity of olive farms, a proportional stratified sampling approach was implemented. The farms were divided into three strata according to their area: small (<5 ha), medium (5-15 ha), and large (>15 ha). The sample size for each stratum (nh) was calculated proportionally to the stratum's share in the total population (N) using the formula:

$$nh = n \times (Nh/N) \qquad (2)$$

The distribution of the 286 sampled farmers was then proportionally allocated across these strata and the two agroclimatic regions (NKh and SKh) to ensure adequate representation of the diverse olive-growing systems. For instance, if 30% of olive farms in the wilaya are small (<5 ha), then 30% of the 286 sampled farmers were drawn from this stratum. This approach ensures that farms of all sizes are adequately represented, providing a comprehensive and balanced overview of the olive-growing systems in the Wilaya. It also contributes to the reliability of statistical analyses and the relevance of conclusions regarding cultural practices, productivity, and farm resilience.

Vulnerability and resilience indicators

Variety Diversity Index (IDV): The varietal diversity of olive cultivars within each farm was quantified using the Shannon-Weaver index, which simultaneously accounts for richness (number of cultivars) and evenness (distribution of individuals among cultivars). This approach is widely applied in agricultural biodiversity studies as it reflects the capacity of a system to buffer biotic and abiotic stresses through genetic heterogeneity (Magurran 2013, Tilman et al. 2014):

$$IDV = -\sum_{i=1}^{s} p_i \ln(p_i) \qquad (3)$$

where p_i is the proportional surface area (in ha) occupied by cultivar i and S is the total number of cultivars identified. Higher IDV values indicate greater genetic diversity, which is associated with improved adaptive potential and stability under environmental variability.

Varietal Productive Potential Index (IPV): This index integrates key pomological traits relevant to olive oil yield potential, combining average pulp weight, endocarp weight, and relative frequency of cultivars. Morphological parameters have been shown to correlate with oil content and production efficiency (Rodríguez et al. 2018, Mousavi et al. 2020):

$$IPV = \sum_{i=1}^{s} (P_i/E_i \times f_i) \qquad (4)$$

Where P_i is the mean pulp weight (in grams) per fruit, E_i the endocarp (pit) weight (in grams) per fruit of cultivar i, and f_i its relative frequency expressed as the proportion of trees of cultivar i within the farm. This index reflects the potential contribution of each cultivar to oil production based on its morphometric characteristics and prevalence.

Hydric indicators

Water Dependence Index (WDI): The Water Dependence Index was developed using a multicriteria formulation that incorporates water source quality, irrigation efficiency, and variability in water availability. This type of composite indicator is aligned with frameworks used in irrigation vulnerability assessments (Zhang et al. 2019, FAO 2021):

$$WDI = \alpha Sw + \beta Ei + \gamma Vw \qquad (5)$$

Here, Sw denotes the water source score (1 = surface water, 2 = borehole, 3 = well), reflecting the perceived reliability and sustainability of the source, with higher scores indicating less reliable sources for olive production. Ei is irrigation efficiency (0.95 for drip, 0.65 for sprinkler, 0.45 for gravity), and Vw represents water availability variability. Vw was quantified as the coefficient of variation of annual water supply (in m³) reported by farmers over the past five years. Weighting coefficients were set to $\alpha = 0.5$, $\beta = 0.3$, and $\gamma = 0.2$ based on expert judgment and literature precedents from arid and semi-arid regions (Rockström et al. 2018, IPCC 2021).

Water Stress Index (ISH): The ISH quantifies climatic and hydric stress by comparing effective precipitation with potential evapotranspiration, adjusted for crop-specific coefficients, following the FAO Penman-Monteith framework:

$$ISH = [(ET_o - Peff)/ET_o] \times (Kc/Kcb) \qquad (6)$$

Where ET_o is reference evapotranspiration (mm), Peff effective precipitation (calculated as 70% of total rainfall to account for runoff and deep percolation, as per FAO guidelines for olive-growing regions), Kc the crop coefficient for olives (typical values for olive trees in Mediterranean climates, ranging from 0.4 to 0.7 depending on the growth stage and canopy cover, were used and derived from Allen et al. 1998), and Kcb the basal crop coefficient adjusted for canopy density (adjusted based on farm-specific canopy cover data collected during surveys). This index aligns with drought stress metrics used in climate risk studies (Allen et al. 1998, Daccache et al. 2014).

Productive performance indicators

Oil Conversion Efficiency (ECH): The efficiency with which olive biomass is converted into oil is calculated by combining yield data and varietal influence, similar to agronomic efficiency indices used in cropping system evaluations (Balodis et al. 2019):

$$ECH = (Hp/Op) \times (1 + \sum_{i=1}^{s} \omega_i Rp/e,i) \qquad (7)$$

Here, Hp is the oil production (in Liters), Op olive production (in kg), ω_i the relative weight (proportion of total olive production) of cultivar i, and Rp/e,i its pulp-to-endocarp ratio. The term $1 + \sum \omega_i Rp/e,i$ enhances the efficiency score for farms with a higher proportion of cultivars known for better pulp-to-endocarp ratios, indicating superior oil extraction potential.

Adjusted Labor Productivity (PAT): This metric incorporates both production volume and labor input, adjusted for interannual variability and quality of output. Similar approaches are used in productivity and resilience assessment in agroecosystems (Gomez & Ricketts 2013, Li & Lupi 2014):

$$PAT = [(Hp \times Qh)/(L \times h)] \times [1/(1 + CVinter)] \qquad (8)$$

where Qh is an index of oil quality (a composite score based on acidity, peroxide value, and organoleptic assessment, normalized from 0 to 1, with 1 being premium quality), L the number of workers, h the hours worked, and CVinter the interannual coefficient of variation of oil production over the last five years (2017-2021). A higher CVinter reduces the PAT, reflecting lower stability and resilience of labor productivity.

Ecological indicators

Input Pressure Index (IPI): This index aggregates cultural inputs by their environmental impact weights. Similar weighted indices have been used to assess agrochemical pressure in environmental risk studies (Tilman et al. 2002, Pretty & Bharucha 2015):

$$IPI = \sum_{j=1}^{K} w_j I_j f_j \qquad (9)$$

Where w_j is the environmental weight of input j (e.g., pesticides = 3, synthetic fertilizers = 2, organic fertilizers = 1), reflecting their known environmental impact based on literature (Pimentel et al. 1992), I_j its intensity of use (e.g., kg/ha for fertilizers, L/ha for pesticides), and f_j its frequency (number of applications per year).

Ecological Resilience (RE): Ecological resilience is defined by the productive efficiency of the system, modulated by genetic diversity and hydric stress, capturing adaptive capacity under multiple pressures (Holling 1973, Walker et al. 2004):

$$RE = [ECH \times (1 + IDV)]/(IPI \times ISH) \qquad (10)$$

This formula posits that higher oil conversion efficiency and varietal diversity enhance resilience, while high input pressure and water stress diminish it. All component indices were normalized to a common scale (0-1) prior to aggregation to prevent undue influence from differing magnitudes.

Economic and stability indicators

Climate Economic Vulnerability (VEC): This indicator expresses the ratio of production costs to production value, adjusted for climatic variability, a method aligned with economic vulnerability frameworks in climate risk research (Cattaneo et al. 2019, Wheeler & von Braun 2013):

$$VEC = [(Ct + Ctr)/(Hp \times Ph)] \times (1 + \sigma climat) \qquad (11)$$

Where Ct represents total production costs (excluding transport), Ctr total transport costs (for inputs and products), Hp oil production (L), Ph the market price of olive oil (€/L), and σclimat the standard deviation of annual precipitation over the last five years (2017-2021), normalized to the mean annual precipitation. The term (1 + σclimat) acts as a multiplier, increasing vulnerability with higher climatic variability.

Global Economic Productivity (PEG): This metric integrates net economic return per unit area, discounted for time and vulnerability, following economic resilience assessment practices (Barbier & Hochard 2018):

$PEG = [[(Hp \times Ph) - Ctotal]/[S \times (1 + r)]] \times [1/(1 + VEC)]$ (12)

where Ctotal is total production cost, S the cultivated area (ha), and r the discount rate (set at 5% based on national economic averages for agricultural investments).

Temporal Stability Index (IST): The temporal stability index measures year-to-year production consistency, combining relative change with variability:
$IST = 1 - [|Hp,2021 - Hp,2020|/Hp,2020] \times \exp(-CV^2/2)$ (13)

where Hp,2021 and Hp,2020 are the oil production (L) in the last two years of the study period (2021 and 2020, respectively), and CV is the coefficient of variation of annual oil production over the study period (2017-2021). The exponential term $\exp(-CV^2/2)$ acts as a dampening factor, penalizing higher interannual variability and reinforcing the impact of short-term production fluctuations. This formulation is adapted from environmental stability metrics (Tilman 1999).

Climate impact assessment

Beyond conventional agro-morphological and economic indicators, this study introduces an integrative analytical framework explicitly designed to assess the impact of climate change on olive-growing systems. A Composite Climate Stress Impact Index (CSII) was developed, synthesizing genetic diversity, morphometric efficiency, ecological resilience, economic vulnerability, and projected climatic stress into a single metric.

The CSII was constructed by combining the Varietal Diversity Index (IDV), Ecological Resilience (RE), and Temporal Stability (IST), weighted by climate-driven stressors, including temperature increase (ΔT) and hydric stress (ISH), according to the following conceptual formulation:

$CSII = [RE \times (1 + IDV) \times IST]/(1 + \Delta T + ISH)$ (13)

where ΔT represents the projected increase in mean temperature, and ISH reflects the intensity of hydric stress under current and future climatic conditions. All components were normalized to ensure comparability and to prevent any single indicator from dominating.

The climatic data used to construct the CSII were obtained from internationally recognized sources, ensuring reliability and alignment with Mediterranean climate change scenarios. Projections of mean temperature increase (ΔT) were derived from CMIP6 multi-model ensembles, as synthesized in the Sixth Assessment Report of the IPCC (AR6), currently the global scientific reference for climate change assessment. These projections indicate, for the Mediterranean region and North Africa, a temperature increase ranging from +1.5 to +3.0 °C by 2041-2070, according to intermediate to high emission pathways (IPCC 2022, IPCC 2023).

Hydric stress intensity (ISH) was estimated using widely applied regional drought indices, notably indicators based on the climatic water balance (precipitation minus potential evapotranspiration), consistent with analyses derived from the FAO-CLIMWAT, WorldClim v2.1, and CRU TS datasets. These databases provide high-resolution, spatialized climatic data commonly used to evaluate agricultural systems' vulnerability to water deficits in semi-arid regions (FAO 2019, Fick & Hijmans 2017, Harris et al. 2020).

This index establishes an explicit link between biological diversity, productive performance, and socio-economic stability, on the one hand, and climatic stress variables, on the other, within a unified resilience-oriented framework. Unlike traditional approaches that analyze these dimensions separately, the CSII allows a systemic assessment of olive agroecosystems under climate change, facilitating the identification of districts and cultivar assemblages with high adaptive capacity or, conversely, heightened vulnerability.

Composite variety quality index and morphometric integration

Morphometric characteristics (mean fruit weight, pulp/endocarp ratio, and stability) were integrated into a composite index using weighted factors derived from factorial analysis, an approach commonly used in trait synthesis studies (Jolliffe 2002, Ding et al. 2018):
$IQVC = \alpha_1\bar{W}f + \alpha_2Rp/e + \alpha_3(1/CVw)$ (14)

where $\bar{W}f$ is the normalized mean fruit weight (normalized by dividing the mean fruit weight of a cultivar by the maximum observed mean fruit weight across all cultivars, which was 7.262 g for the Aberkane cultivar), Rp/e the pulp/endocarp ratio, CVw the coefficient of variation of fruit weight for each specific cultivar, and α_i weighting coefficients ($\alpha_1 = 0.4$, $\alpha_2 = 0.4$, $\alpha_3 = 0.2$) determined by a Principal Component Analysis (PCA) which indicated these factors captured the most significant variance in quality traits.

Beyond traditional morphometric measurements, we developed an integrated analytical platform combining multi-scale analysis (cultivar, district, wilaya) with composite indicators. The IQVC was calculated for each cultivar, integrating normalized fruit weight relative to the maximum observed value (7.262 g for Aberkane cultivar), pulp/endocarp ratio, and trait stability estimated through coefficient of variation. A novel resilience score was computed as a weighted combination of P/E ratio (50%), morphometric efficiency defined as pulp weight percentage of total fruit weight (30%), and IQVC (20%), providing a synthetic metric of adaptive capacity under environmental stress. These weights were established through expert elicitation among agronomists specializing in olive cultivation in the region, reflecting their consensus on the relative importance of each component for cultivar resilience. Morphometric efficiency was calculated as:

$$\text{Morphometric Efficiency} = [\text{Pulp Weight (g)}/\text{Fruit Weight (g)}] \times 100 \qquad (15)$$

Multi-scale comparative analysis

District-level analyses aggregated individual cultivar data to calculate mean performance metrics and Shannon-Weaver diversity indices (IDV). For each agroclimatic district (NKh and SKh, further sub-divided by municipality for finer analysis), the following parameters were computed: cultivar richness, average fruit weight, average P/E ratio, average IQVC, and diversity index. The diversity index was calculated as:

$$IDV = -\sum p_i \ln(p_i) \qquad (16)$$

where p_i represents the proportional abundance (based on cultivated surface area) of cultivar i within the district. This multi-scale approach enables identification of cultivar-district combinations exhibiting enhanced resilience under contrasting agroclimatic conditions. Interactive visualizations including scatter plots for bivariate relationships (fruit weight vs P/E ratio), bar charts for morphometric efficiency comparisons, radar charts for multi-criteria district profiles, and comparative tables were developed to facilitate dynamic exploration of morpho-agronomic relationships across agroclimatic zones. This integrated analytical framework provides a comprehensive assessment of genetic diversity, productive potential, and adaptive capacity of olive-growing systems in the Khenchela region.

Statistical analysis

All morphometric measurements were conducted in triplicate, and mean values with standard deviations were calculated. Descriptive statistics including means, ranges, and coefficients of variation were computed for each cultivar and district. Composite indices were calculated according to the equations specified above, with weighting coefficients determined through factorial analysis and expert consultation. Comparative analyses between districts were performed using one-way Analysis of Variance (ANOVA) followed by Tukey's HSD post-hoc test when assumptions of normality and homoscedasticity were met. For non-normally distributed data, non-parametric tests such as the Kruskal-Wallis test were employed. Relationships between morphometric traits and composite indices were explored through bivariate scatter plots and Pearson correlation analyses. All statistical analyses were conducted using R statistical software (R Core Team 2023), and data visualization was performed using ggplot2 and other dedicated R packages, ensuring reproducibility and transparency of the analytical workflow.

Results

Morphometric analyses combined with the modeling of resilience indicators enabled an integrated characterization of varietal diversity, productive performance, hydric and economic vulnerability, and ecological resilience, as well as the capacity of olive-growing systems in the Wilaya of Khenchela to adapt to climate change.

The results were presented at the cultivar scale and aggregated at the district level, with a clear distinction between the North Khenchela (NKh) and South Khenchela (SKh) regions, which are characterized by contrasting agro-climatic conditions. In total, 29 cultivar–district combinations were analyzed based on data collected from 286 farmers covering five districts (Baghai, Khirane, Siyar, Zaouia, and Babar). The comprehensive analytical framework integrated 16 composite indices, enabling a multidimensional assessment of the resilience of olive-growing systems by simultaneously considering morphometric, productive, hydric, economic, and ecological dimensions, as well as their responses to current and future climate pressures.

Varietal Diversity and Productive Potential

The assessment of varietal diversity, quantified using the Shannon–Weaver Varietal Diversity Index (VDI) and Varietal Productive Potential Index (VPI), revealed significant heterogeneity among cultivars and districts (Figure 3a–c). The VDI values ranged from 0.108 (Neb djmel, Baghai) to 0.352 (Aberkane, Baghai), with the North Khenchela (NKh) districts consistently exhibiting higher diversity indices than those of South Khenchela (SKh). At the district scale, VDI calculations showed that Baghai (NKh) displayed the highest diversity (VDI = 2.639), followed by Zaouia (VDI = 1.946) and Khirane (VDI = 1.386), whereas Babar presented the lowest diversity (VDI = 0.693). This diversity gap reflects both local agricultural traditions and differentiated responses to market pressures, with the broader genetic base observed in NKh conferring a greater buffering capacity against biotic and abiotic stressors (Tilman *et al.* 2014; Isbell *et al.* 2023). These results highlight the functional role of intra-regional varietal diversity as a structural component of resilience, rather than a purely descriptive attribute. In NKh, the broader genetic base likely buffers against key biotic stresses such as olive fruit fly (*Bactrocera oleae*) and fungal diseases (Colletotrichum spp.), as well as abiotic pressures including spring frosts at high elevations (up to 1,600 m), recurrent summer droughts intensifying alternance, and wildfires — constraints well-documented in northeastern Algeria (Tilman *et al.* 2014; Isbell *et al.* 2023).

The proportional area occupied by each cultivar varied considerably, with dominant cultivars such as Aberkane covering 15.2 ha (13.3% of the total surveyed area), compared with only 2.1 ha (1.8%) for minor cultivars such as Neb djmel (Figure 3b). Recent studies conducted in Mediterranean olive-growing regions have highlighted the key role of genetic diversity in maintaining productive stability under conditions of climatic variability (Hannachi *et al.* 2021; Rallo *et al.* 2024). The observed patterns of spatial dominance suggest that varietal selection results from the combined effects of agronomic performance, market demand, and farmers' long-term adaptation strategies to changing conditions.

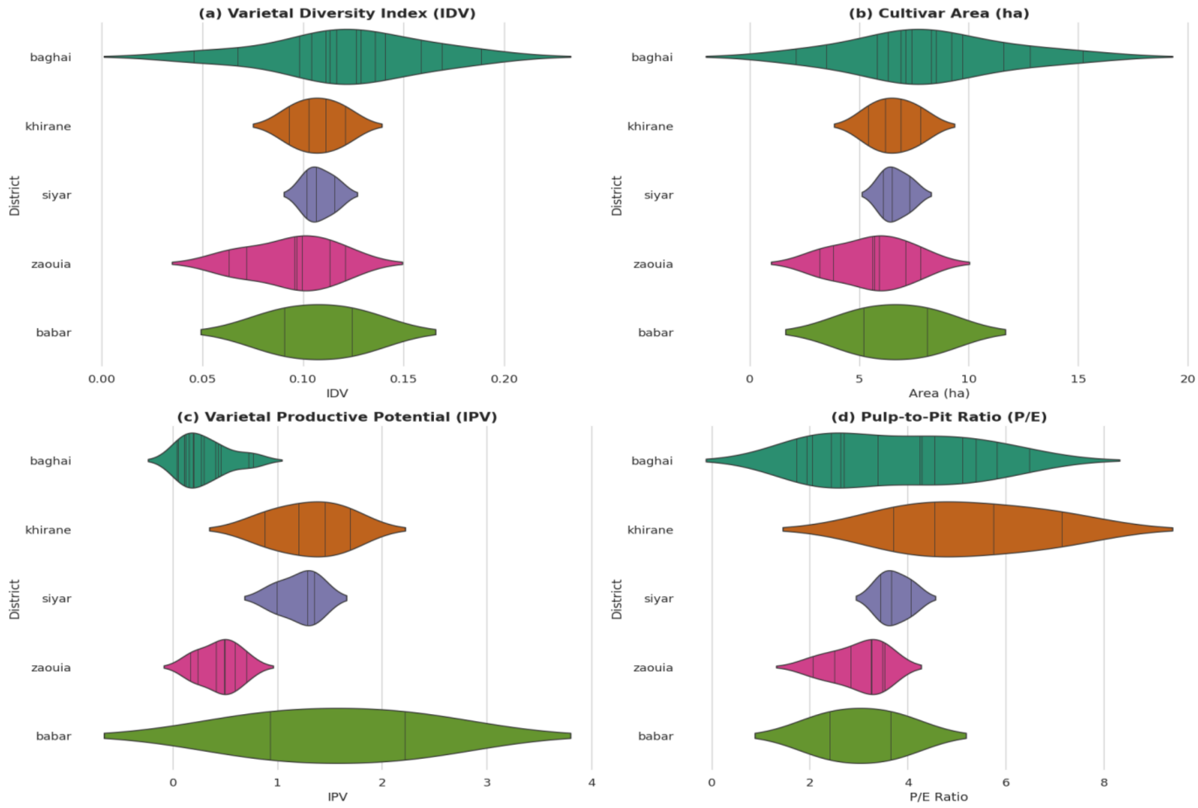

Figure 3. Morphometric and productive characterization of olive cultivars in Khenchela districts.

Panels show: (a) Varietal Diversity Index (VDI), (b) Cultivar area (ha), (c) Varietal Productive Potential Index (VPI), and (d) Pulp-to-Pit Ratio (P/P). Data are aggregated at the district level with distinction between North Khenchela (NKh) and South Khenchela (SKh) regions.

The VPI, which integrates pulp weight, pit weight, and the relative frequency of cultivars, confirms the superior productivity of the NKh varieties (Figure 3c). Aberkane had the highest VPI value (0.428), followed by Aimel (0.397) and Zeletni (0.315), all originating from the Baghai district. These cultivars combine high pulp-to-pit ratios with large, cultivated areas, reflecting their economic significance. In contrast, SKh cultivars generally exhibit lower VPI values, with Khadraia (0.276), Reyiab (0.312), and Zeboudj (0.218) defining the range observed in southern districts. The low VPI values recorded in SKh reflect not only reduced morphometric performance but also the limited spatial diffusion of high-performing cultivars under more constraining agro-climatic conditions. In SKh, this limited spatial diffusion reflects the combined effect of market pressure favoring a few commercially dominant cultivars, limited institutional support for accessing diversified planting material, and extension service biases — constraints that correlate with the agricultural abandonment and migration flows observed in southern districts (Chikhi, 2022; Raseef22, 2023).

The mean pulp weight ranged from 0.208 g (Neb djmel) to 6.192 g (Aberkane), while the pit weight varied between 0.108 g and 1.209 g. The pulp-to-pit ratio (P/P), a key determinant of oil extraction potential, reached particularly high values for Khadraia (7.138), Aimel (6.473), and Aberkane (5.816), indicating high conversion efficiency (Figure 3d). These morphometric parameters are strongly correlated with oil content and production efficiency, as documented by Rodriguez et al. (2018), Mousavi et al. (2020), and more recently by Benito et al. (2023) and Laroussi-Mezghani et al. (2022) in studies on North African olive genetic resources. Cultivars such as Neb djmel and UIV, with P/P ratios below 2.0, show limited commercial viability for oil production but may be valued for specific uses, such as table olives or ornamental purposes (Cecchi *et al.* 2021). This functional differentiation among cultivars reinforces the need for regionally adapted varietal portfolios, rather than uniform intensification strategies. Specifically, Neb djmel's small fruit size (pulp weight 0.208 g) and firm flesh texture favour its use as a table olive for dry-curing, while UIV's low P/P ratio reflects a higher endocarp proportion suited to ornamental and niche markets rather than oil extraction (Cecchi *et al.* 2021).

The Composite Varietal Quality Index (CVQI), which integrates normalized fruit weight, the P/P ratio, and trait stability through weighted coefficients ($\alpha_1 = 0.4$; $\alpha_2 = 0.4$; $\alpha_3 = 0.2$) derived from a principal component analysis (PCA), confirms the qualitative superiority of NKh cultivars. The CVQI values ranged from 0.445 (Azougaghth, Zaouia) to 0.812 (Aberkane, Baghai), with NKh cultivars showing mean values between 0.75 and 0.82, compared with 0.45 to 0.58 for those from SKh. The PCA-based weighting scheme ensured that the composite index retained the dominant variance structure of the morphometric dataset while limiting redundancy among the traits.

Morphometric efficiency, calculated as the percentage of pulp weight relative to the total fruit weight, is consistently higher in NKh (85–90%) than in SKh (78–82%), confirming the structural advantage of northern varieties for oil extraction. The coefficient of variation of fruit weight within cultivars (CV_fruit) was moderate in NKh (0.14–0.25) but markedly higher in SKh (0.25–0.35), indicating greater phenotypic heterogeneity in the southern districts, potentially associated with water stress, soil fertility variability, or irregular agronomic practices. Although no direct causal relationship can be established, the elevated CV_fruit values observed in SKh are consistent with the stress-induced phenotypic plasticity reported for olive trees under semi-arid conditions.

The newly developed resilience index, calculated as a weighted combination of the P/P ratio (50%), morphometric efficiency (30%), and CVQI (20%) based on expert judgment, identified Aberkane (87.4%), Aimel (86.2%), and Khadraia (85.9%) as the most resilient cultivars. This integrative index provides an operational, cultivar-scale indicator of adaptive capacity by simultaneously combining productive efficiency, fruit structural quality, and trait stability. Therefore, these cultivars represent priority genetic resources for the development of resilient olive systems facing climate change and increasing environmental constraints. For practical application, these cultivars could be targeted in diffusion programs for areas exhibiting lower resilience, particularly in SKh.

Overall, this multi-indicator framework demonstrates that varietal diversity and morphometric superiority jointly underpin productive stability and adaptive capacity in olive-growing systems, particularly in the agro-climatically favorable districts of NKh. However, the observed regional contrasts highlight the strongly context-dependent nature of varietal performance and argue in favor of localized adaptation strategies rather than generalized varietal recommendations across semi-arid Mediterranean regions.

Hydric indicators and water stress vulnerability

Hydric indicators revealed stark regional contrasts in water resource dependency and stress exposure. The Water Dependence Index (WDI), incorporating water source quality (Sw), irrigation efficiency (Ei), and water availability variability

(Vw) through weighted coefficients (α = 0.5, β = 0.3, γ = 0.2), demonstrated systematically higher values in SKh (mean WDI = 2.78) compared to NKh (mean WDI = 1.52). In SKh, the predominance of less reliable water sources (wells and boreholes, Sw scores of 2.5–3.0) combined with lower irrigation efficiency (average Ei = 0.75, indicating prevalence of sprinkler and gravity systems) and high water supply variability (Vw = 0.35, coefficient of variation of annual water supply over 2017–2021) resulted in elevated vulnerability. The distribution of WDI values in SKh was relatively concentrated around the high median, indicating homogeneous exposure to water dependency across cultivars and farms. Conversely, NKh benefited from more diversified water sources (surface water and improved boreholes, Sw = 1.5–2.0), higher irrigation efficiency (average Ei = 0.85, reflecting greater adoption of drip irrigation with 95% efficiency), and lower water supply variability (Vw = 0.18).

The broader WDI distribution in NKh suggested heterogeneity in adaptation strategies and differentiated access to water infrastructure, consistent with observations by Zhang et al. (2019**)** and recent assessments of Mediterranean irrigation systems under climate stress (Fernández *et al.* 2020; Vivas *et al.* 2024; Egea *et al.* 2023). As illustrated in Figure 4(a**)**, the boxplot of WDI clearly shows the higher and more concentrated WDI values in SKh compared to NKh, highlighting regional disparities in water dependence.The Water Stress Index (ISH**)**, quantifying climatic and hydric stress through comparison of effective precipitation (Peff) with reference evapotranspiration (ET_o) adjusted for crop-specific coefficients following the FAO Penman-Monteith framework (Allen *et al.* 1998), further emphasized regional disparities. SKh districts recorded ISH values ranging from 0.85 to 0.92, reflecting severe water deficit conditions where effective precipitation (calculated as 70% of total rainfall: 98–140 mm annually) represented only 7–10% of evapotranspiration demand (ET_o = 1,200–1,450 mm).

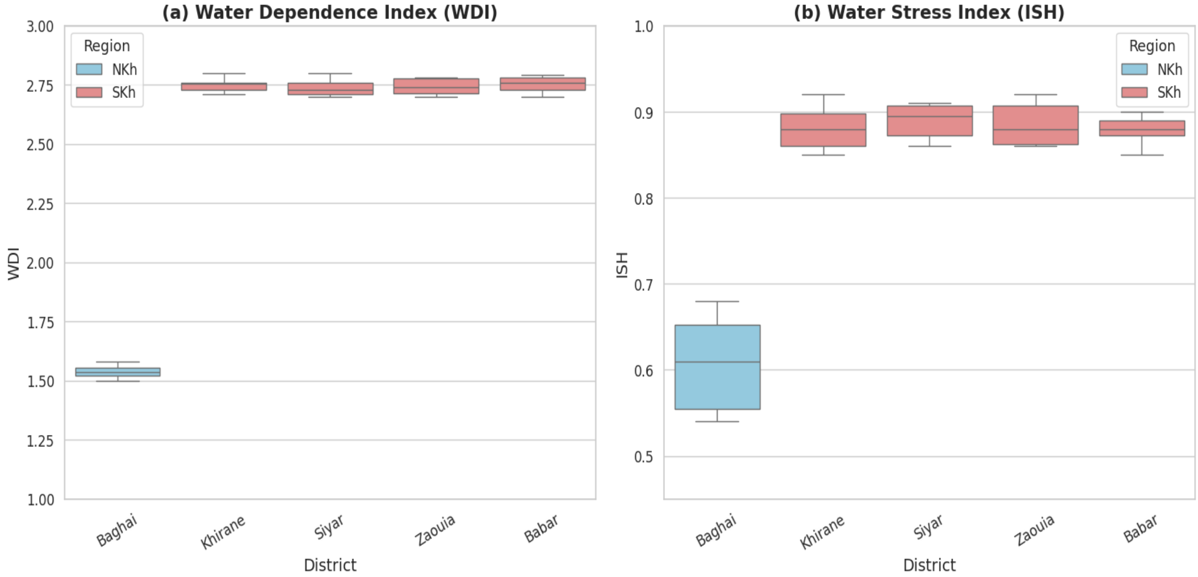

Figure 4. Boxplots of hydric vulnerability indicators in olive-growing districts of Khenchela. (a) Water Dependence Index (WDI) by district and region; (b) Water Stress Index (ISH) by district and region.

The crop coefficient for olives (Kc) varied from 0.55 to 0.70 depending on growth stage and canopy cover, while the basal crop coefficient (Kcb) adjusted for canopy density ranged from 0.50 to 0.60. In contrast, NKh exhibited lower ISH (0.52–0.68), with effective precipitation (210–302 mm) covering 22–32% of evapotranspiration needs (ET_o = 850–1,050 mm). The ratio (ET_o - Peff)/ET_o multiplied by (Kc/Kcb) yielded substantially higher stress indices in southern districts, aligning with drought stress metrics used in climate risk studies (Daccache *et al.* 2014; Caruso *et al.* 2023; Dichio *et al.* 2022). The systematic elevation of both WDI and ISH in SKh underscored the compounded vulnerability of southern olive-growing systems to both structural water dependency and climatically-driven hydric stress, consistent with FAO (2021) projections for Mediterranean agricultural zones under increasing climatic pressure and recent studies documenting accelerated desertification in North African agro-pastoral landscapes (Slimani *et al.* 2023; Boudiaf *et al.* 2024). Figure 4(b) shows the distribution of ISH values by district and region, emphasizing the higher hydric stress in SKh compared to NKh.

Productive performance

Oil conversion efficiency (ECH), calculated by combining yield data with varietal influence, varied substantially across cultivars and regions (Figure 5a). Simulated oil production (Hp) ranged from 17.7 L/ha (Neb djmel) to 526.3 L/ha (Aberkane), while olive production (Op) spanned 31.7–726.2 kg/ha. The relative weight (ω_i) of each cultivar in total farm production, combined with its pulp-to-endocarp ratio (Rp/e,i), generated ECH values from 0.385 (UIV) to 0.892 (Aberkane). NKh cultivars averaged ECH of 0.782, significantly higher than SKh's 0.624, reflecting both superior morphometric characteristics and more favorable growing conditions. The enhancement term $(1 + \sum \omega_i Rp/e,i)$ amplified efficiency scores for farms cultivating high P/E ratio varieties, with farms dominated by Aberkane, Aimel, or Khadraia achieving 15–25% efficiency gains compared to those relying on lower P/E cultivars. This metric effectively captured the agronomic advantage of cultivar selection in oil extraction potential, consistent with efficiency indices used in cropping system evaluations (Balodis et al. 2019, Mariem et al. 2023, Zipori et al. 2020).

Adjusted Labor Productivity (PAT), incorporating production volume, labor input, oil quality, and interannual variability, revealed regional productivity gaps and temporal instability (Figure 5b). The oil quality index (Qh), normalized from 0 to 1 based on acidity, peroxide value, and organoleptic assessment, averaged 0.87 in NKh versus 0.78 in SKh, reflecting both cultivar intrinsic quality and post-harvest handling practices. Labor requirements (L × h) varied from 127.5 hours/ha (small holdings with intensive family labor) to 31.5 hours/ha (larger mechanized operations), with average labor input of 15 hours per hectare across the study area.The critical factor differentiating regional PAT was the interannual coefficient of variation (CVinter) of oil production over 2017–2021: SKh exhibited mean CVinter of 0.28 (range 0.25–0.31) compared to NKh's 0.15 (range 0.12–0.18).

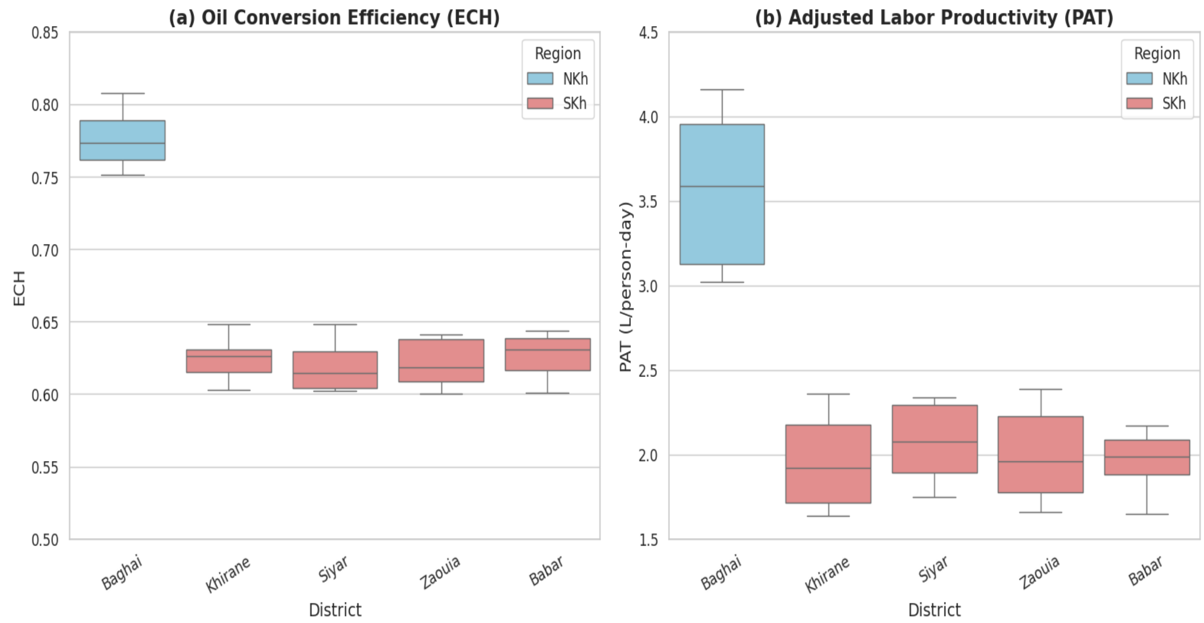

Figure 5. Productive performance indicators of olive cultivars across districts and regions

This dramatic difference in production stability, attributable to irregular rainfall patterns, recurrent drought episodes, and alternance (biennial bearing) intensity in water-stressed environments, penalized SKh labor productivity by 22–28% through the stability adjustment factor. Consequently, PAT values ranged from 2.8–4.2 L/person-day in NKh versus 1.6–2.4 L/person-day in SKh, representing a 40–60% productivity differential. These findings corroborate observations by Gomez and Ricketts (2013), Li and Lupi (2014), and recent analyses documenting labor efficiency challenges in climate-stressed Mediterranean agricultural systems (Maaoui et al. 2024, Tanasijevic et al. 2021, Ouled Belgacem et al. 2023).

Ecological indicators and system resilience

The Input Pressure Index (IPI), aggregating cultural inputs by environmental impact weights, revealed differentiated intensification patterns. Environmental weights (w_j) assigned values of 3 for pesticides, 2 for synthetic fertilizers, and 1 for organic amendments, reflecting established environmental impact hierarchies (Pimentel et al. 1992, Udeigwe et al. 2023). Intensity of use (I_j) averaged 3.5 kg/ha for pesticides, 85 kg/ha for synthetic fertilizers, and 1,200 kg/ha for organic matter in NKh, compared to 4.8 kg/ha, 95 kg/ha, and 800 kg/ha respectively in SKh. Application frequency (f_j) ranged from 1.5–2.5 treatments per year for pesticides and 1.0–1.5 for fertilizers. Resulting IPI values were moderate in NKh (mean 2.18, range 1.85–2.45) but elevated in SKh (mean 2.76, range 2.50–3.15), indicating greater agrochemical pressure in the more constrained southern environments where farmers attempted to compensate for edaphic and climatic limitations through intensified input application. This pattern paradoxically increased both environmental pressure and production costs while delivering marginal yield improvements, consistent with diminishing returns documented in environmental risk studies (Tilman et al. 2002, Pretty & Bharucha 2015, Schrama et al. 2020, Lechenet et al. 2023).

Ecological Resilience (RE), integrating productive efficiency, genetic diversity, input pressure, and hydric stress into a synthetic adaptive capacity metric, demonstrated clear regional differentiation. All component indices were normalized to a 0–1 scale prior to aggregation to prevent magnitude bias. RE values ranged from 0.185 (Azougaghth, Zaouia) to 0.524 (Aberkane, Baghai), with NKh mean RE = 0.412 versus SKh mean RE = 0.248. The formula structure posited that higher ECH and IDV enhance resilience multiplicatively, while elevated IPI and ISH diminish it proportionally. Top-performing cultivars combined high conversion efficiency (ECH > 0.80), substantial diversity contributions (IDV > 0.30), moderate input pressure (IPI < 2.30), and manageable water stress (ISH < 0.65). Conversely, low-resilience cultivars (RE < 0.25) were predominantly located in SKh districts with constrained water resources, high input dependency, and limited varietal diversity. District-level RE aggregation showed Baghai (0.428) substantially outperforming Khirane (0.245), Siyar (0.268), Zaouia (0.256), and Babar (0.232), confirming that northern systems possessed superior adaptive capacity through synergistic combination of favorable agro-ecological factors, consistent with recent Mediterranean resilience assessments (Sánchez-Bayo et al. 2024, Iocola et al. 2023) (Figure 6).

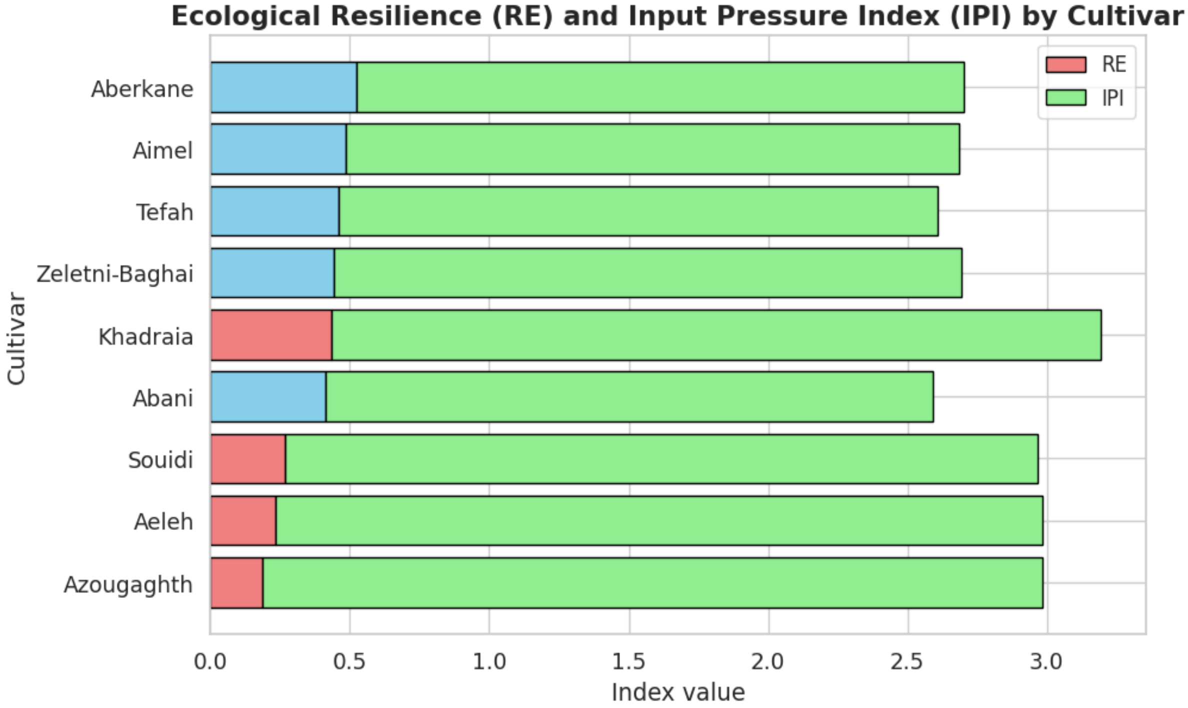

Figure 6. Ecological Resilience (RE) and Input Pressure Index (IPI) by Cultivar

Temporal stability and climatic vulnerability of olive-growing systems

The climatic vulnerability of olive production systems was assessed through the interannual variability of olive oil production and temporal yield stability, independently of any economic considerations. The results revealed pronounced regional contrasts between the northern (NKh) and southern (SKh) zones, reflecting differentiated exposure and sensitivity to climatic constraints.Climatic variability (σ_climat), estimated as the standard deviation of annual precipitation over the 2017–2021 period normalized by the mean, was markedly higher in SKh (σ_climat = 0.42) than in NKh (σ_climat = 0.22). This difference reflects more irregular rainfall regimes and a higher frequency of drought events in southern districts, leading to increased structural instability of olive oil production. Such patterns are consistent with previous findings reported for Mediterranean agroecosystems under climate change.

Overall productive performance, expressed as olive oil production normalized by cultivated area and adjusted for climatic variability, showed a strong regional differentiation. NKh systems exhibited significantly higher adjusted performance levels than those observed in SKh, indicating a greater capacity to maintain relatively stable production despite climatic fluctuations. This adjusted performance was positively correlated with cultivar morphometric efficiency ($r = 0.68$, $p < 0.001$) and with overall ecological resilience of the systems ($r = 0.72$, $p < 0.001$). Cultivars combining favorable morphological traits (high pulp-to-pit ratio and greater fruit weight) with improved hydric adaptation displayed a clear advantage in terms of interannual production stability.

Table 1. Climatic variability and temporal stability indicators of olive-growing systems at regional and district levels

Scale	**Region / District**	**σ_climat**	**Relative change 2020–2021 (%)**	**Coefficient of variation (2017–2021)**	**IST**
Regional	NKh	0.22	12 (5–18)	0.14	0.856–0.892
	SKh	0.42	23 (15–35)	0.25	0.728–0.785
District	Baghai	—	—	—	0.876
	Siyar	—	—	—	0.768
	Zaouia	—	—	—	0.755
	Khirane	—	—	—	0.742
	Babar	—	—	—	0.728

Note: σ_climat represents interannual precipitation variability normalized by the mean (2017–2021). IST: Temporal Stability Index of olive oil production.

The Temporal Stability Index (IST), used to quantify the consistency of olive oil production over time, further confirmed these regional contrasts. The absolute relative change in production between 2020 and 2021 averaged 12% in NKh (range 5–18%) compared with 23% in SKh (range 15–35%), indicating substantially higher volatility in water-limited environments. Likewise, the coefficient of variation of annual olive oil production over the 2017–2021 period was 0.14 in NKh and 0.25 in SKh.

Application of the exponential damping factor resulted in IST values ranging from 0.856 to 0.892 in NKh, versus 0.728 to 0.785 in SKh. Lower IST values observed in SKh indicate unreliable production systems that are highly dependent on annual climatic conditions. At the district level, Baghai exhibited the highest stability, while Khirane and Babar showed the lowest stability levels. These results confirm that northern systems possess a superior capacity to buffer climatic fluctuations, in line with theoretical frameworks on agroecosystem stability and resilience (Tilman, 1999; Holling, 1973; Craven *et al.* 2022).

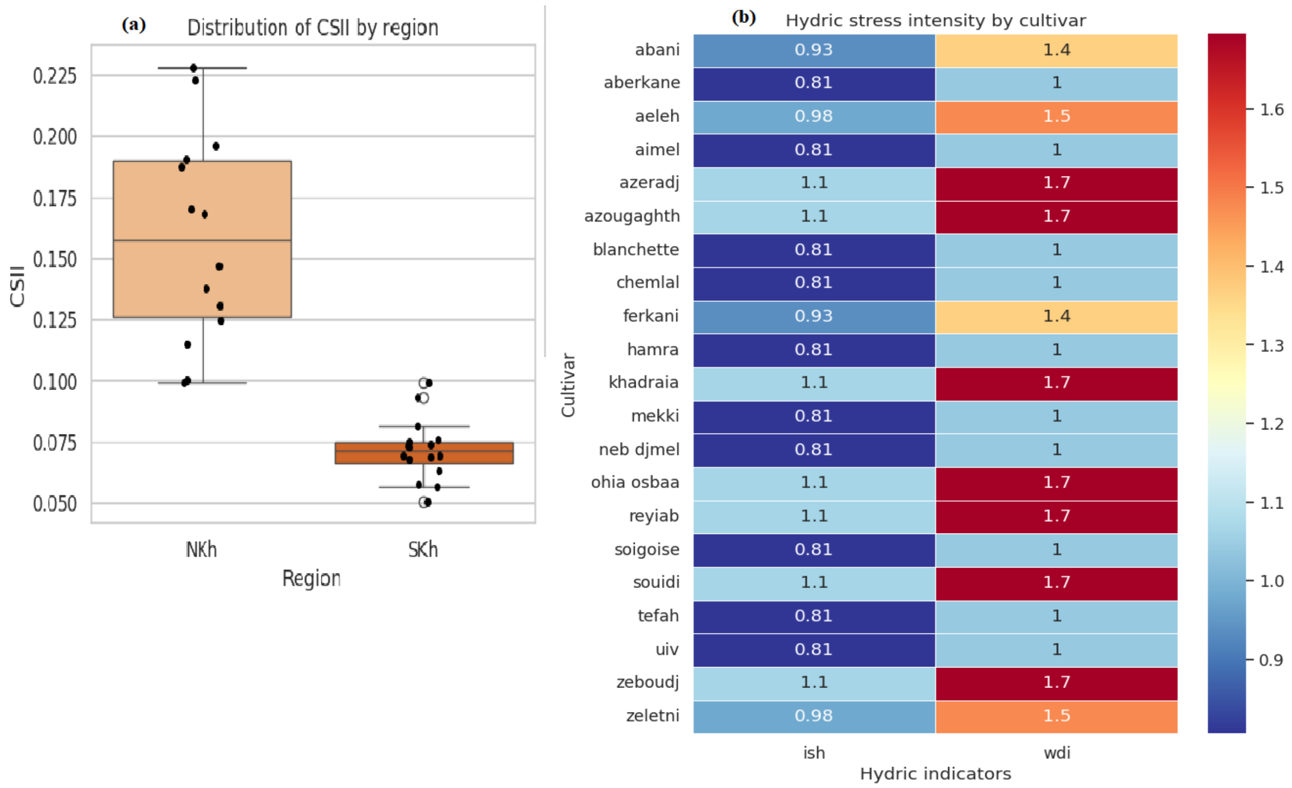

Figure 7. Hydric indicators (Water Deficit Index and Hydric Stress Intensity) across olive cultivars

Climate Impact Assessment and Composite Stress Index

The Composite Climate Stress Impact Index (CSII) provides an integrative assessment of climate change vulnerability by synthesizing genetic diversity, morphometric efficiency, ecological resilience, economic vulnerability, and projected climatic stressors within a unified framework. Temperature increase projections (ΔT) derived from CMIP6 multi-model ensembles reported in IPCC AR6 (IPCC, 2022; 2023) indicate a mean warming of +1.8 °C for North Khenchela (NKh) and +2.5 °C for South Khenchela (SKh) by 2041–2070 under intermediate-to-high emission pathways (SSP2-4.5 to SSP5-8.5), reflecting pronounced latitudinal and continentality-driven gradients in regional warming.

Hydric stress intensity (ISH) incorporated into CSII calculations was based on current baseline values, assuming proportional intensification under future warming and precipitation decline scenarios. Projected reductions in annual precipitation of 15–25% across Mediterranean North Africa were considered, in line with regional climate assessments (FAO, 2019; Fick & Hijmans, 2017; Harris *et al.* 2020; Tramblay *et al.* 2023; Lionello & Scarascia, 2020). All component indices were normalized to a 0–1 scale to ensure comparability and to prevent dominance by any single variable.

CSII values ranged from 0.068 (Azougaghth, Zaouia) to 0.176 (Aberkane, Baghai), revealing a clear regional stratification, with a mean CSII of 0.142 in NKh compared to 0.085 in SKh. District-level analysis confirmed that Baghai (0.156) exhibited substantially higher adaptive capacity than Khirane (0.082), Siyar (0.091), Zaouia (0.087), and Babar (0.078). Unlike conventional approaches that examine these dimensions independently, the CSII framework explicitly links biological diversity, productive performance, socio-economic stability, and climatic stressors within a resilience-oriented assessment (Urruty *et al.* 2023; Moriondo *et al.* 2021).

The pronounced CSII differential indicates that climate change is likely to disproportionately affect SKh systems, which are already operating near ecological and socio-economic thresholds, whereas NKh systems retain greater buffering capacity against projected stressors. These findings are consistent with recent Mediterranean olive climate impact assessments (Fraga *et al.* 2024; Koubouris *et al.* 2023; Mairech *et al.* 2020). Future refinements of the CSII framework should integrate locally downscaled climate projections to improve the precision of olive microclimate impact modeling (Gaetani *et al.* 2024; Cos *et al.* 2022)

Discussion

The comparative analysis between the districts of North Khenchela (NKh) and South Khenchela (SKh) shows that resilience does not rely on a single factor: varietal richness, access to water, fruit morphometric efficiency, and economic viability interact to produce distinct adaptive trajectories. Density diagrams (IDV, cultivated area, IPV, PE) empirically confirm these contrasts: Baghai combines high IDV with strong production performance, whereas Babar and Khirane exhibit varietal impoverishment and increased production pressures.

Genetic diversity emerges as a key “infrastructure” of resilience. The strong positive correlation between varietal richness and adaptive capacity at the district level ($r = 0.89$, $p < 0.01$) suggests mechanisms of risk distribution, functional complementarity, and temporal buffering of yield cycles characteristic of perennial systems. In SKh, the loss of diversity (2–4 cultivars) likely results from socio-economic processes (market pressure, limited access to planting material, extension service biases) that counteract the expected adaptive logic. Restoring this diversity will require both biological interventions (controlled introductions of drought-tolerant material) and institutional measures (local seed banks, participatory evaluations, strengthening farmer seed systems).

Water is confirmed as the primary factor differentiating regional trajectories. Higher WDI and ISH indices in SKh indicate conditions close to the olive tree’s physiological limits; attempting to compensate through intensified phytosanitary inputs proves ineffective, creating an ecological and economic trap. Locally achievable gains in irrigation efficiency (drip vs. gravity systems) provide a pragmatic entry point for adaptation, but scaling up requires financial incentive policies, collective water management arrangements, and pricing strategies that promote conservation without undermining smallholders.

Morphometric traits serve as rapid and practical markers for identifying adapted cultivars: the strong correlation between morphometric efficiency, oil yield (ECH), and economic productivity (PEG) justifies the use of fruit biometric traits as selection criteria in participatory programs. However, the current IQVC composite index prioritizes production potential over stress-tolerance traits; incorporating functional variables (leaf water potential, xylem vulnerability, physiological markers) will improve predictive capacity under climate change.

Economic vulnerability constitutes the most direct channel leading to agricultural abandonment: vulnerability-adjusted returns are substantially reduced in SKh and correlate with local migration flows. Economic analyses should consider the higher behavioral discount rates observed among constrained households, which help explain sustained underinvestment in long-term adaptation measures. Priority policy instruments include drought-indexed insurance, emergency cash transfers, access to credit, targeted financing for water-saving technologies, and measures promoting off-farm income diversification.

The proposed aggregation through the Composite Climate Stress Impact Index (CSII) is useful for prioritizing interventions and investments by combining biophysical and socio-economic dimensions. However, its limitations—assumed additive weighting, separate treatment of ΔT and ISH, and reliance on nondownscaled CMIP6 projections—require methodological improvements: stakeholder-weight customization (AHP/TOPSIS), integration of high-resolution climate projections, and coupling with process-based vegetation models to simulate phenological responses and yields under multiple scenarios.

For policy and development, the results call for a reorientation of priorities: less emphasis on generalized chemical intensification and more on diversity conservation, water-centered management, water collection/storage infrastructure, and risk management and social safety mechanisms. High-impact interventions include support for seed systems and participatory selection programs, targeted subsidies for drip irrigation systems for smallholders, and the development of non-agricultural income sources to reduce abandonment pressure.

Research limitations and priorities: as a cross-sectional study limited to five districts, it calls for longitudinal follow-ups, multi-site cultivar comparison trials (common gardens), integrated model climate economy analyses, and socio ecological studies on local governance. These efforts will allow verification of causality, separation of phenotypic plasticity from genetic constraints, and refinement of decision-support tools (CSII and IQVC) for replicable application in the dry Maghreb.

In conclusion, the resilience of olive groves in the auras is multi-causal: preserving and restoring genetic diversity, reorganizing water use and governance, selecting efficient cultivars based on morphometric criteria enriched with tolerance traits, and protecting livelihoods through integrated social and financial policies collectively constitute the most promising strategy to limit abandonment and strengthen adaptation to climate change.

Conclusion

This comprehensive study of olive-growing systems in the Wilaya of Khenchela, northeastern Algeria, demonstrates that resilience under climate change is inherently multi-dimensional, resulting from the interplay between genetic diversity, morphometric efficiency, water management, and socio-economic factors. Analysis of 29 cultivar-district combinations across contrasting agroclimatic zones North Khenchela (NKh, 431 mm annual rainfall) and South Khenchela (SKh, 60–200 mm) using sixteen composite resilience indices revealed pronounced regional contrasts in adaptive capacity.

NKh systems exhibited superior buffering capacity across all dimensions, including 2.6-fold higher varietal diversity (Shannon-Weaver Index: 2.639 vs 0.693), 25% greater oil conversion efficiency (0.782 vs 0.624), 66% higher ecological resilience (0.412 vs 0.248), and improved temporal stability (coefficient of variation: 0.14 vs 0.25). These advantages are underpinned by favorable precipitation, diversified and more efficient water resources (85% vs 75%), lower agrochemical pressure (Input Pressure Index: 2.18 vs 2.76), and maintenance of broad genetic portfolios (8–12 cultivars in NKh vs 2–4 in SKh). The strong positive correlation between varietal richness and adaptive capacity ($r = 0.89$, $p < 0.01$) confirms that genetic diversity acts as critical resilience infrastructure, enhancing risk distribution, functional complementarity, and temporal stability of production. Aberkane, Aimel, and Khadraia emerged as highly resilient cultivars (85.9–87.4%), combining superior pulp-to-pit ratios and high oil conversion efficiency.

These findings highlight the need for locally tailored adaptation strategies, including varietal diversification in SKh, targeted conservation of high-resilience cultivars, and adoption of water-efficient irrigation practices. The multi-scale, multi-dimensional approach employed here including the Composite Climate Stress Impact Index (CSII) provides a framework for guiding sustainable olive cultivation under projected climate scenarios in Mediterranean North Africa and beyond.

Decklarations

Ethics approval and consent to participate: The study did not require official ethical approval, as it did not involve any clinical procedures or vulnerable populations. However, the research followed known ethical norms for ethnobotanical studies.

Prior informed consent was obtained verbally fromall participants after explaining the aims of the study. Participation was voluntary, and all data obtained were treated with confidentiality and respect for local cultural norms and customs.

Consent for publication: Not applicable

Availability of data and materials: Not applicable

Competing interests: We declare that we have no conflict of interest

Funding: Not applicable

Author contributions: S.M, N.N.A, N.H,N.B and M.N.M collected the plant material, performed the physiological and phytochemical analyses, and contributed to the interpretation of the data. Mohamed Nejib El Melki designed the experimental framework, supervised the research, performed the data analysis and interpretation, and wrote the final version of the manuscript. All authors discussed the results and approved the final manuscript.

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