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Assessing the effects of climatic characteristics on *trans-resveratrol* amounts of red wines: A case study in Türkiye

Kırmızı şaraplardaki *trans-resveratrol* miktarları üzerinde iklimsel özelliklerin etkilerinin değerlendirilmesi: Türkiye'de bir örnek çalışma

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ABSTRACT

Objective: Polyphenolic compounds are secondary metabolites synthesized by plants as part of their defense mechanisms and are known for their bioactive benefits to human health. Among them, *trans-resveratrol* (*t*-RES) is remarkable for its strong biological activity and high presence in red wines. This study investigates the effects of climatic factors on *t*-RES accumulation and evaluates the potential of Turkish viticultural regions for quality red wine production.

Material and Methods: Red wines were produced from 'Boğazkere' and 'Öküzgözü' grapes grown in vineyards located in the Aegean, Eastern Anatolia, and Southeastern Anatolia. *T*-RES concentrations were determined by High Performance Liquid Chromatography (HPLC), while climate parameters were obtained from regional meteorological stations.

Results: Analyses showed that geographic location significantly affected *t*-RES content, with the lowest value observed in wines from 'Boğazkere' grapes grown in İzmir and the highest in wines from 'Öküzgözü' grapes cultivated in Elazığ (1.481 and 3.349 mg/L). Effective Heat Summation (EHS) values ranged between 2380.6 and 2940.4 day-degree, while Branas Heliothermal Index values varied from 4.24 to 5.46.

Conclusion: Climatic conditions strongly influence *t*-RES accumulation, highlighting the potential of specific Turkish regions for producing high-quality red wines.

ÖZ

Amaç: Polifenolik bileşikler, bitkiler tarafından savunma mekanizmalarının bir parçası olarak sentezlenen sekonder metabolitlerdir ve insan sağlığına yararlı biyoaktif özellikleriyle öne çıkmaktadırlar. Bu bileşikler arasında *trans-resveratrol* (*t*-RES), güçlü biyolojik aktivitesi ve kırmızı şaraplarda yüksek düzeyde bulunmasıyla dikkat çekmektedir. Bu çalışma, iklim faktörlerinin *t*-RES birikimi üzerindeki etkilerini incelemeyi ve Türkiye'nin farklı bağcılık bölgelerinin kaliteli kırmızı şarap üretimine uygunluğunu değerlendirmeyi amaçlamaktadır.

Materyal ve Yöntem: Ege, Doğu Anadolu ve Güneydoğu Anadolu bölgelerinde yetiştirilen 'Boğazkere' ve 'Öküzgözü' üzümlerinden kırmızı şarap üretilmiştir. *T*-RES düzeyleri Yüksek Performanslı Sıvı Kromatografisi (HPLC) ile belirlenmiş, iklim verileri bölgesel meteoroloji istasyonlarından elde edilmiştir.

Araştırma Bulguları: Analizler, coğrafi konumun *t*-RES içeriğini önemli ölçüde etkilediğini göstermiştir. En düşük değer İzmir'de yetiştirilen 'Boğazkere' üzümlerinden yapılan şaraplarda, en yüksek değer ise Elazığ'da yetiştirilen 'Öküzgözü' üzümlerinden yapılan şaraplarda gözlemlenmiştir (1.481 ve 3.349 mg/L). Etkili Sıcaklık Toplamı (EST) değerleri 2380.6 ile 2940.4 gün-derece arasında değişirken, Branas Heliothermal İndeksi değerleri 4.24 ile 5.46 arasında değişmiştir.

Sonuç: Bulgular, iklim koşullarının *t*-RES birikimini önemli ölçüde etkilediğini ve bazı bölgelerin yüksek kaliteli kırmızı şarap üretimi için güçlü bir potansiyele sahip olduğunu göstermektedir.

INTRODUCTION

The health benefits of polyphenolic compounds have recently gained increasing attention among researchers due to their strong antioxidant, antiallergic, anti-inflammatory, antidiabetic, antimicrobial, antiviral and antithrombotic properties, which have a positive effect on human cells (Dutta et al., 2017; Ragusa et al., 2017; Pérez-Vizcaíno & Fragad, 2018; Teissedre et al., 2018; Tzanova & Peeva, 2018; Fraga et al., 2019; Shaito et al., 2020; Salehi et al., 2021). These compounds are generally classified into two main groups: flavonoids and non-flavonoids. *Trans*-resveratrol (*t*-RES; 3,5,4'-trihydroxystilbene) is a polyphenolic compound with proven biological activity (Keskin et al., 2009) and belongs to the stilbenes, a subgroup of non-flavonoids (Çelik & Keskin, 2025). *T*-RES has various biological activities that benefit human health, including antioxidant, antibacterial, anti-inflammatory, cardioprotective and cancer-preventive effects (Berman et al., 2017; Ferraz da Costa et al., 2017, 2020; Keskin & Kunter, 2017; Fernández-Marín et al., 2021; Zhu et al., 2025). While *t*-RES is found in the seeds, pulp, and skin of many plants and fruits as a defence metabolite, grapes are considered the richest natural source, particularly in the skin of red varieties (Gambini et al., 2015; Keskin et al., 2020; Xi et al., 2020).

The concentration of *t*-RES in grapes and wine varies according to factors such as grape variety, geographical location, soil composition, stage of ripening, vineyard management practices, climatic conditions and winemaking processes (Bavaresco et al., 2016; Irimia et al., 2018; Topçu Altıncı & Cangi, 2019; Soltekin et al., 2021). Several studies have reported *t*-RES levels in wines from various viticultural regions around the globe (Lingua et al., 2016; Ragusa et al., 2017; Osorio-Macías et al., 2018). Meanwhile, research has increasingly emphasised the importance of analysing spatial climate conditions and applying indices such as Huglin, Branas and hydrothermal indices to evaluate viticultural suitability (Atak, 2023). Nevertheless, research specifically addressing the relationship between *t*-RES accumulation and climatic characteristics remains limited.

The aim of this study is to determine the *t*-RES content of red wines produced from 'Boğazkere' and 'Öküzgözü' grapes cultivated in three different regions of Türkiye. The grapes were obtained from four vineyard locations in areas with distinct climatic conditions: İzmir and Denizli (Aegean region), Elazığ (Eastern Anatolia region) and Diyarbakir (Southeastern Anatolia region). Secondly, the study aims to calculate effective heat summation and Branas Heliothermal Index values based on climate data such as daily average temperature and sunshine duration in these regions. These calculations are essential for assessing the suitability of vineyards for grape production in terms of climate, since grapes grown under optimum conditions are known to be of higher quality and to have a higher polyphenolic content (Irimia et al., 2018).

MATERIALS and METHODS

Meteorological Data

Among the leading six viticulture countries worldwide, Türkiye ranks fifth, accounting for 52.9% of table grape production, 36.3% of dried grape production, and 10.8% of wine grape production (Ateş & Uysal, 2017). Owing to this rich viticultural heritage and highly diverse terroirs, a wide range of grape varieties are employed in Turkish winemaking. Among these, 'Boğazkere' and 'Öküzgözü', two traditional black grape varieties, hold particular prominence in red wine production. Originating from the Eastern and Southeastern Anatolia regions, these varieties are now also cultivated in several other viticultural zones, including the Aegean region. In the present study, wines produced from 'Boğazkere' and 'Öküzgözü' grapes cultivated in three distinct regions of Türkiye were investigated to evaluate the influence of regional viticultural conditions and terroir characteristics on their composition and quality.

The selected study sites were located in four major viticultural regions of Türkiye: İzmir and Denizli in the Aegean region, Elazığ in Eastern Anatolia, and Diyarbakır in Southeastern Anatolia. The geographical coordinates and altitudes of these sites are presented in Table 1.

Table 1. Geographic coordinates, altitude, and Köppen climate classification of the study sites in Türkiye

Çizelge 1. Türkiye'deki çalışma alanlarının coğrafi koordinatları, rakımı ve Köppen iklim sınıflandırması

Province	Latitude (°N)	Longitude (°E)	Altitude (m)	Köppen Climate Classification
İzmir	28°26'	27°09'	25	Csa (Mild winter, very hot and dry summer climate-Mediterranean)
Denizli	37° 4'36"	29°17'29"	450	Csa (Mild winter, very hot and dry summer climate-Mediterranean)
Elazığ	38°41'	39°30'	1015	Bsk (Semi-arid steppe climate-Cold)
Diyarbakır	37°54'39"	40°14'12"	677	Csa (Mild winter, very hot and dry summer climate-Mediterranean)

The Köppen Climate Classification and the geological characteristics of viticultural regions are crucial in viticulture studies, as they offer valuable insights into the climatic and environmental factors that influence grapevine growth and wine production. The Köppen system classifies regions based on temperature, precipitation, and seasonal variations, all of which directly affect grapevine phenology. These include factors such as the length of the growing season, thermal unit accumulation, and the balance between day and night temperatures. These climatic conditions are essential in determining the suitability of specific grape varieties, as well as their ripening patterns, chemical composition, and the overall quality of the resulting wine. Alongside climate, the geological characteristics (including soil composition, drainage, topography, and elevation) are key in shaping a region's terroir, influencing vine health, root development, and water retention, all of which are critical for producing high-quality grapes. Therefore, understanding both the climatic classification and geological features of a region provides a comprehensive framework for optimizing vineyard management, ensuring sustainable grape production, and enhancing wine quality. According to the Köppen climate classification, İzmir, Denizli and Diyarbakır fall under the hot-summer Mediterranean climate (Csa), whereas Elazığ is classified as cold semi-arid (BSk) (Figure 1).

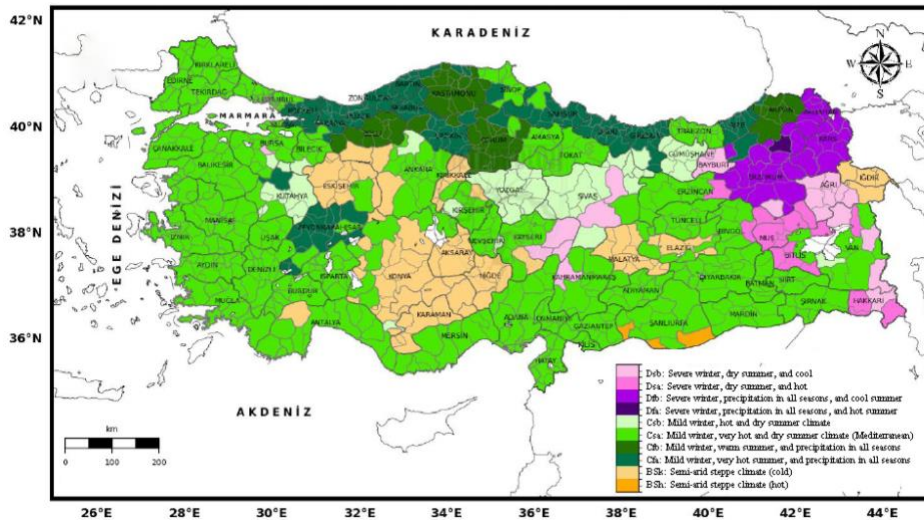


Figure 1. Köppen climate classification of Türkiye (HGM, 2025).

Şekil 1. Türkiye'nin Köppen iklim sınıflandırması (HGM, 2025).

Daily temperature and total sunshine duration data for the period 2023-2024 were obtained from meteorological stations located in Elazığ (Central Eastern Anatolia), İzmir and Çeşme, Denizli Güney (Aegean region), and Diyarbakır Central (Southeastern Anatolia). All meteorological data were monitored and provided by the Turkish State Meteorological Service (MGM, 2025).

Mean temperatures for winter, summer, and the grapevine growing season, as well as the vegetation time (VT) and sunshine duration (SD), were calculated using average daily temperature values. VT and SD were determined for the period between April 1st and September 30th, corresponding to the recognized active vegetative growth period for grapevines in the Northern Hemisphere. The calculated climatic parameters for the analyzed regions are summarized in Table 2.

Table 2. Geographic and climatic characteristics of the study sites in Türkiye

Çizelge 2. Çalışma alanlarının Türkiye'deki coğrafi ve iklimsel özellikleri

Region	Location	SD (hours)	VT (days)	¹ T _{avg-y} (°C)	² T _{avg-w} (°C)	³ T _{avg-s} (°C)	⁴ T _{avg-gs} (°C)
Aegean	İzmir	1878.9	165	9.67	0.5	21.31	20.42
	Denizli	1686.2	174	9.27	-1.34	17.89	24.42
Eastern Anatolia	Elazığ	1915.2	178	5.46	-6.79	17.60	22.97
Southeastern Anatolia	Diyarbakır	1855.1	181	8.32	-4.97	21.04	21.46

* ¹T_{avg-y} (°C): Mean temperature of the year, ²T_{avg-w} (°C): Mean temperature of winter, ³T_{avg-s} (°C): Mean temperature of summer, ⁴T_{avg-gs} (°C): Mean temperature of growing season.

Methodology for determining t-RES concentrations

Wine Production Method

The study was conducted in the Food Technology Laboratory at the Ege Vocational School of Ege University in 2024 and 2025. The wines analysed were produced using 'Boğazkere' and 'Öküzgözü' grapes, which were harvested in the regions specified in the 'Meteorological Data' section during the 2023-2024 growing season. Ampelographic characteristics of grape varieties were given in Table 3 (Çelik, 2006).

Table 3. Ampelographic characteristics 'Boğazkere' and 'Öküzgözü' grape varieties

Çizelge 3. 'Boğazkere' ve 'Öküzgözü' üzüm çeşitlerinin ampelografik özellikleri

Characteristics	Boğazkere	Öküzgözü
Berry Characteristics	Color	Violet-Black
	Form and Seed	Black with gray bloom
	Size	Round, 2-3
	Flavor	Ellipsoidal, 2-3
Cluster Characteristics	Size	Large, 3.4 g
	Form	Winged conical
	Compactness	Large, 6 g
	Flavor	Hightly tanninous
Cultural Characteristics	Form	Winged conical
	Size	Very large, 490 g
	Compactness	Wellfilled
	Location	Wellfilled
Cultural Characteristics	Ripening	Late
	Pruning	Late
	Location	Cane
	Diyarbakır, Elazığ, Malatya	Elazığ Malatya

The black grapes were harvested at the optimal time, transported to the pilot facility where production would take place and crushed in preparation for fermentation. The crushed grapes were then subjected to primary fermentation for five days, to which *Saccharomyces cerevisiae* yeast and sulfur dioxide (SO₂) were added. The must obtained by pressing was then transferred to fermentation tanks under controlled conditions and alcoholic fermentation was completed. The resulting wines were clarified using gelatin, followed by filtration to remove sediments and ensure proper waste management. Finally,

the wines were bottled to preserve their chemical composition and sensory characteristics, then stored at 10°C until analysis. This standardised winemaking procedure ensured consistent evaluation of polyphenolic compounds, particularly *t*-RES, across different grape varieties and growing regions.

Trans-resveratrol determination and chromatographic procedure

In this study, *T*-RES (Catalogue number R5010) and HPLC-grade solvents, including methanol and acetonitrile, were used. Quantitative analyses of *t*-RES concentrations in wine samples were performed using a Shimadzu SCL-10A VP HPLC system (Tokyo, Japan) equipped with a UV-VIS detector (SPD-10A VP). The system comprised an LC-10AT quaternary gradient pump and a degasser unit (DGU-14A). Wine samples (20 µL) and calibration standards were injected directly into a LiChrospher RP-18 column (250 × 4 mm, 5 µm particle size). For *t*-RES elution, distilled water (pump A) and acetonitrile (pump B) were employed as the mobile phase at a ratio of 65:35, with a flow rate of 1 mL/min. Detection was carried out using the UV-VIS detector set at 289 nm, and chromatographic peaks were identified based on retention times, with *t*-RES eluting at approximately 6.5 min under these conditions. All wine samples were analyzed in triplicate to ensure reproducibility.

A stock solution of *t*-RES was prepared by dissolving 0.0005 g in 10 mL methanol. Calibration solutions ranging from 0 to 10 mg/L were prepared from this stock solution. *T*-RES concentrations in wine samples were quantified in mg/L using the standard calibration curve.

Methodology for determining climatic indices

In this study, the analysis of climatic potential has used effective heat summation (EHS, day-degree) and Heliothermic Index (HI) values. These indices are considered important parameters for determining the viticultural potential of regions. To calculate these indices, the values of vegetation time (VT) and sunshine duration (SD) must first be determined. VT is calculated using daily mean temperatures of at least 10°C between 1 April and 30 September (Ateş & Uysal, 2017; Irimia et al., 2018). Additionally, the sum of SD for each region between 1 April and 30 September was calculated as suggested by Irimia et al. (2018).

The most important parameter in determining the viticultural potential of a region is the effective heat summation (EHS). All grape varieties require a certain amount of total temperature during the growing season to reach maturity. The minimum average temperature required for the growth of vine plants is 10°C (the threshold temperature). 10°C is a base temperature; below this, vine plants are assumed to require additional heat. It should be noted that EHS is expressed in day-degrees and is calculated using the following formula (Branas et al., 1946):

$$EHS = \sum(T_m - 10) \cdot VT$$

In this equation, T_m is the daily mean temperature during the growing season (April 1st to September 30th) and VT is the number of days when the temperature is at least 10°C during this period.

In addition to air temperature, the balance between temperature and sunshine duration should be considered to determine regions' suitability for viticulture. In the literature, the heliothermic index (HI) is evaluated using two different methods: the Branas heliothermic index (Branas et al., 1946) and the Huglin heliothermic index (Huglin, 1978).

While the calculation of the Branas Heliothermic Index (BHI) requires average daily temperature and total sunshine duration values, the Huglin Heliothermic Index (HHI) necessitates daily maximum and minimum temperature data. Due to the unavailability of these data, the HHI was not calculated in the present study.

The Branas Heliothermic Index was calculated using the following equation:

$$BHI = \sum (T_m - 10) \times VT \times SD \times 10^{-6}$$

where T_m is the mean daily temperature during the growing season (April 1st and September 30th); VT represents the number of days with temperatures of at least 10°C within this period, and SD denotes the total sunshine duration (hours) between April 1st and September 30th.

RESULTS and DISCUSSION

The *t*-RES concentrations of red wines produced from 'Boğazkere' and 'Öküzgözü' grape varieties are summarized in Table 4 and illustrated in Figure 2. Figure 2 presents the comparative distribution of *t*-RES levels between the two grape varieties, highlighting the variability and relative differences in transveratrol content among the analyzed wine samples.

Table 4. *T*-RES concentrations in red wines from 'Boğazkere' and 'Öküzgözü' grapes across key viticultural regions of Türkiye

Çizelge 4. Türkiye'nin önemli bağcılık bölgelerinde yetiştirilen 'Boğazkere' ve 'Öküzgözü' üzümlerinden elde edilen kırmızı şaraplarda *t*-RES konsantrasyonları

Region	Location	Grape Variety	<i>T</i> -RES Concentrations (mg/l)
Aegean	İzmir	Boğazkere	1.481
		Öküzgözü	1.686
	Denizli	Boğazkere	2.283
		Öküzgözü	2.387
Eastern Anatolia	Elazığ	Öküzgözü	3.349
Southeastern Anatolia	Diyarbakır	Boğazkere	2.970

The results clearly indicate that geographic location exerts a significant influence on *t*-RES content, with concentrations ranging from 1.481 to 3.349 mg/L. The lowest concentration (1.481 mg/L) was observed in wines from 'Boğazkere' grapes cultivated in İzmir (Aegean region), while the highest value (3.349 mg/L) was detected in wines from 'Öküzgözü' grapes grown in Elazığ (Eastern Anatolia). Furthermore, 'Öküzgözü' wines consistently exhibited higher *t*-RES levels across all regions compared to 'Boğazkere' wines, with mean concentrations of 2.474 mg/L and 2.245 mg/L, respectively.

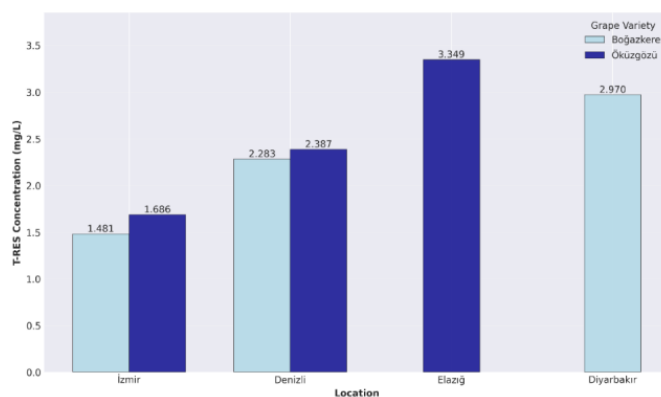


Figure 2. *T*-RES concentrations in red wines from 'Boğazkere' and 'Öküzgözü' grapes.

Şekil 2. 'Boğazkere' ve 'Öküzgözü' üzümlerinden elde edilen kırmızı şaraplarda *t*-RES konsantrasyonları.

To further elucidate the impact of climatic conditions on vineyard potential, Branas Heliothermic Index (BHI) and Effective Heat Summation (EHS) values during the vegetation period were calculated, taking into account both daily mean temperatures and sunshine duration (Table 5).

The results demonstrate marked regional differences, with EHS values ranging from 2380.6 to 2940.4 and BHI values from 4.24 to 5.46. The highest EHS (2940.4) was recorded in Diyarbakır (Southeastern Anatolia), whereas the lowest (2380.6) occurred in Elazığ (Eastern Anatolia). Climatic data analysis revealed that both EHS and vegetation period length are higher in Southeastern Anatolia, which also exhibited the highest BHI value (5.46) (Table 5).

Table 5. Effective Heat Summation (EHS) and Heliothermic Index (HI) values of vineyards in Aegean, Eastern, and Southeastern Anatolia Regions of Türkiye

Çizelge 5. Türkiye'nin Ege, Doğu ve Güneydoğu Anadolu Bölgelerindeki bağ alanlarında Etkili Sıcaklık Toplamı (EST) ve Heliotermik İndeks (HI) Değerleri

Region	Location	EHS (day-degree)	BHI
Aegean	İzmir	2537	4.77
	Denizli	2516.5	4.24
Eastern Anatolia	Elazığ	2380.6	4.56
Southeastern Anatolia	Diyarbakır	2940.4	5.46

T-RES concentrations in red wines show a notable variation, ranging from low levels such as 0.047 mg/L in Portuguese wines to high levels such as 21.07 mg/L in Serbian wines. This wide range reflects the combined effects of grape variety, cultural practices applied in viticulture, climatic differences, soil structure, and differences in winemaking techniques. Studies conducted in European countries show relatively high *t-RES* concentrations in red wines from Romania (1.51-11.75 mg/L) (Nour et al., 2012; David et al., 2015; Craciun & Gutt, 2020), Poland (0.82-11.13 mg/L) (Bernarska et al., 2019) and Russia (0.85-18.7 mg/L) (Suprun et al., 2021) show relatively high *t-RES* concentrations in red wines, while values found in Italian wines (0.72-6.0 mg/L) are consistent but moderate across multiple wine-growing regions (Ragone et al., 2015; Preti et al., 2016; Ragusa et al., 2017; Ragusa et al., 2019; Rocchetti et al., 2021; Razem et al., 2022; Rapa et al., 2025). In addition, significantly lower concentrations were found in Greek wines (0.352-1.99 mg/L) (Kallithraka et al., 2001; Gerogiannaki-Christopoulou et al., 2006) and Portuguese wines (0.047-2.39 mg/L) (Rocha et al., 2019). According to recent research results, concentrations of 0.209-3.58 mg/L were found in Spain (Guerrero et al., 2020), 1.7-2.85 mg/L in Croatia (Rastija et al., 2009; Rossi et al., 2020; Rocchetti et al., 2021), Bulgaria 1.03-5.95 mg/L (Tzanova et al., 2020), and Israel 0.3-2.63 mg/L (Lubin et al., 2022).

Examining the results of studies conducted in other countries reveals that *t-RES* concentrations have been reported to be in the range of 1.62-6.79 mg/L in Chinese wines (Cui & Lv, 2015); 0.33-3.0 mg/L in Brazilian wines (Padilha et al., 2017); 0.2-5.8 mg/L in South American wines (Osorio-Macias et al., 2018); 0.3-5.76 mg/L in Argentinian wines (Lingua et al., 2016); and 1.63-1.91 mg/L in Australian wines (Agatonovic-Kustrin et al., 2015).

Examining the results of studies conducted in Türkiye reveals that the concentration range in Turkish red wines is relatively low (0.312-2.59 mg/L), compared to results found in other countries. Anlı et al. (2006) reported values between 0.422 and 1.722 mg/L in the four main wine-growing regions of Türkiye, while Gürbüz et al. (2007) studied black grape varieties such as 'Kalecik Karası', 'Çalkarası', 'Boğazkere', 'Öküzgözü', 'Cabernet Sauvignon', 'Cinsaut' and 'Merlot', finding concentration values ranging from 0.176 to 4.403 mg/L. More recent studies have found the highest *t-RES* content in red wines produced from the 'Öküzgözü' black grape variety grown in Elazığ in eastern Anatolia (Kelebek et al., 2010; Yaman et al., 2016; Tahmaz & Söylemezoğlu, 2022). Overall, these findings suggest that Turkish wines contain lower levels of resveratrol than those produced in leading viticulture regions such as Serbia, Romania, Russia and Italy.

Research findings suggest that the differences in *t*-RES concentrations detected in red wines are due to a complex interaction of genetic, ecological, and technological determinants. In this context, while Türkiye's contribution remains regionally significant, it remains quantitatively lower on a global scale, highlighting the need for targeted viticulture and winemaking strategies to increase the levels of bioactive compounds in its wines.

A comprehensive summary of reported *t*-RES concentrations in red wines from different countries, combining both earlier and more recent studies, is summarized in Table 6. According to this table, the values emphasize the significant global variability, ranging from a low level of 0.047 mg/L in Polish wines to a high level of 18.7 mg/L in Russian wines, highlighting the combined effect of genetic, environmental, and technological factors on resveratrol biosynthesis and accumulation.

This study yielded comparable results, with the highest *t*-RES concentration of 3.349 mg/L detected in red wines produced from 'Öküzgözü' black grapes grown in Elazığ, in the Eastern Anatolia region. Similar results were observed in wines produced from 'Boğazkere' black grapes grown in Diyarbakır, in the Southeastern Anatolia region (2.97 mg/L), while wines produced from black grapes grown in the Aegean region had relatively lower *t*-RES levels in both varieties (1.481-2.487 mg/L) (Table 4). When considering the *t*-RES concentrations reported in previous studies in Türkiye (Anlı et al., 2006; Gürbüz et al., 2007; Yaman et al., 2016), the concentration range found in this study (1,481-3,349 mg/L) is consistent with findings previously obtained both in Türkiye and in other wine-producing countries. In particular, many studies conducted in Türkiye have shown that wines produced from 'Öküzgözü' black grapes grown in Elazığ have the highest *t*-RES concentrations. This result also suggests that the grape-terroir interaction in this region may play a critical role in increasing stilbene accumulation compared to other viticultural areas.

Table 6. Reported concentration ranges of *T*-RES in red wines across global wine-producing countries

Çizelge 6. Dünya çapındaki şarap üretim bölgelerinde kırmızı şaraplarda *T*-RES konsantrasyon aralıkları

Country	<i>T</i> -RES (mg/L)	References
Argentina	0.3 - 5.76	Lingua et al. (2016)
Australia	1.63 - 1.91	Agatonovic-Kustrin et al. (2015)
Brazil	0.33 - 3.0	Padilha et al. (2017)
Bulgaria	1.03 - 5.95	Tzanova et al. (2020)
China	1.62 - 6.79	Cui & Lv, (2015)
Croatia	1.7 - 2.85	Rastija et al. (2009); Rossi et al. (2020); Rocchetti et al. (2021)
Greece	0.352 - 1.99	Kallithraka et al., (2001); Gerogiannaki-Christopoulou et al. (2006)
Israel	0.3 - 2.63	Lubin et al. (2022)
Italy	0.72 - 6.0	Ragone et al. (2015); Preti et al. (2016); Ragusa et al. (2017); Ragusa et al. (2019); Rocchetti et al. (2021); Razem et al. (2022); Rapa et al. (2025)
Poland	0.82 - 11.13	Bernarska et al. (2019)
Portugal	0.047 - 2.39	Rocha et al. (2019)
Romania	1.51 - 11.75	Nour et al. (2012); David et al. (2015); Craciun & Gutt, (2020)
Russia	0.85 - 18.7	Suprun et al. (2021)
Serbia	0.11 - 21.07	Cvejić et al. (2010); Atanacković et al. (2012); Radović et al. (2015); Krstonošić et al. (2020); Petrović et al. (2024); Mavric-Scholze et al. (2025)
South America	0.2 - 5.8	Osorio-Macias et al. (2018)
Spain	0.209 - 3.58	Guerrero et al. (2020)
Türkiye	0.312 - 2.59	Anlı et al. (2006); Gürbüz et al. (2007); Kelebek et al. (2010); Yaman et al. (2016); Tahmaz & Söylemezoğlu (2022)

In the second part of this study, meteorological data (including daily mean temperature and total sunshine duration) were used to calculate vegetation time (VT), effective heat summation (EHS), sunshine duration (SD), and the Branas Heliothermic Index (BHI). Among these, BHI is a widely recognized climatic index in viticulture and is frequently employed to evaluate the suitability of regional climatic potential for grape cultivation (Irimia et al., 2018). Both EHS and SD were assessed to better understand their impact on the accumulation of phenolic compounds in grapes and consequently in wines, while VT remains an essential determinant of both grapevine productivity and wine quality. VT, defined as the number of days with mean daily temperatures exceeding 10°C between April 1 and September 30, was calculated as 164, 174, 178, and 181 days for İzmir, Denizli, Elazığ, and Diyarbakır, respectively (Table 2). Considering that an optimum VT is generally regarded as being above 180 days (Çelik et al., 1998), Diyarbakır in Southeastern Anatolia appears to provide the most favorable conditions, although the other sites presented values only slightly below this threshold.

EHS and BHI values further support the suitability of Southeastern Anatolia, with the highest measurements observed in Diyarbakır (2940.4 day-degree and 5.46, respectively), compared to the other regions. Interestingly, although Elazığ in Eastern Anatolia demonstrated slightly lower heliothermal conditions, it yielded the highest *t*-RES concentration in 'Öküzgözü' wines (3.349 mg/L; Table 5). This finding suggests that climatic suitability alone does not fully account for phenolic accumulation, and that specific grape-terroir interactions, including local soil characteristics, solar radiation, and cultivar physiology, likely play a significant role (van Leeuwen & Darriet, 2016).

Additional climatic parameters were also analyzed, including mean annual temperature (T_{avg-y}), mean temperature of the coldest month (T_{avg-w}), mean summer temperature (T_{avg-s}), and mean temperature of the growing season (T_{avg-gs} ; Table 2). According to established viticultural thresholds, suitable regions typically require $T_{avg-y} > 9^{\circ}\text{C}$, $T_{avg-w} \geq 0^{\circ}\text{C}$, $T_{avg-s} > 20^{\circ}\text{C}$, and $T_{avg-gs} > 13^{\circ}\text{C}$ (Çelik et al., 1998; Drappier et al., 2019). Based on these criteria, İzmir (Aegean region) met the requirements most consistently, particularly with a coldest-month average of 0.5°C and a summer mean of 21.31°C, while Elazığ and Denizli showed comparatively cooler conditions. Nonetheless, all regions exhibited growing season means well above the recommended minimum (20.42-24.42°C), indicating overall suitability for viticulture.

Sunshine duration, another decisive parameter influencing photosynthetic activity, also demonstrated favorable conditions across all studied regions. Grapevines are known to require at least 1250-1300 h of sunshine during the growing season, with 1500-1600 h being considered optimal (Çelik et al., 1998; Köse, 2014). In this study, all locations exceeded this threshold, with Elazığ achieving the highest value (1915.2 h; Table 2). This finding aligns with the well-established role of solar radiation in driving sugar accumulation, berry development, and phenolic biosynthesis, provided that excessive light is not accompanied by suboptimal temperatures that might trigger photo-inhibition (Martínez-Lüscher et al., 2019).

When evaluated according to the Winkler classification, which categorizes regions by EHS into cool (<1700), warm temperate (1701-2250), and hot (>2251 day-degree) viticultural zones (Winkler et al., 1974), all four Turkish locations fall within the hot climate category (>2251 day-degree). The EHS requirements of the studied grape varieties (1525°C for 'Boğazkere' and 1542°C for 'Öküzgözü'; Ateş & Uysal (2017) were greatly exceeded, with all sites surpassing 2300 day-degree (Table 5). This highlights the capacity of these regions to support full grapevine development, albeit with potential implications for accelerated ripening and altered phenolic profiles under increasingly warm conditions (van Leeuwen et al., 2024).

Finally, BHI values confirmed the high heliothermal potential of all studied sites, ranging from 4.24 in Elazığ to 5.46 in Diyarbakır (Table 5), well above the minimum threshold of 2.6 required for viable viticulture (Irimia et al., 2018). Taken together, these results demonstrate that although Southeastern Anatolia exhibits the most favorable climatic potential according to established indices, Eastern Anatolia (particularly Elazığ) produces wines with the highest *t*-RES levels. This discrepancy underlines the importance of integrating climatic indices with terroir-specific factors and grape cultivar characteristics in assessing viticultural suitability and wine quality.

CONCLUSIONS

This study quantified *t*-RES concentrations in red wines produced from the native Turkish cultivars 'Boğazkere' and 'Öküzgözü', and evaluated key climatic determinants (VT, EHS, SD, BHI and seasonal temperature metrics) across representative sites in the Aegean, Eastern and Southeastern Anatolia regions. The principal empirical outcome is that 'Öküzgözü' wines exhibited the highest *t*-RES levels overall, with concentrations in the present dataset ranging from 1.481 to 3.349 mg·L⁻¹ (highest value: 'Öküzgözü' from Elazığ). These values are consistent with previously published Turkish studies (Anlı et al., 2006; Gürbüz et al., 2007; Yaman et al., 2016) and fall within the broader international distribution summarized in the Results (Tables 5 & 6).

Climatic analyses show that all four study sites present substantial heliothermal potential: EHS values exceeded 2251 day-degree and BHI values were well above the commonly cited minimum for viable viticulture (Irimia et al., 2018), placing the locations in the "hot" Winkler category for grape development (Winkler et al., 1974). Vegetation time (VT) and growing-season means were also adequate for quality grape production (Tables 2,5,6). Nevertheless, the spatial pattern of *t*-RES accumulation did not map one-to-one onto broad climatic suitability indices: although Diyarbakır (Southeastern Anatolia) exhibited the highest EHS and BHI, Elazığ (Eastern Anatolia) produced the highest *t*-RES in 'Öküzgözü' grapes. These results indicate that, even under generally favorable climatic conditions for viticulture, the interaction between cultivar-specific traits and terroir factors plays a critical role in regulating stilbene biosynthesis. This divergence highlights that aggregate climatic indices (EHS, BHI, VT) are necessary but not sufficient predictors of stilbene accumulation; fine-scale terroir factors (solar irradiance during ripening, UV exposure, soil characteristics, diurnal temperature span), cultivar-specific metabolic responses, and vineyard management interact to determine phenolic biosynthesis (van Leeuwen & Darriet, 2016; Martínez-Lüscher et al., 2019).

From an applied perspective, the consistently elevated *t*-RES in 'Öküzgözü' (particularly from Elazığ) identifies this cultivar-site combination as a promising target for viticultural practices and breeding programs aimed at enhancing stilbene content. Yet, the findings also caution that enhancing phenolic content cannot rely solely on selecting climatically "hot" regions; targeted manipulations (canopy management, controlled water deficit, timing of harvest) and site-specific assessments of light quality and soil-plant interactions are likely required to steer stilbene biosynthesis reliably.

Finally, several limitations moderate the generalizability of these conclusions and indicate productive directions for future research. This study is constrained by its geographic and (single-vintage) temporal scope; multi-year monitoring is necessary to partition vintage versus site effects and to evaluate interannual climatic variability. Future work should integrate: (i) replicated, multi-season sampling across micro-sites; (ii) detailed soil and canopy microclimate measurements (photosynthetically active radiation, UV-B flux, soil water status); (iii) experimental viticultural treatments to test causal drivers of stilbene induction; and (iv) molecular assays (e.g. stilbene synthase expression) to link environmental stimuli with biochemical pathways. Such an integrative approach will improve mechanistic understanding and provide actionable guidance for producers wishing to optimize phenolic profiles without compromising other quality attributes.

In sum, the present study confirms that Türkiye's Aegean, Eastern and Southeastern regions are broadly climatically suitable for viticulture and that 'Öküzgözü' from Elazığ stands out for high *t*-RES accumulation. Translating this empirical pattern into consistent production outcomes will require combining climatic indexing with terroir-level measurements, cultivar physiology, and adaptive vineyard management.

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: BA, VS; sample collection: BA; analysis and interpretation of data: BA; statistical analysis: VS; visualization: VS; writing manuscript: BA, VS.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that an ethics committee is not required for this study.

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