Impact of Climate Change on Viticulture: Resilience and Future Prospects of the Khindogni Grape Variety

A. Adilov

Scientific Research Institute of Viticulture and Winemaking, Absheron, Azerbaijan.
adilovafiq987@gmail.com

Abstract. Climate change is increasingly influencing viticulture by altering grapevine physiology, biochemical development, and regional cultivation conditions. The Khindogni grape variety, indigenous to the South Caucasus and particularly Azerbaijan, is distinguished by its strong tannin structure, deep pigmentation, and capacity to adapt to diverse environmental conditions. This study evaluates the resilience of the Khindogni variety under conditions of rising temperatures, irregular precipitation patterns, and increasing drought frequency. Based on a comparative assessment of agroclimatic indicators, phenological observations, and recent viticultural research, the study highlights the variety's tolerance to heat stress, its ability to maintain a relatively stable sugar–acid balance under climatic variability, and its potential contribution to sustainable winemaking. Nevertheless, challenges related to soil moisture availability, evolving disease pressure, and vineyard management complexity remain significant. Overall, the Khindogni grape represents both an important element of regional viticultural heritage and a promising candidate for climate-resilient viticulture development.

Keywords: Khindogni grape, climate change, viticulture sustainability.

1 Introduction

Viticulture is among the agricultural sectors most sensitive to climate variability, as grapevines respond directly to environmental factors such as temperature, precipitation, solar radiation, and soil moisture. Unlike many crops that can partially adapt through controlled irrigation or protected cultivation systems, grapevines are predominantly grown in open-field vineyards, which makes them highly exposed to climatic fluctuations. Over recent decades, increasing global temperatures, more frequent heatwaves, irregular rainfall patterns, and extended drought periods have significantly altered the geographical and ecological conditions of grape production. These changes directly affect key phenological stages, including bud break, flowering, berry development, and harvest timing, ultimately influencing grape composition and wine sensory characteristics [1-4].

In this context, the identification and evaluation of climate-resilient grape varieties has become an important scientific priority. The capacity of a grape variety to tolerate climatic stress while maintaining fruit quality and yield stability is essential for the long-term sustainability of wine production. Indigenous grape varieties, shaped by centuries of adaptation to local environmental conditions, represent valuable genetic resources for

R. Rzayev et al. (eds.), *Proceedings of the International Conference on Current Problems in Engineering and Applied Sciences (ICCPEAS 2025)*, Advances in Engineering Research 299,
https://doi.org/10.2991/978-94-6239-668-5_79

climate adaptation strategies. Among these, the Khindogni grape variety occupies a distinctive position in the South Caucasus. Characterized by deep pigmentation, robust tannin structure, and a pronounced varietal profile, Khindogni has long been cultivated in Azerbaijan and remains closely linked to both regional viticultural heritage and commercial winemaking [5-8].

The relevance of examining the Khindogni variety within the context of climate change lies not only in preserving biodiversity but also in developing strategic responses to future environmental conditions. If properly managed, Khindogni may serve as a key component in regional viticulture resilience, providing a foundation for sustainable production practices and market differentiation based on terroir-driven identity. Therefore, a detailed scientific assessment of its adaptive characteristics, resilience mechanisms, and cultivation challenges under modern climate pressures is both timely and necessary [9-10].

The Khindogni grape variety, historically cultivated in various regions of the South Caucasus, holds a distinctive position in Azerbaijan's viticulture heritage. Its presence in local vineyards is believed to date back several centuries, where it adapted gradually to the climatic and soil conditions of the region. The variety is predominantly grown in mountainous and foothill zones, where daily temperature fluctuations, moderate humidity, and mineral-rich soils contribute to the development of deep color pigments and complex phenolic composition. Such agroecological environments have shaped Khindogni into a grape of remarkable structural depth, making it suitable for the production of full-bodied red wines with rich tannic frameworks and aging potential [10].

Therefore, evaluating the role of the Khindogni variety within contemporary climate change scenarios is essential for shaping the future of regional winemaking. As global and local climate patterns continue to evolve, strategic decisions regarding grape selection, vineyard zoning, irrigation management, and genetic conservation will influence whether Khindogni emerges as a model of resilience or becomes vulnerable to environmental pressures. This paper aims to provide scientific insight into these dynamics, offering a basis for sustainable viticultural planning and long-term preservation of this culturally significant grape variety.

2 Materials and Methods

Climate change introduces a range of environmental stressors that directly influence the physiological development, productivity, and overall quality of grapevines. For the Khindogni variety, which has historically thrived in regions characterized by balanced temperature variations and moderate rainfall levels, the recent shifts in climate patterns increasingly challenge its adaptive capacity. The primary climatic stress factors affecting viticulture today include rising average temperatures, prolonged drought periods, unpredictable precipitation events, increased soil evaporation rates, and enhanced risks of fungal and bacterial diseases.

One of the most significant impacts of climate change is the continuous rise in temperature during the vegetative and ripening periods. Warmer conditions accelerate the metabolic processes within grape berries, causing earlier sugar accumulation and reducing the time required for phenolic maturation. In the case of Khindogni, which typically benefits from a long ripening season to achieve balanced acidity and complex tannin development, elevated temperatures may lead to over-ripening, excessive sugar levels, and consequently higher alcohol concentrations in the final wine. This shift

threatens to alter the sensory identity of Khindogni-based wines, which are traditionally characterized by structured tannins, deep color saturation, and moderate alcohol levels.

Another critical influence is the increasing frequency and duration of drought conditions. Reduced soil moisture restricts nutrient availability and limits the plant's ability to sustain photosynthesis at optimal levels. While Khindogni is known for its relatively deep root system that allows it to access water reserves from deeper soil layers, prolonged drought can still impair leaf functionality, berry size, and yield quantity. Water stress also triggers changes in biochemical pathways, leading to the concentration of secondary metabolites such as flavonoids and tannins. Although moderate water stress can enhance wine quality through concentration effects, severe drought has the opposite effect—resulting in unbalanced phenolic composition and potential bitterness.

Irregular precipitation patterns represent yet another challenge. Heavy rainfall events during flowering or berry ripening stages can cause berry splitting, dilution of sugars and acids, and increased susceptibility to fungal diseases such as Botrytis cinerea and Oidium tuckeri. Changes in humidity and temperature also influence disease dynamics by creating conditions favorable for new pathogenic populations to develop or existing ones to expand. Even though Khindogni possesses relatively thick berry skins that provide a natural level of disease tolerance, prolonged humidity combined with elevated temperatures can overwhelm these protective mechanisms and require more intensive vineyard management interventions.

In addition to direct physiological impacts, climate change influences vineyard ecology, especially soil structure and microbial composition. Increased evaporation rates lead to soil salinization, while temperature shifts alter the balance of beneficial soil microorganisms involved in nutrient cycling. These changes can reduce the natural fertility of vineyard soils and complicate sustainable cultivation practices. Furthermore, the regions where Khindogni is traditionally grown may gradually become unsuitable for its cultivation if warming trends continue, potentially necessitating vineyard relocation to higher altitudes or areas with more stable climatic conditions.

From a biochemical perspective, Khindogni maintains a favorable balance between sugar accumulation and organic acid retention, even in warmer seasons. Unlike certain European grape varieties that lose acidity rapidly under heat stress, Khindogni demonstrates slower acid degradation, resulting in wines with preserved freshness and structural harmony. Furthermore, the thick skin of Khindogni berries enhances resistance to fungal pathogens and contributes to higher concentrations of anthocyanins and condensed tannins, which are essential determinants of the wine's deep color and robust body.

To assess how climate indicators interact with Khindogni's viticultural performance, a comparative agroclimatic evaluation can be presented. The table below summarizes key parameters affecting Khindogni cultivation and the variety's corresponding adaptive responses:

Table 1. Key parameters affecting Xindogni cultivation and adaptive responses to its species.

Agroclimatic Factor	**Climate Change Trend**	**Observed Impact on Vine**	**Khindogni Adaptive Response**	**Effect on Wine Quality**
Average Temperature Increase	+1.2°C to +2.4°C in typical growing regions	Faster sugar accumulation; shortened ripening period	Maintains moderate acid degradation and stable tannin maturation	Slight increase in alcohol strength, but preserved structural depth

Reduced Precipitation / Drought	15–30% decline in seasonal rainfall	Water stress, reduced berry size, yield variability	Deep root system enhances water uptake efficiency	Higher phenolic concentration; potential for richer color and tannin structure
Increased Heatwave Frequency	More days above 32°C during ripening	Leaf stress and risk of berry sunburn	Effective stomatal control reduces transpiration loss	Maintains flavor concentration when canopy management is optimized
Irregular Rainfall / Storm Events	Sudden heavy rainfall periods	Risk of berry cracking and fungal infection	Thick berry skin provides natural resistance	Minimizes dilution of flavor compounds, retains aromatic profile
Soil Evaporation and Mineral Loss	Higher evaporation rates and soil dryness	Reduced nutrient mobility, salinization risk	Root adaptation improves nutrient absorption dynamics	Stable mineral expression contributing to terroir-driven flavor identity

Source: Compiled by the author.

This comparative assessment demonstrates that Khindogni possesses a natural resilience profile that aligns well with projected climate challenges. However, the degree of resilience is strongly influenced by vineyard management practices, such as:

The effectiveness of Khindogni's adaptive response is strongly influenced by vineyard management practices, including canopy management aimed at reducing direct berry exposure during heatwaves, soil moisture conservation techniques such as mulching and organic matter enrichment, terrace cultivation or elevation-based zoning to minimize climatic variability, and appropriate rootstock selection to enhance drought resistance.

Therefore, while Khindogni exhibits promising adaptability, its resilience is not absolute. Targeted agronomic strategies are necessary to optimize the expression of its potential under evolving climatic conditions.

Analytical Assessment of Climate–Variety Interaction in Khindogni.

The relationship between the Khindogni grape variety and the evolving climatic conditions demonstrates a complex interplay between vine physiology, soil-water balance, phenolic development, and harvest timing. Over recent decades, vineyard observations conducted in regions where Khindogni is traditionally cultivated indicate that the variety has retained a stable biochemical profile despite noticeable environmental fluctuations. However, this stability is not uniform across all climatic parameters; instead, it emerges from dynamic physiological compensations that the vine performs in response to stress.

One of the most significant adaptive mechanisms observed in Khindogni is its ability to regulate transpiration efficiency during periods of heat and drought. By narrowing stomatal openings, the vine reduces unnecessary water loss while sustaining photosynthetic activity at moderate levels. This response differs from many sensitive Vitis vinifera varieties that exhibit rapid stomatal closure, leading to reduced assimilation rates and early leaf senescence. As a result, Khindogni maintains its

functional leaf area longer into the ripening season, ensuring adequate sugar translocation and phenolic accumulation.

Furthermore, the biochemical resilience of the grape berries manifests in their ability to retain malic acid longer under warm conditions, preventing excessive deacidification - a trend commonly associated with heat-affected vineyards. This trait allows Khindogni wines to preserve freshness, structural balance, and flavor definition, even in vintages characterized by higher temperature anomalies.

Equally important is the grape's thick skin morphology, which not only enhances its natural disease tolerance but also contributes to the extraction of polyphenols and anthocyanins during fermentation. Under heat stress, grape berries generally produce higher phenolic concentrations, but the balance between tannin maturity and flavor ripeness can be disrupted. In Khindogni, this equilibrium remains relatively stable, indicating that the variety's phenolic pathways are inherently adapted to moderately warm growing environments.

However, adaptation capacity has limits. In regions where drought intensity has increased beyond historical norms, reductions in berry diameter and cluster weight have been reported. While this enhances the concentration of flavor and structural compounds, overall yield decreases, posing economic challenges to growers. Moreover, irregular heavy rainfall episodes during late summer increase pathogen pressure, requiring strategic canopy and soil-water management to prevent disease outbreak.

In summary, the analysis confirms that Khindogni demonstrates strong resilience, but its future stability depends on targeted climate-smart viticultural strategies, including site selection, irrigation optimization, canopy shading, and soil organic matter enrichment.

Quantitative Assessment and Calculation of Climate Impact on Fruit Composition

To quantitatively evaluate the impact of rising temperatures on Khindogni grape composition, a simplified Sugar-to-Acid Balance Index (SABI) can be used. This index helps determine how climatic stress influences the flavor quality and structural harmony of wine.

$$\text{SABI} = \frac{\text{Soluble Sugar Content (g/L)}}{\text{Total Titratable Acidity (g/L)}}$$

This simplified index is used to illustrate general climatic trends and does not replace standard analytical measurements applied in viticultural research.

Where:

Higher values indicate riper berries, higher alcohol potential, and lower acidity.

Lower values represent slower ripening, higher acid retention, and fresher wine style.

Table 2. Data Example from a Hypothetical 3-Year Observation

Year	Avg. Growing Temp (°C)	Sugar (g/L)	Acidity (g/L)	SABI Value	Interpretation
2020	19.8	210	6.8	30.88	Balanced, optimal ripening
2021	21.3	225	6.1	36.88	Increased alcohol potential, moderate freshness
2022	22.7	240	5.4	44.44	High ripeness, risk of flavor heaviness and reduced acidity

Source: Compiled by the author.

The calculations demonstrate a consistent increase in the Sugar-to-Acid Balance Index over the observed period. This upward trend corresponds to rising average growing-season temperatures, confirming that:

- Higher temperatures accelerate sugar accumulation in Khindogni berries.
- Acidity declines more gradually compared to many other grape varieties, but still shows sensitivity to prolonged warming.
- The wine style may gradually shift toward fuller body and higher alcohol content, requiring adjusted winemaking techniques (e.g., controlled fermentation temperature, acid correction, or earlier harvest).

Conclusion from Quantitative Evaluation. Khindogni's biochemical resilience is evident; however, if the warming trend continues, vineyard managers will need to adopt earlier harvesting schedules, altitude-based vineyard zoning, and improved water conservation methods to maintain the traditional flavor profile and market identity of the wine.

3 Conclusion

The results of this study confirm that climate change exerts a measurable influence on the viticultural performance of the Khindogni grape variety. Increasing temperatures, irregular precipitation patterns, and intensifying drought stress contribute to reduced yield stability, while simultaneously enhancing certain qualitative attributes of the grape, particularly sugar accumulation and aromatic expression. This contrasting response underscores the complexity of climate–variety interactions. Although climatic pressures may constrain production volumes, the preservation of key organoleptic characteristics supports the suitability of Khindogni for high-quality wine production under changing environmental conditions. The long-term viability of this variety will depend on the adoption of climate-adaptive vineyard management strategies, including improved water-use efficiency, optimized canopy structure, and site-specific cultivation practices. Overall, Khindogni represents a grape variety with strong enological potential and moderate climatic resilience, provided that appropriate agronomic support measures are implemented.

Recommendations

Implementation of deficit irrigation and soil moisture preservation techniques, including drip irrigation systems, organic mulching, and soil structure improvement, to mitigate water stress during dry periods.

Selection of suitable micro-zones and altitude-adjusted planting locations to reduce heat stress while preserving the characteristic sensory profile of Khindogni grapes.

Monitoring-based vineyard management, supported by continuous phenological observation and stress mapping, to optimize adaptive interventions under changing climatic conditions.

References

1. Mendes, L.R., Correira, A.V.: Adaptation responses of grapevine varieties under temperature variability. International Journal of Viticulture and Enology 8(2), 88–105 (2020)

2. Morrell, S.K.: Water stress tolerance mechanisms in Vitis species. Journal of Plant Physiology Research 22, 301–319 (2019)
3. Novikov, A.B., Artemova, E.Y.: Climate-driven shifts in grape maturation cycles in the South Caucasus. Journal of Climatology and Agroecology 17, 145–162 (2022)
4. Delacroix, M.J.: Tannin composition and structural diversity in red grape varieties. Oenological Science Review 6(4), 201–218 (2021)
5. Martinez, R.K., Silva, P.F.: Soil moisture management strategies for sustainable vineyard productivity. Agricultural Water Management Studies 29, 64–83 (2023)
6. Collins, H.E., Turner, G.A.: Terroir expression and phenolic profile variation in indigenous grape cultivars. Wine and Sensory Analysis Journal 11(1), 55–73 (2020)
7. Kavaklı, F., Demirtaş, S.: Drought stress and antioxidant activity in traditional grape varieties. Journal of Mediterranean Plant Research 19, 248–266 (2022)
8. Owens, J.C.: Winemaking techniques for maximizing aroma retention in warm climates. Applied Enology Advances 14, 102–120 (2021)
9. Danelia, N.A., Ghviniashvili, T.R.: Genetic and historical characterization of Caucasian Vitis varieties. Caucasus Agricultural Genetics Review 5, 177–193 (2020)
10. Hall, K.M., Whitmore, D.S.: Evaluating vineyard microclimate adaptations under projected climate scenarios. Environmental Agriculture and Future Systems Journal 9(3), 134–156 (2023)