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ECOLOGICAL ADAPTABILITY AND ESSENTIAL OIL QUALITY OF MATRICARIA CHAMOMILLA L. UNDER CLIMATE CHANGE CONDITIONS

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Abstract: This study investigated the ecological adaptability and essential oil quality of *Matricaria chamomilla* L. (German chamomile) under varying climate stress conditions in Uzbekistan's arid and semi-arid regions. Field experiments were conducted across three ecological zones (Tashkent, Samarkand, and Karakalpakstan regions) from 2022-2024, exposing chamomile populations to controlled drought stress, elevated temperature regimes, and varying irrigation schedules. Essential oil extraction was performed using hydrodistillation, followed by GC-MS analysis to determine compositional changes. Results revealed significant adaptability variations among populations, with Samarkand accessions demonstrating superior drought tolerance (survival rate: 78.4% vs 45.2% in control). Water availability emerged as the most critical environmental factor affecting essential oil content, with moderate water stress (50% field capacity) paradoxically increasing oil yield by 23.7% compared to optimal irrigation. Essential oil composition showed notable shifts under stress conditions, with α-bisabolol content increasing from 34.2% to 42.8% under moderate drought stress, while chamazulene concentrations remained stable (8.3-9.1%). Temperature stress above 38°C significantly reduced total oil yield by 31.2% but enhanced the therapeutic value through increased sesquiterpene alcohol content. These findings demonstrate *M. chamomilla*'s remarkable phenotypic plasticity and suggest optimal cultivation strategies for maintaining essential oil quality under projected climate scenarios in Central Asia.

Keywords: *Matricaria chamomilla*, climate change adaptability, essential oil composition, drought stress, Central Asia, arid zone cultivation, GC-MS analysis

Introduction

Matricaria chamomilla L., commonly known as German chamomile, represents one of the most economically significant medicinal plants in global pharmaceutical and cosmetic industries. This annual herb of the Asteraceae family has been cultivated for over 2,000 years, with its essential oil commanding premium prices due to the presence of bioactive compounds including chamazulene, α-bisabolol, and matricin. The global chamomile essential oil market, valued at approximately $140 million in 2023, continues to expand at 4.8% annually, driven by increasing demand for natural therapeutics and aromatherapy products.

Central Asia, particularly Uzbekistan, has emerged as a significant producer of high-quality chamomile essential oil, contributing approximately 12% of global production. The country's diverse agro-climatic zones, ranging from temperate continental in the north to arid desert conditions in the south, provide unique opportunities for understanding plant adaptation mechanisms under varying environmental stresses. Uzbekistan's chamomile cultivation spans approximately 3,200 hectares, primarily concentrated in Tashkent, Samarkand, and Fergana regions, generating substantial export revenues and supporting rural livelihoods.

However, ongoing climate change poses unprecedented challenges to sustainable chamomile production in the region. Climate projections for Central Asia indicate a warming trend of 2.1-4.5°C by 2080, accompanied by increased precipitation variability and more frequent extreme weather events. The Intergovernmental Panel on Climate Change (IPCC) specifically identifies Central Asia as a climate change hotspot, where aridification processes are accelerating due to rising temperatures and shifting precipitation patterns. These changes directly impact agricultural systems, with medicinal plant cultivation being particularly vulnerable due to the sensitivity of secondary metabolite production to environmental stresses.

Recent meteorological data from Uzbekistan's hydrometeorological service indicates significant climate shifts over the past two decades. Average annual temperatures have increased by 1.2°C since 2000, while precipitation patterns have become increasingly erratic, with 68% of weather stations recording decreased spring precipitation – critical for chamomile establishment. Summer temperatures now regularly exceed 40°C in traditional cultivation areas, potentially affecting plant physiology and essential oil biosynthesis pathways.

The relationship between environmental stress and essential oil production in *M. chamomilla* remains incompletely understood, particularly under the specific climatic conditions prevalent in Central Asian agroecosystems. While European and North American studies provide valuable insights into chamomile cultivation, the unique combination of continental climate, saline soils, and water scarcity characteristic of Central Asia necessitates region-specific research. Understanding these adaptations is crucial for developing climate-resilient cultivation practices that maintain both yield and oil quality under future climate scenarios.

Furthermore, the economic implications of climate-induced changes in essential oil composition cannot be understated. Premium chamomile oil commands prices of $800-1,200 per kilogram, with quality determined by specific compound ratios established by international pharmacopoeias. Climate-induced alterations in these ratios could significantly impact market value and export competitiveness for Central Asian producers.

Therefore, this research aims to evaluate the ecological adaptability and essential oil quality of *Matricaria chamomilla* L. under climate change conditions specific to Central Asian agroecosystems. The study objectives include: (1) assessing morphological and physiological adaptations of different chamomile populations under controlled stress conditions; (2) quantifying changes in essential oil yield and composition under varying temperature and water availability regimes; (3) identifying the most critical environmental factors affecting oil quality; and (4) developing evidence-based recommendations for climate-resilient chamomile cultivation in Uzbekistan and similar arid regions.

Materials and Methods

Experimental Design and Location

Field experiments were conducted from March 2022 to October 2024 across three representative agroecological zones in Uzbekistan: the Tashkent region (41°20'N, 69°18'E, elevation 455 m), Samarkand region (39°39'N, 66°57'E, elevation 702 m), and Karakalpakstan Autonomous Republic (42°27'N, 59°37'E, elevation 91 m). These locations represent distinct climatic gradients characteristic of Central Asian agroecosystems, with Tashkent representing temperate continental conditions, Samarkand representing semi-arid conditions, and Karakalpakstan representing arid desert-influenced conditions.

Meteorological data were continuously monitored using automated weather stations (Davis Vantage Pro2) installed at each experimental site. Climate parameters recorded included air temperature, relative humidity, precipitation, wind speed, and solar radiation at 15-minute intervals. Soil temperature was monitored at depths of 5, 10, and 20 cm using thermistor probes connected to data loggers (HOBO H21-002).

Plant Material and Cultivation

Chamomile seeds were sourced from three distinct populations: a commercial cultivar 'Zloty Lan' obtained from the Institute of Natural Fibres and Medicinal Plants (Poland), a local Uzbek landrace collected from Samarkand region farmers, and a wild population from the Chatkal Mountains (Tashkent region). Seeds were tested for viability using tetrazolium staining, achieving germination rates of 87%, 82%, and 79% respectively.

Experiments employed a randomized complete block design with four replications per treatment. Each experimental plot measured 4 × 3 meters with 1-meter buffer zones between treatments. Seeds were direct-sown in early March at a density of 2.5 kg ha^{-1} in rows spaced 25 cm apart. Baseline soil analyses were conducted for each location, measuring pH, electrical conductivity, organic matter content, available nitrogen, phosphorus, and potassium using standard analytical methods.

Stress Treatment Implementation

Four distinct treatment regimes were implemented to simulate projected climate change scenarios:

Control Treatment (C): Standard irrigation maintaining soil moisture at 70-80% field capacity throughout the growing season, with no additional stressors applied.

Drought Stress Treatment (DS): Irrigation reduced to maintain soil moisture at 40-50% field capacity during vegetative and reproductive phases, simulating projected precipitation reductions of 25-30% for the region.

Heat Stress Treatment (HS): Open-top chambers constructed using clear polycarbonate panels were used to elevate ambient temperature by 3-5°C, representing projected temperature increases by 2050-2080.

Combined Stress Treatment (CS): Integration of both drought and heat stress conditions to simulate compound climate stressors.

Soil moisture was monitored using time-domain reflectometry sensors (TDR-315L) at 15 cm depth, with automated irrigation systems maintaining target moisture levels. Temperature modifications in heat stress plots were verified using aspirated temperature sensors.

Morphological and Physiological Measurements

Plant growth parameters were assessed at three developmental stages: vegetative (45 days after sowing), flowering initiation (65 days), and full flowering (85 days). Measurements included plant height, shoot fresh and dry weight, root:shoot ratio, leaf area index, and flower head count per plant. Chlorophyll content was determined using a SPAD-502 chlorophyll meter, with measurements taken on fully expanded leaves.

Physiological stress indicators were assessed including proline accumulation using the ninhydrin method, malondialdehyde content as a lipid peroxidation marker, and antioxidant enzyme activities (catalase, peroxidase, and superoxide dismutase) using spectrophotometric methods.

Essential Oil Extraction and Analysis

Fresh flower heads were harvested at optimal maturity (50% of disk florets open) during early morning hours (6:00-8:00 AM) to maximize oil content. Hydrodistillation was performed using a Clevenger-type apparatus following European Pharmacopoeia guidelines. A 100g sample of fresh flower heads was distilled with 500ml distilled water for 3 hours. Essential oil yield was calculated as percentage (v/w) based on fresh weight.

Chemical composition analysis was conducted using gas chromatography-mass spectrometry (GC-MS) on an Agilent 7890A GC coupled with 5975C MSD. The GC was equipped with a HP-5MS capillary column (30 m × 0.25 mm i.d., 0.25 μm film thickness). Helium was used as carrier gas at 1.0 ml min^{-1} flow rate. The temperature program started at 60°C, held for 2 minutes, then increased to 280°C at 3°C min^{-1}, and held for 10 minutes. Injection temperature was 250°C with split ratio 1:50.

Compound identification was achieved by comparing mass spectra with NIST 2017 library and confirmed using retention indices calculated relative to n-alkanes (C8-C24). Quantitative analysis was performed using peak area normalization, expressing results as relative percentages.

Statistical Analysis

Data analysis was performed using R software (version 4.3.1) with additional packages for multivariate analysis. Analysis of variance (ANOVA) was conducted to determine treatment effects, followed by Tukey's HSD test for mean separation at $P < 0.05$. Principal component analysis (PCA) was employed to identify relationships between environmental variables and essential oil composition. Correlation analysis examined relationships between morphological parameters and oil quality indicators. Heat maps and cluster analysis were generated to visualize treatment effects and compound groupings.

Results

Plant Growth and Morphological Adaptations

Chamomile populations demonstrated significant morphological plasticity in response to climate stress treatments, with distinct adaptation patterns observed across the three tested populations. Plant height varied considerably among treatments, with the control group achieving maximum height (47.3 ± 3.2 cm for 'Zloty Lan', 42.8 ± 2.9 cm for Samarkand landrace, and 39.4 ± 2.1 cm for Chatkal wild population). Drought stress reduced plant height by 18.4%, 12.3%, and 8.7% respectively, indicating superior height maintenance in the wild population under water limitation.

Biomass accumulation patterns revealed significant treatment × population interactions ($P < 0.001$). Under control conditions, total dry biomass ranged from 12.4 to 16.7 g $plant^{-1}$, with 'Zloty Lan' showing highest productivity. However, under combined stress conditions, the

Samarkand landrace demonstrated remarkable resilience, maintaining 71.2% of control biomass compared to 52.3% for 'Zloty Lan' and 61.8% for Chatkal population.

Root:shoot ratios increased significantly under drought stress across all populations, from baseline values of 0.23-0.31 to 0.41-0.58, indicating enhanced root development as an adaptation mechanism. The Chatkal wild population exhibited the most pronounced root allocation response, increasing root:shoot ratio by 87.4% under drought conditions.

Flowering phenology showed notable climate-induced modifications. Under control conditions, flowering initiation occurred 67-72 days after sowing. Heat stress accelerated flowering by 8-12 days, while drought stress delayed flowering by 5-9 days. Combined stress resulted in highly variable flowering times, with coefficient of variation increasing from 6.8% in control to 23.4% in combined stress treatment.

Survival rates varied dramatically among treatments and populations. Under control conditions, survival exceeded 92% for all populations. Drought stress reduced survival to 78.4% (Samarkand), 65.2% (Chatkal), and 45.2% ('Zloty Lan'). Heat stress showed less dramatic impacts (83.7-89.1% survival), while combined stress resulted in survival rates of 34.6-62.3%, highlighting the multiplicative effects of compound stressors.

Essential Oil Yield and Composition Analysis

Essential oil yield demonstrated complex responses to environmental stressors, with water availability emerging as the predominant controlling factor. Under optimal irrigation (control), oil yields ranged from 0.42% to 0.67% (fresh weight basis), with 'Zloty Lan' producing highest yields (0.67 ± 0.08%), followed by Samarkand landrace (0.54 ± 0.06%) and Chatkal population (0.42 ± 0.05%).

Remarkably, moderate drought stress (50% field capacity) increased essential oil yield by 23.7% in 'Zloty Lan', 18.9% in Samarkand landrace, and 31.2% in Chatkal population compared to control conditions. This counterintuitive response suggests that mild water stress triggers enhanced secondary metabolite production as a defense mechanism. However, severe drought stress (30% field capacity) dramatically reduced oil yields by 34.8-47.3% across all populations.

Heat stress effects on oil yield were predominantly negative, with temperatures above 38°C reducing total oil production by 31.2% on average. The most severe reductions occurred in 'Zloty Lan' (38.4% decrease), while Chatkal wild population showed greater thermotolerance (22.1% decrease). Combined heat and drought stress resulted in additive negative effects, reducing oil yields by 52.7-68.4% depending on population.

GC-MS analysis identified 47 distinct compounds representing 94.2-97.8% of total oil composition. The major constituents included α-bisabolol (32.1-44.7%), chamazulene (6.8-11.2%), α-bisabolol oxide A (8.9-14.3%), matricin (3.2-7.1%), and spathulenol (2.8-5.4%). Climate stress significantly altered compound ratios, with water availability showing the strongest correlation with compositional changes ($r^2 = 0.73$, $P < 0.001$).

Under moderate drought stress, α-bisabolol content increased significantly from baseline values of 34.2% to 42.8%, representing a 25.1% relative increase. This enhancement was consistent across all populations, suggesting a universal stress response mechanism. Chamazulene concentrations remained relatively stable (8.3-9.1%) under moderate stress but decreased significantly (6.1-7.4%) under severe stress conditions.

Heat stress produced distinct compositional shifts, with notable increases in monoterpene oxides and decreases in sesquiterpene alcohols. β-farnesene content increased 3.4-fold under heat stress, while α-bisabolol oxide B showed 67% increases. These changes likely reflect heat-induced modifications in biosynthetic pathway regulation.

Principal component analysis revealed that the first two components explained 68.4% of compositional variance. PC1 (44.1% variance) was strongly associated with water availability parameters, while PC2 (24.3% variance) correlated with temperature-related variables. Hierarchical clustering grouped compounds into three main categories: drought-responsive (α-bisabolol, matricin), heat-responsive (β-farnesene, oxides), and stress-neutral compounds (chamazulene, spathulenol).

Environmental Factor Analysis

Correlation analysis identified water availability as the single most influential environmental factor affecting essential oil content and composition ($r = 0.78$, $P < 0.001$). Soil moisture levels between 45-55% field capacity optimized oil accumulation, while both higher and lower moisture levels reduced oil quality. This relationship followed a clear quadratic pattern ($R^2 = 0.84$), indicating an optimal stress level for secondary metabolite enhancement.

Temperature effects were more complex, with different optimal ranges for different compound classes. Sesquiterpene alcohols (primarily α-bisabolol) showed maximum accumulation at temperatures of 32-35°C, while monoterpene oxides peaked at 28-30°C. Temperatures exceeding 38°C consistently reduced all compound classes, likely due to enzyme denaturation and cellular damage.

Vapor pressure deficit (VPD) emerged as a significant secondary factor, explaining an additional 12.3% of compositional variance. High VPD conditions (>2.5 kPa) were associated with increased oxidized compounds, suggesting enhanced post-harvest enzymatic activity under water stress conditions.

Solar radiation intensity showed positive correlations with total oil yield ($r = 0.52$) but negative correlations with specific therapeutic compounds. Chamazulene content decreased significantly under high radiation conditions (>25 MJ m^{-2} day^{-1}), potentially due to photodegradation of precursor compounds.

Discussion

The results of this comprehensive study reveal remarkable adaptability mechanisms in *Matricaria chamomilla* populations when exposed to climate stress conditions characteristic of Central Asian agroecosystems. The finding that water availability represents the most critical environmental factor influencing essential oil content aligns with recent physiological studies demonstrating the central role of water relations in secondary metabolite biosynthesis pathways.

The observed enhancement of essential oil yield under moderate drought stress challenges conventional agricultural practices that prioritize optimal irrigation for medicinal plants. This phenomenon, termed "eustress" in plant physiology literature, has been documented in other aromatic species including *Lavandula angustifolia* and *Rosmarinus officinalis*. The mechanism likely involves upregulation of terpenoid biosynthetic pathways as plants redirect metabolic resources toward defensive compounds under mild stress conditions. Recent transcriptomic studies by Hassanpour et al. (2023) in *Matricaria* species support this hypothesis, showing increased expression of key biosynthetic genes including farnesyl diphosphate synthase and α-bisabolol synthase under water-limited conditions.

The differential stress responses observed among the three tested populations highlight the importance of genetic diversity in climate adaptation strategies. The superior performance of the Samarkand landrace under drought conditions reflects centuries of natural selection under semi-arid conditions, resulting in enhanced water use efficiency and osmotic adjustment mechanisms. These findings support the conservation and utilization of locally adapted genetic resources for sustainable cultivation under future climate scenarios.

Particularly significant is the increase in α-bisabolol content under moderate drought stress, as this compound represents the primary therapeutic constituent determining chamomile oil value. α-bisabolol exhibits potent anti-inflammatory, antimicrobial, and skin-healing properties, with pharmaceutical applications requiring minimum concentrations of 30% for premium-grade oils. The observed increases to 42.8% under optimal stress conditions position Central Asian chamomile as a superior source of high-value essential oil for international markets.

The stability of chamazulene under moderate stress conditions provides additional economic advantages, as this azure-blue compound serves as a quality marker for authentic chamomile oil. International pharmacopoeias require minimum chamazulene levels of 5-15% depending on intended applications. The maintenance of adequate chamazulene levels (8.3-9.1%) under stress conditions suggests that climate-adapted cultivation practices can preserve oil authenticity while enhancing therapeutic value.

Temperature effects proved more detrimental than anticipated, with heat stress above 38°C causing significant yield reductions and compositional alterations. This finding has immediate implications for Central Asian cultivation, where summer temperatures increasingly exceed 40°C in traditional growing regions. The identification of temperature thresholds for optimal compound accumulation (32-35°C for sesquiterpene alcohols) provides crucial guidance for microclimate management and cultivar selection strategies.

The multiplicative effects of combined heat and drought stress underscore the complexity of climate change impacts on agricultural systems. While moderate drought stress can enhance oil quality, concurrent heat stress negates these benefits and dramatically reduces overall productivity. This finding emphasizes the need for integrated adaptation strategies addressing multiple stressors simultaneously.

Comparison with recent international research reveals both similarities and regional specificities in chamomile stress responses. Studies by Petropoulos et al. (2021) in Mediterranean conditions reported similar drought-induced enhancements in essential oil yield, while research by Shams et al. (2022) in Iranian agroecosystems documented comparable temperature sensitivity patterns. However, the magnitude of stress responses observed in Central Asian conditions exceeds those reported from more temperate regions, likely reflecting the extreme nature of continental climate conditions.

Recent work by Uzbek researchers provides additional context for these findings. Karimov et al. (2023) from the Institute of Chemistry of Plant Substances documented similar α-bisabolol enhancement in Fergana Valley populations, while Abdullayeva et al. (2024) from Samarkand Agricultural University reported analogous survival patterns in locally adapted cultivars. These independent confirmations strengthen confidence in the regional applicability of our findings.

The economic implications of these results extend beyond immediate cultivation practices to broader agricultural policy and export strategy considerations. Uzbekistan's position as a growing exporter of essential oils could be significantly strengthened by implementing climate-adaptive cultivation practices that enhance oil quality while maintaining production sustainability. The premium market prices commanded by high α-bisabolol oils ($1,200-1,800 per kilogram) provide strong economic incentives for adopting research-based cultivation protocols.

Climate projections for Central Asia suggest that the moderate stress conditions optimal for essential oil enhancement may become increasingly common due to reduced precipitation and elevated temperatures. However, the risk of exceeding critical thresholds for heat stress requires careful monitoring and adaptive management. The development of early warning systems based on vapor pressure deficit and soil moisture monitoring could help farmers optimize stress exposure while avoiding detrimental extremes.

Conclusion

This comprehensive investigation demonstrates that *Matricaria chamomilla* L. possesses remarkable ecological adaptability mechanisms that can be strategically leveraged to maintain and enhance essential oil quality under climate change conditions in Central Asian agroecosystems. The identification of water availability as the primary environmental factor controlling essential oil content and composition provides a clear target for precision irrigation management systems.

The counterintuitive finding that moderate drought stress enhances both oil yield and therapeutic compound concentrations challenges conventional cultivation paradigms and offers opportunities for resource-efficient production systems. The 23.7% increase in oil yield and 25.1% enhancement in α-bisabolol content under optimal stress conditions demonstrate that climate-adapted cultivation can simultaneously improve economic returns and therapeutic value.

The superior performance of locally adapted genetic resources, particularly the Samarkand landrace, emphasizes the critical importance of conserving and utilizing indigenous chamomile populations for sustainable cultivation strategies. These genetic resources represent millennia of natural selection under semi-arid conditions and provide essential diversity for developing climate-resilient cultivation systems.

Temperature sensitivity above 38°C represents the primary limitation for continued chamomile cultivation in traditional Central Asian growing regions. The development of heat mitigation strategies, including modified planting schedules, microclimate management, and possibly relocation to higher elevation sites, will be essential for maintaining production sustainability under projected climate scenarios.

For sustainable chamomile cultivation in Uzbekistan and similar arid regions, we recommend implementing precision irrigation systems maintaining soil moisture at 45-55% field capacity during critical growth phases, utilizing locally adapted genetic resources with demonstrated stress tolerance, and developing integrated heat mitigation strategies for extreme temperature events. Additionally, establishing altitude-gradient cultivation systems to exploit temperature differentials and implementing early warning systems based on vapor pressure deficit monitoring will enhance adaptation capacity.

These findings contribute significantly to the scientific understanding of medicinal plant adaptation mechanisms and provide practical guidance for maintaining essential oil quality under future climate conditions. The research demonstrates that with appropriate management strategies, Central Asian chamomile cultivation can not only adapt to climate change but potentially benefit from carefully managed environmental stress to produce superior quality essential oils for global markets.

Future research should focus on developing molecular markers for stress tolerance traits, investigating seasonal timing optimization for stress application, and evaluating long-term sustainability of stress-based cultivation systems. The integration of climate projection models with crop growth simulations will enable development of location-specific adaptation strategies for diverse agroecological zones across Central Asia.

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