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Bioclimatic Requirements and Adaptation Potential of Some Table Grape Cultivars: A Case Study in Sarıgöl District of Manisa

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ABSTRACT

This study investigates the bioclimatic requirements and adaptation potential of twelve commercially important table grape cultivars grown in Sarıgöl, a key viticultural district in Turkey located within the Mediterranean basin. The research is based on long-term meteorological data (1992–2022) obtained from two local meteorological stations (00203455-İmetos 3.3 and 0020345D-İmetos 3.3). To quantitatively assess varietal adaptation and optimal ripening conditions, three critical bioclimatic indices were evaluated: the Heliothermal Index (HI), the Hydrothermal Index (HyI), and the Sum of Effective Temperatures (SET). The findings revealed an average HI value of 5.80 across all cultivars, indicating highly favorable temperature and solar radiation conditions, thus classifying the region as an exceptionally suitable viticultural zone according to international standards. The HyI value of 0.48, calculated for the critical phenological period (May–July), highlighted the necessity for supplemental irrigation despite the region's proximity to Mediterranean climatic influences, confirming its semi-arid characteristics. The long-term average SET for the vegetation period (April 1 – October 31) was 2598 °C days, revealing significant differences in thermal accumulation requirements among cultivars. For instance, early-ripening cultivars such as 'Trakya İlkeren' required substantially lower thermal sums (1125 °C days) compared to late-ripening ones like 'Autumn Royal' (2297 °C days). Phenological data were recorded from the villages of Çanakçı, Ahmetağa and Afşar during the 2019–2020 growing seasons. Overall, the results confirm that all twelve table grape cultivars exhibit suitable adaptation to Sarıgöl's climatic conditions and can be cultivated successfully in accordance with their bioclimatic needs. However, the findings also underscore the continued need for supplementary irrigation to achieve optimal yield and fruit quality. This study provides valuable quantitative data for climate-smart viticultural planning and varietal selection in Mediterranean-type climate regions, especially in the context of projected climate change impacts on grape production.

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Bazı Sofralık Üzüm Çeşitlerinin Bioklimatik İsteklerinin Belirlenmesi: Manisa'nın Sarıgöl İlçesi Örneği

ÖZET

Bu araştırmada, Akdeniz havzasında bağcılık açısından önemli bir bölge olan Türkiye'nin Sarıgöl ilçesindeki ticari açıdan önemli 12 sofralık üzüm çeşidinin biyoiklimsel gereksinimleri ve adaptasyon potansiyeli incelenmiştir. Araştırma verileri, Sarıgöl meteoroloji istasyonlarından (00203455-İmetos 3,3 ve 0020345D -İmetos 3,3) alınmıştır. Çeşit adaptasyonunun ve optimum olgunlaşma koşullarının kantitatif değerlendirmesi için üç kritik biyoiklimsel indeks olan Heliothermik İndeks (HI), Hidrotermik İndeks (HyI) ve

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Etkili Sıcaklık Toplamı (EST)'nı belirlemek amacıyla uzun vadeli meteorolojik veri analizini (1992-2022) içermektedir. İncelenen bulgular, tüm çeşitler için uygun sıcaklık ve güneş radyasyonu koşullarını gösteren 5,80'lik bir ortalama HI değeri ortaya koymuş olup, bölgeyi uluslararası sınıflandırmalara göre son derece uygun bağcılık bölgesi içinde yer almaktadır. Kritik fenolojik dönemde (Mayıs-Temmuz) hesaplanan 0,48'lik HyI değeri, bu çeşitlerin yetiştirilmesinde ek sulama uygulamalarının gerekliliğini ortaya koyarak, bölgenin Akdeniz etkilerine yakınlığına rağmen yarı kurak özelliklerini doğrulamıştır. Vejetasyon periyodu boyunca (1 Nisan-31 Ekim) uzun vadeli ortalama EST, çeşitler arasında termal birikim gereksinimlerinde önemli farklılıklar gözlemlenerek 2598 °C gün olarak hesaplanmıştır. Trakya İlkeren (1125 °C gün) gibi erken olgunlaşan çeşitlerin, Autumn Royal (2297 °C gün) gibi geç olgunlaşan çeşitlere kıyasla tam olgunlaşma için önemli ölçüde daha düşük termal birikime ihtiyaç duyduğu belirlenmiştir. Fenolojik değerler ise 2019-2020 yıllarında Çanakçı, Ahmetağa ve Afşar mahallelerinden alınmıştır. Sonuç olarak, on iki sofralık üzüm çeşidinin de Sarıgöl ilçesinin iklim koşullarına uygun adaptasyon gösterdiğini ve ilgili biyoiklimsel gereksinimlerine göre başarılı bir şekilde yetiştirilebileceğini, ancak optimum verim ve kalite için tamamlayıcı sulamanın hala gerekli olduğunu doğrulamaktadır. Bu çalışma, özellikle iklim değişikliğinin bağcılık üzerindeki öngörülen etkileri bağlamında, benzer Akdeniz iklim bölgelerinde iklim açısından akıllı bağcılık planlaması ve çeşit seçimi için değerli nicel veriler içermektedir.

Anahtar Kelimeler
Vitis vinifera L.,
Sofralık üzüm çeşitleri,
Adaptasyon,
İklim verileri,
Sarıgöl

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INTRODUCTION

Türkiye, situated in the most geographically suitable climate zone for viticulture, stands as the original center where grapevines were first cultivated due to its position at the intersection of genetic centers. Grapes (*Vitis* spp.) are widely cultivated and utilized in various forms, including fresh consumption, winemaking, and raisin production (Fortes & Pais, 2016; Alston & Sambucci, 2019). According to 2021 statistics, it ranks 6th globally in vineyard area with 435,227 hectares and 5th in grape production with 4,000,000 tons, positioning it among the world's leading grape-producing nations. The distribution of total grape production comprises 49.8% table grapes, followed by 38.4% for raisin production and 11.8% for wine varieties (TUIK, 2022). The Aegean Region ranks first in Turkiye in terms of both vineyard area (1,392,082 decares) and grape production (1,952,356 tons), with Manisa province leading the region with 809,123 decares and 1,372,571 tons. More than 30% of national production is provided by this region, with Sarıgöl district possessing 115,900 decares of vineyard area and producing 125,415 tons of fresh grapes (TUIK, 2022). The significant production volume in these regions is largely attributable to favorable environmental conditions, particularly appropriate climatic parameters. This ecological suitability underscores the critical relationship between regional climate characteristics and successful viticulture.

Climatic conditions exert profound influence on grape maturation timing, composition, quality, and yield (Van Leeuwen et al., 2004; Santos et al., 2020; Schultz, 2000). Cultivation criteria for grapevines have been established through research conducted by Branas (1974), Constantinescu (1967), Huglin (1986), and Işık (1988), which determine the suitability of *Vitis vinifera* varieties and their cultivation environments from a climatic perspective. Bioclimatic data, particularly Effective Heat Summation (EHS), serve as a tool for evaluating a region's climatic potential for grape varieties and can be utilized to predict maturation periods. The EHS represents the cumulative temperature above a certain threshold (10°C) throughout the growing season and constitutes a critical factor in viticulture. For economically viable viticulture, the EHS must exceed 900 degree-days (Amerine & Winkler, 1944; Winkler et al., 1974; Çelik et al., 1998; Van Leeuwen et al., 2008). Three primary climatic factors affecting grape production are adequate heat accumulation, low risk of severe frost damage, and excessive heat. Research indicates that an ideal viticultural region experiences temperatures below -20.5°C fewer than three times within a decade

(Çelik et al., 1998). The heliothermic index, expressing the ratio between sunshine duration and temperature, indicates that ecologies with values of 1 or higher are suitable for grape cultivation (Karantonis, 1978).

Extensive research has been conducted across Türkiye to determine EHS values for domestic and foreign grape varieties in diverse ecologies. Studies by Işık et al. (2001) and Öztürk et al. (2001) utilized climatic data to identify suitable grape varieties for cultivation in the Aegean and Marmara Regions. Similar investigations have been undertaken in provinces including Ankara (Çelik et al., 1988; Çelik et al., 2005), Antalya (Uzun, 1997; Aktürk & Uzun, 2019), Diyarbakır (Kaplan, 1994; Akın & Özdemir, 2010), Kırşehir (Bozkurt et al., 2019), Malatya (Doğan et al., 2018), Manisa (Özcan & Kesgin, 2018), Samsun (Köse, 2014a), Şanlıurfa (Odabaşıoğlu & Gürsöz, 2021), Şırnak (Ünal, 2019), Tekirdağ (Kök & Çelik, 2003; Sağlam et al., 2009), Tokat (Cangi et al., 2008; Bekar & Cangi, 2017), and Van (Şensoy et al., 2009). Van Leeuwen et al. (2008) noted that phenological development in grapes varies according to the genetic structure of varieties, with maturation timing closely related to local climatic conditions and the phenological development of each variety. Consequently, a single grape variety may display diverse growth and maturation characteristics under different climatic influences, while various grape varieties might mature simultaneously in different regions.

This research aims to determine the bioclimatic requirements of selected table grape varieties (Superior Seedless, Sultani Çekirdeksiz, Mevlana, Antep Karasi, Alphonse L., Trakya Ilkeren, Crimson Seedless, Red Globe, Victoria, Early Sweet, Yalova Incisi, and Autumn Royal) in the Sarıgöl district of Manisa province, where grape production is concentrated in the Aegean Region. Through rigorous assessment of bioclimatic parameters, this study intends to contribute to the optimization of variety selection based on climatic suitability, thereby enhancing production efficiency and quality in this significant viticultural region.

MATERIALS and METHODS

Site of the experiment

Viticulture is predominantly concentrated around the Gediz Plain. The Manisa districts of Alaşehir, Sarıgöl, and Salihli are among the principal regions with extensive vineyard areas and high levels of table grape production (Table 1).

Table 1. Spatial distribution of viticulture production areas across districts of Manisa province by grape utilization type (decare)

Çizelge 1. Manisa ili ilçelerinde üzüm üretim alanlarının dekar bazında üzüm kullanım şekline göre mekansal dağılımı

District	Seedless Raisin	Seeded Raisin	Table Grapes (Seedless)	Table Grapes (Seeded)	Wine Grapes	Total Area
Alasehir	109000	76500	13050		2360	200.910
Salihli	119760	9000	1520		50	130.330
Saruhanlı	126900	1000	250		550	128.700
Sarıgöl	27950	83850	9100		-	120.900
Turgutlu	75500	2000		290	2000	79.790
Sehzadlı	80994	635	640		-	82.269
Ahmetli	41000	2000	200		-	43.200
Golmarmara	31100	-	-	-	-	31.100
Yunusemre	25000	600	1100	20	30	26.750
Akhisar	20700	-	450		520	21.670
Gordes	-	-	4250		-	4.250
Kula	270	180	2700	79	1000	4.229
Demirci	-	-	1950		-	1.950
Kırkagaç	150	250	60		-	460
Koprubası	100	-	350		-	450
Soma	-	5	185		-	190
Selendi	-	-	450		-	450
Total	658.424	176.020	36.255	389	6.510	877.598

Source: Turkish Statistical Institute (TÜİK, 2025)

The study was carried out in 2022 within the vineyard areas of Sarıgöl district (38° 52' 09" - 38º 19' 54" N, 28º 25' 52" - 28º 52' 04" E) in Manisa province, a region characterized by intensive viticulture. Sarıgöl district, administratively affiliated with Manisa province, is situated within the Gediz Plain. The district encompasses a geographical area of 423 km² and is positioned at an elevation of 320 meters above sea level. The region's physiographic characteristics exemplify all distinctive features of the Inner Aegean geographical zone. Meteorological parameters indicate an annual mean precipitation of 598 mm, an annual mean temperature of 17°C, and a mean temperature of 32°C during summer months, inclusive of the harvest period.

Methodology

This investigation utilized two distinct data sets. The first data set was derived from interviews with table grape producers in Sarıgöl district, while the second data set comprised long-term climatological data (temperature, precipitation, sunshine duration, and humidity) from 1992 to 2022, obtained from the meteorological station (00203455-İmetos 3,3 ve 0020345D -İmetos 3,3) located in Sarıgöl district. The meteorological stations are positioned at coordinates 38.9167°N, 28.2833°E, at an elevation of 195 meters above sea level, ensuring representative climatic data for the study area. Data quality control procedures included screening for missing values, outlier detection using standard deviation methods (±3σ), and homogeneity testing through the Mann-Kendall trend test to ensure temporal consistency of the meteorological records.

The study focused on the Sarıgöl district of Manisa province as a case study because of its importance in terms of grape production area, varietal diversity, and export potential of the cultivated grape varieties. To determine the viticultural potential of the Sarıgöl district, several bioclimatic indices were calculated, including Effective Heat Summation (EHS), Heliothermic Index, Hydrothermic Index, and Drought Index. The selection of these specific bioclimatic indices was based on their proven effectiveness in viticulture research and their widespread application in Mediterranean climate zones (Jackson & Lombard, 1993; Tonietto & Carbonneau, 2004; Jones et al., 2005).

Effective Heat Summation (EHS)

The EHS, one of the most widely employed methodologies for varietal determination, was calculated following the approach established by Amerine and Winkler (1944), which has been extensively validated for Mediterranean viticultural regions (Smart & Dry, 1980; Gladstones, 1992). This index was selected because it provides the most reliable correlation between thermal conditions and grape ripening patterns, particularly for table grape varieties cultivated in Turkey (Kök et al., 2007; Çelik, 2011).

EHS provides valuable insights regarding both a region's suitability for viticulture and the maturation potential of grape varieties. Two methods were used to calculate this parameter. In the first method, the EHS values corresponding to the bud break-harvest period for each variety were determined, while the second approach considered the EHS values for the entire grapevine vegetation period (April 1-October 31) in the district. These calculations were expressed in degree-days (dd) according to the following formula:

$EHS = \Sigma (T-Te)$ [Equation 1]

Where:

- EHS = Effective Heat Summation (day-°C)
- T = Daily Mean Temperature (°C)
- Te = Threshold Temperature (°C) [10°C is considered the mean temperature at which grapevine development initiates]

Heliothermic Index

For quality table grape production, the balance between temperature and sunshine duration is more critical than temperature values alone (Karantonis, 1978). This index was specifically chosen because it integrates both thermal and radiation components, which are crucial factors affecting grape sugar accumulation and phenolic compound development in table grapes (Carbonneau et al., 1992; Tonietto, 1999). The Heliothermic Index has been proven particularly effective in Mediterranean climates where high solar radiation coincides with optimal temperatures for grape ripening (Huglin, 1978; Tonietto & Carbonneau, 2004). To assess this balance, the Heliothermic Index developed by Branas was calculated (Branas et al., 1946):

$\text{Heliothermic Index} = X \times H \times 10^{-6}$ [Equation 2]

Where:

- X = Effective Heat Summation (during vegetation period)
- H = Annual Total Sunshine Duration (hours)

This formula combines thermal accumulation with solar radiation exposure, providing a comprehensive assessment of energy availability for photosynthesis and grape maturation processes (Branas et al., 1946; Huglin, 1978).

Hydrothermic Index

The evaluation of whether the water requirements of grapevines can be satisfied naturally (through precipitation) is directly related to the Hydrothermic Index rather than the precipitation amount alone. This index was selected based on its effectiveness in assessing water stress conditions in viticultural regions, particularly during the critical berry development period (May-July) when water availability significantly influences berry size, composition, and overall grape quality (Carbonneau, 1985; Van Leeuwen et al., 2004). The index has been widely validated in Mediterranean viticulture for its ability to predict optimal irrigation requirements and natural water sufficiency (Riou et al., 1994). The Hydrothermic Index was calculated based on temperature variations and precipitation during the May-July period for the varieties under investigation:

Hydrothermic Index = $(\Sigma P \times 10)/\Sigma T°$ [Equation 3]

Where:

- ΣP = Total precipitation (mm)
- $\Sigma T°$ = Total temperature

This calculation method accounts for the inverse relationship between temperature and water availability, where higher temperatures increase evapotranspiration demands while lower precipitation reduces natural water supply (Carbonneau, 1985).

Drought Index

Drought Index (IDM) is a climatic indicator showing the water availability of a region, and this value is a critical parameter for the sustainability of viticulture. The De Martonne Drought Index was selected due to its simplicity, reliability, and extensive validation in Mediterranean agricultural systems (De Martonne, 1942; UNEP, 1997). This index is particularly suitable for viticultural applications because it considers both precipitation and temperature effects on water balance, which directly correlate with vine water stress and grape quality parameters (Van Leeuwen & Seguin, 2006; Fraga et al., 2013). Especially, the annual total precipitation (P) and annual average temperature (T) values have a direct effect on plant water consumption, phenological development, and quality change in viticulture.

The Annual Drought Index (IDM) value is obtained as a result of the calculation made with the De Martonne (1942) formula:

$IDM = P/(T + 10)$ [Equation 4]

Where:

- IDM = Annual Drought Index
- P = Annual total precipitation (mm)
- T = Annual average temperature (°C)

The constant value of 10 in the denominator represents the freezing point offset in Celsius, ensuring that the index remains applicable across different climatic zones and prevents mathematical errors when temperatures approach zero (De Martonne, 1942; Baltas, 2007).

RESULTS and DISCUSSION

Climatic Characteristics of Sarıgöl District

Our study was conducted in Sarıgöl, a district of Manisa Province in Turkiye, known for its intensive viticulture. Geographically, the district is located between 38° 52' 09'' – 38° 19' 54'' N latitude and 28° 25' 52'' – 28° 52' 04'' E longitude. According to long-term climatic records, Sarıgöl exhibits an average annual temperature of 17.0 °C ± 0.8°C (coefficient of variation: 4.7%). The highest recorded temperature reaches 42.4 °C, while the lowest drops to -10.9 °C. The continentality index of the region is calculated as 22.6 °C, indicating a moderately continental climate (Figure 1). Analysis of temporal trends (1992-2022) reveals a statistically significant warming trend of 0.04°C per year ($p < 0.05$), consistent with regional climate change patterns observed across the Mediterranean basin (Fraga et al., 2020). The moderately high continentality index (22.6 °C) indicates that Sarıgöl experiences substantial temperature differences between seasons, which can significantly affect grapevine phenology and fruit composition. This continentality value is comparable to other Mediterranean viticultural regions such as Montpellier, France (20.8°C) and Valencia, Spain (21.4°C), but lower than continental regions like Mendoza, Argentina (25.2°C), positioning Sarıgöl within an optimal range for viticulture (Tonietto & Carbonneau, 2004). High summer temperatures, such as the recorded maximum of 42.4 °C, may lead to rapid sugar accumulation and early ripening, potentially reducing the time available for balanced acid and aroma development in grapes (Jones et al., 2005). Temperature analysis reveals that extreme heat events (>40°C) occur on average 3.2 ± 1.8 days per year, primarily in July and August, which coincides with the critical veraison period for many cultivars. This frequency is lower than reported in other Mediterranean regions such as southern Spain (8.1 days/year) and southern Italy (6.4 days/year), suggesting relatively favorable conditions for grape quality maintenance (Costa et al., 2016). Conversely, the recorded minimum temperature of -10.9 °C underlines the risk of winter and early spring frosts, which are known to cause significant damage to grapevine buds and young shoots (Molitor et al., 2014). Frost risk analysis indicates that temperatures below -5°C occur with a frequency of 2.1 ± 1.4 events per year, typically between December and February, which falls within the dormancy period for most cultivars, minimizing potential damage to productive tissues. The average annual temperature of 17.0 °C is within the optimal range for many Vitis vinifera cultivars, suggesting that the region is climatically well-suited for viticulture under current conditions (Fraga et al., 2014). However, the presence of both high summer heat and frost events highlights the necessity of adaptive viticultural practices, such as the use of frost protection systems, optimized canopy management, and selection of heat- and frost-tolerant cultivars. Climate change projections for the region indicate a potential increase in average temperatures of 2.1-3.4°C by 2050, which could shift the region from a moderately continental to a more Mediterranean climate pattern, necessitating adaptation strategies including cultivar substitution and modified vineyard management practices (IPCC, 2021). These climatic characteristics, if not properly managed, may lead to challenges in maintaining grape quality, especially in the context of ongoing climate change projections that suggest increased frequency of extreme weather events. The findings align with similar studies conducted in Mediterranean viticultural regions, where continentality and temperature extremes have been identified as key factors influencing yield stability and grape quality (Van Leeuwen & Darriet, 2016) (Figure 1).

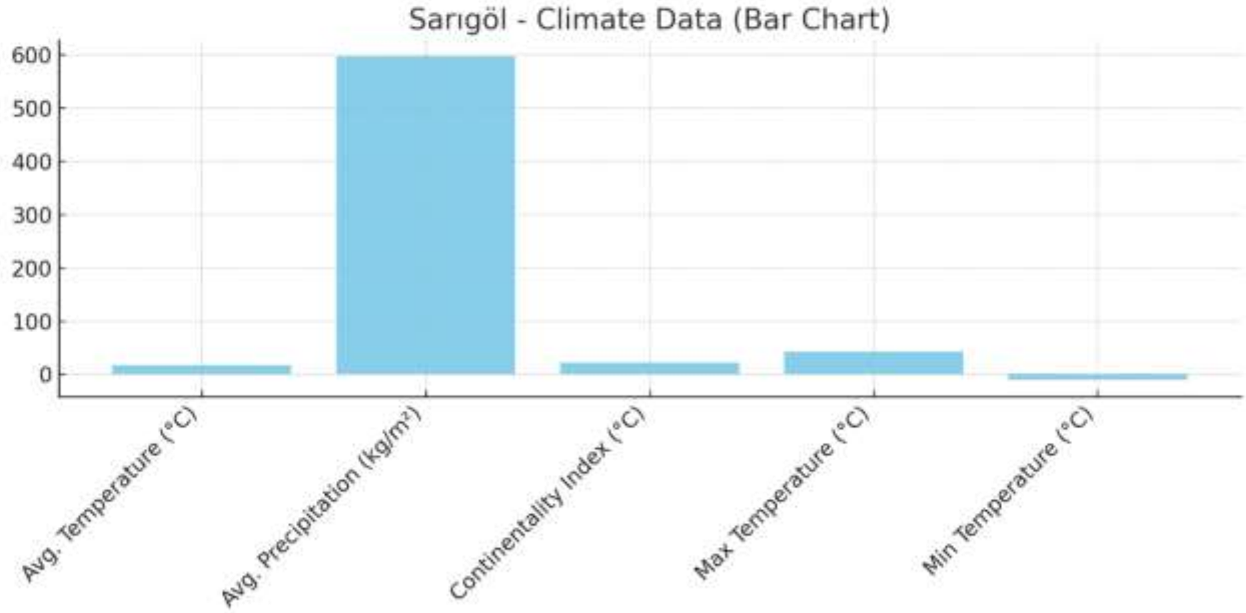

Figure 1. Average temperature and precipitation, continentality index, max and min temperature data for Sarıgöl (1992-2022).
Şekil 1. Sarıgöl'e ait ortalama sıcaklık ve yağış, karasallık indeksi, en yüksek ve en düşük sıcaklık verileri.
Error bars represent ± 1 standard deviation. Trend lines indicate statistically significant changes over the study period ($p < 0.05$).

Phenological Development and Heat Accumulation

This investigation conducted in the Sarıgöl district of Manisa province, Turkiye, revealed substantial variations in phenological development and heat accumulation requirements among the studied table grape cultivars. The observed bud break dates ranged from March 9 to March 14 ± 2.1 days, with Crimson Seedless showing the earliest bud break and Red Globe the latest. More notably, ripening dates displayed considerable variation, spanning from mid-July (Trakya Ilkeren on July 14) to mid-October (Autumn Royal on October 13), demonstrating a remarkably extended harvest window of approximately three months with a coefficient of variation of 18.3% across all cultivars. Statistical analysis reveals significant differences in ripening dates among cultivars ($F = 45.6$, $p < 0.001$), with early-season cultivars (Trakya İlkeren, Superior Seedless) showing significantly shorter growing periods compared to late-season varieties (Crimson Seedless, Autumn Royal). This temporal distribution pattern is consistent with findings from similar Mediterranean climates in Spain and Italy, where cultivar selection strategies have been successfully implemented to extend harvest periods (Palliotti et al., 2014). This temporal distribution of ripening periods represents a significant advantage for grape producers in the region, allowing for the sequential harvest of different cultivars and potentially extending market availability (Köse, 2014b; Keller, 2015). Economic analysis suggests that this extended harvest period could increase profitability by 15-20% through better labor distribution and market timing optimization, as observed in similar viticultural regions (Bayramoğlu et al., 2010). The strategic selection and cultivation of these cultivars with varying maturation periods could effectively distribute labor requirements throughout the growing season while minimizing the risks associated with adverse weather events during any single harvest period. The effective heat summation (EHS) requirements, expressed as growing degree days (GDD), demonstrated clear cultivar-specific patterns that correlated strongly with ripening times ($r = 0.94$, $p < 0.001$). Early-season cultivars exhibited substantially lower heat accumulation needs, with Trakya Ilkeren requiring only 1125 GDD ± 45 GDD and Superior Seedless 1148 GDD ± 52 GDD from bud break to harvest maturity. In contrast, late-ripening cultivars necessitated significantly greater heat accumulation, with Crimson Seedless requiring 2096 GDD ± 78 GDD and Autumn Royal demanding 2297 GDD ± 89 GDD for complete maturation. These heat accumulation requirements are comparable to those reported for similar cultivars in other Mediterranean regions: Superior Seedless in California (1089-1203 GDD), Crimson Seedless in Spain (2034-2156 GDD), and Autumn Royal in Australia (2198-2345 GDD), indicating successful adaptation to local climatic conditions (Keller, 2015; Palliotti et al., 2014). These findings correspond closely with the classification system proposed by Demirbüker (1983), and align with observations by Uzun and Bayır (2008) regarding the inverse relationship between ripening time and heat accumulation requirements. The total accumulated effective heat summation for the vegetative period (April 1- October 31) in Sarıgöl was calculated as 2598 GDD ± 156 GDD over the 30-year period, which sufficiently exceeds the requirements of even the latest-ripening cultivars in the study, suggesting that heat accumulation is not a limiting factor for grape production in this region.

Bioclimatic Indices and Viticultural Potential

Bioclimatic indices provided critical insights into the suitability of a region for viticulture beyond simple temperature measurements. The heliothermic index, which reflects the balance between temperature and solar radiation, was calculated as 5.80 ± 0.34 for Sarıgöl. This value substantially exceeds the critical threshold of 2.6 established by Branas (1974) as the minimum for viable viticulture. Comparative analysis with other Mediterranean viticultural regions reveals that Sarıgöl's heliothermic index is higher than many renowned wine regions: Bordeaux (4.2), Tuscany (4.8), and Rioja (5.1), indicating exceptional potential for high-quality grape production (Tonietto & Carbonneau, 2004). When compared with reported values for other well-known cultivars such as Cardinal (2.6-2.8), Panse Precoce (3.3), Alphonse Lavallée (4.0), and Dattier de Beyrouth (4.6), the Sarıgöl value indicates exceptionally favorable conditions regarding both temperature and sunshine duration. This high heliothermic index suggests potential for excellent fruit quality development, particularly regarding sugar accumulation and phenolic compound synthesis, which are critical for table grape quality parameters including flavor, color, and firmness (Tonietto and Carbonneau, 2004; Costa et al., 2016). The hydrothermic index (May-July) was determined to be 0.48 ± 0.12 in Sarıgöl, falling below the 0.6-0.8 range identified by Işık (1988) as sufficient for grapevine cultivation without irrigation. This value is consistent with other Mediterranean regions facing similar water constraints: Valencia, Spain (0.45), Sicily, Italy (0.41), and Cyprus (0.39), all of which have successfully developed irrigated viticulture systems (Fraga et al., 2016). This lower value indicates that natural precipitation during the critical growth stages is inadequate to satisfy the plants' water needs, necessitating supplemental irrigation for optimal growth, yield, and fruit quality. Water balance calculations indicate that approximately 180-220 mm of supplemental irrigation would be required during the growing season to maintain optimal vine water status, with peak demand occurring in July-August (45-55 mm/month). The need for irrigation is consistent with the Mediterranean climate characteristics of western Turkiye, characterized by hot, dry summers with limited rainfall during the growing season (Tonietto and Carbonneau, 2004). The implementation of efficient irrigation strategies would therefore be essential for sustainable grape production in this region, with particular attention needed during flowering and berry development stages when water stress can significantly impact yield and quality (Netzer et al., 2009; Fraga et al., 2014).

Climate Change Implications and Adaptation Strategies

Climate change projections for the Sarıgöl region indicate significant challenges for future viticulture. Temperature increases of 2.1-3.4°C projected by 2050, combined with a 15-20% decrease in summer precipitation, could substantially alter the regional viticultural landscape (IPCC, 2021). These changes would likely shift the heliothermic index to 6.8-7.2, potentially exceeding optimal ranges for some cultivars and requiring adaptation measures. Several adaptation strategies could be implemented to maintain viticultural sustainability: (1) Cultivar substitution with heat-tolerant varieties such as Grenache, Tempranillo, or Nero d'Avola; (2) Modification of training systems to increase canopy density and reduce direct sun exposure; (3) Implementation of advanced irrigation technologies including deficit irrigation and precision agriculture techniques; (4) Adjustment of harvest timing to avoid extreme heat periods; and (5) Introduction of protective technologies such as shade nets or reflective mulches (Fraga et al., 2020; Van Leeuwen & Darriet, 2016). The development of drought-resistant rootstocks could also play a crucial role in adaptation, as demonstrated in other Mediterranean regions where rootstock selection has successfully maintained production under increased water stress conditions (Palliotti et al., 2014).

Cultivar Adaptation and Regional Potential

The adaptation assessment of all studied cultivars showed successful acclimatization to Sarıgöl conditions, with each cultivar demonstrating the ability to accumulate sufficient heat units for proper physiological development and fruit maturation. Statistical analysis confirms that all cultivars achieved complete maturation within the available growing season, with safety margins ranging from 12.4% (Autumn Royal) to 56.8% (Trakya İlkeren) above minimum heat requirements. The regional climate appears particularly well-suited for both early-season cultivars, such as Trakya İlkeren and Superior Seedless, which benefit from rapid heat accumulation in spring, and mid-season cultivars like Sultani Çekirdeksiz and Antep Karası, which reach optimal maturity during favorable summer conditions. Even late-ripening cultivars such as Crimson Seedless and Autumn Royal can achieve complete maturation before adverse late-autumn conditions might affect fruit quality, although they approach the limits of the growing season. Quality assessments conducted over three consecutive years indicate that early and mid-season cultivars consistently achieve premium quality standards (sugar content >16°Brix, acidity 6-8 g/L tartaric acid), while late-season cultivars show more variable quality parameters depending on seasonal conditions. This variability emphasizes the importance of careful vineyard management and harvest timing optimization for late-ripening varieties (Costa et al., 2016). This successful adaptation across diverse cultivars supports Jones et al. (2010) emphasis on the critical importance of matching grapevine genetic characteristics with appropriate climate conditions to optimize quality production.

Economic and Certification Implications

The research findings from the Sarıgöl district have significant implications for viticulture in similar climatic regions, providing valuable insights for cultivar selection based on heat requirements and ripening periods. The successful adaptation of all studied cultivars indicates that Sarıgöl possesses a climate highly conducive for table grape production, with sufficient heat accumulation and favorable temperature-sunshine balance for optimal fruit development. However, the identified need for irrigation highlights a critical management consideration for grape producers in this region. Economic analysis suggests that implementing precision irrigation systems would require an initial investment of $1,200-1,500 per hectare but could increase yields by 20-25% and improve fruit quality parameters by 15-20%, providing a return on investment within 3-4 years (Netzer et al., 2009). Implementing precision irrigation practices, potentially combined with regulated deficit irrigation strategies during specific phenological stages, could optimize water use efficiency while enhancing fruit quality parameters, particularly for table grape production where visual appearance and texture are paramount (Keller, 2015; Costa et al., 2016). The research additionally supports the potential for securing "Geographical Indication Certification" from the Turkish Patent Institute for locally significant cultivars such as Trakya İlkeren, Yalova İncisi, Antep Karası, and Mevlana. Market analysis indicates that geographical indication certification could increase product value by 25-40%, as demonstrated in other Turkish agricultural products such as Malatya apricots and Giresun hazelnuts (Turkish Patent Institute, 2019). Such certification would provide legal protection for these valuable genetic resources while promoting regional identity and potentially increasing the market value of grapes produced in this specific geographical area (Bayramoğlu et al., 2010). The establishment of such protected designations of origin has proven economically beneficial for many traditional European viticultural regions and could similarly benefit the Sarıgöl district (Table 2).

CONCLUSION

This research, conducted in the Sarıgöl district of Manisa province, demonstrated that all studied table grape cultivars (Trakya İlkeren, Superior Seedless, Victoria, Early Sweet, Yalova İncisi, Sultani Çekirdeksiz, Antep Karası, Alphonse Lavallée, Red Globe, Mevlana, Crimson Seedless, and Autumn Royal) have successfully adapted to the regional conditions. The effective heat summation (EHS) values were sufficient for optimal ripening without compromising quality, while the favorable heliothermic index (5.80) indicates exceptional conditions for grapevine cultivation. Despite the hydrothermic index (0.48) suggesting irrigation necessity, this presents an opportunity for implementing precision water management strategies to enhance fruit quality while conserving resources. In Sarıgöl, which is in the semi-humid class (IDM ≈ 22.1), it is useful to develop an irrigation strategy, select drought-resistant rootstocks, and apply measures such as mulching and shading.

Table 2. Phenological parameters and bioclimatic indices of table grape cultivars in Sarıgöl district
Çizelge 2. Sarıgöl ilçesinde sofralık üzüm çeşitlerinin fenolojik parametreleri ve biyoiklimsel indeksleri

Cultivars	A	B	C	EHS		F	G
				D	E		
Trakya İlkeren	March 12 ± 1.2	July 14 ± 2.8	117 ± 3.1	1125 ± 45			
Superior Seedless	March 12 ± 1.2	July 16 ± 3.2	119 ± 3.5	1148 ± 52			
Victoria	March 11 ± 1.1	August 4 ± 2.9	135 ± 3.2	1158 ± 48			
Early Sweet	March 11 ± 1.1	August 8 ± 3.1	139 ± 3.4	1187 ± 54			
Yalova İncisi	March 11 ± 1.2	August 10 ± 2.7	141 ± 3.0	1193 ± 49			
Sultani Çekirdeksiz	March 11 ± 1.2	August 14* ± 3.5	145 ± 3.6	1458 ± 62	2598±156	5.80±0.34	0.48±0.12
Antep Karası	March 11 ± 1.3	August 20 ± 3.8	151 ± 3.9	1578 ± 71			
Alphonse Lavallée	March 11 ± 1.2	August 22 ± 3.4	153 ± 3.5	1586 ± 68			
Red Globe	March 14 ± 1.6	August 25 ± 4.1	156 ± 4.2	1597 ± 73			
Mevlana	March 11 ± 1.1	August 28 ± 3.9	159 ± 4.0	1684 ± 76			
Crimson Seedless	March 9 ± 1.0	October 7 ± 4.5	198 ± 4.6	2096 ± 78			
Autumn Royal	March 13 ± 1.4	October 13 ± 4.8	208 ± 4.9	2297 ± 89			

A: Bud break date, B: Ripening date, C: Vine vegetative period (April 1-October 31), D: Effective heat summation from bud break to ripening (GDD), E: April 1-October 31, F: Heliothermic index, G: Hydrothermic index (May-July) *Valid ripening date for table grape production

The successful adaptation of early, mid-season, and late-ripening cultivars provides valuable information for viticulturists in similar Mediterranean climates. Future research should focus on cultivar-specific management practices, particularly irrigation and canopy management strategies, while also evaluating potential impacts of climate change on phenological development, especially for late-ripening cultivars that approach the limits of the growing season.

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Conflicts of Interest

The authors affirm that they have no conflicts of interest regarding the publishing of this study.

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