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The Effect of Different Water Levels on Yield, Quality, and Biochemical Properties of Red Cabbage (Brassica oleracea f. rubra)

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ABSTRACT
This study was conducted under field conditions in Canakkale Province, Türkiye, during the 2021–2022 growing seasons and investigated the effects of different irrigation levels on the yield, quality, and biochemical properties of red cabbage (Brassica oleracea f. rubra). Four irrigation regimes were applied: 100% ($I_{1.0}$: full irrigation), 70% ($I_{0.7}$: mild stress), 30% ($I_{0.3}$: severe stress), and 0% ($I_{0.0}$: rainfed only). Morphological, physiological, and biochemical responses of plants to water stress were examined, with particular emphasis on the accumulation of flavonoids, anthocyanins, and phenolic compounds to evaluate adaptive capacity and nutritional quality. The data showed that yield decreased significantly as water deficit increased. The highest yields were obtained under full irrigation, with 1514.2 g plant^{-1} in 2021 and 1252.6 g plant^{-1} in 2022, demonstrating the positive effect of adequate water supply on productivity. The lowest yields were recorded under non-irrigated (rainfed) conditions. In contrast to yield trends, water restriction increased the accumulation of bioactive compounds. As irrigation decreased, flavonoid, phenolic, and anthocyanin contents as well as antioxidant activity (measured by DPPH and CUPRAC assays) increased significantly. The highest anthocyanin content (1.31 mg g^{-1}) and antioxidant activity were found under severe stress in the second experimental year. These findings indicate that water stress negatively affects yield but strongly stimulates secondary metabolite synthesis, thereby enhancing the nutritional and functional quality of the crop. Therefore, controlled or moderate water stress can be strategically used as a sustainable agricultural practice to improve the biochemical quality of red cabbage, particularly in water-limited farming systems. The results highlight the importance of effective irrigation management and adaptive strategies to sustain crop yield and quality under future climate change scenarios.

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Farklı Su Seviyelerinin Kırmızı Lahananın (Brassica oleracea f. rubra) Verim, Kalite ve Biyokimyasal Özellikleri Üzerine Etkisi

ÖZET
Bu çalışma, 2021–2022 yetiştirme sezonlarında Türkiye'nin Çanakkale ilinde tarla koşullarında yürütülmüş olup, kırmızı lahananın (Brassica oleracea f. rubra) verim, kalite ve biyokimyasal özellikleri üzerine farklı sulama düzeylerinin etkilerini araştırmıştır. Dört farklı sulama rejimi uygulanmıştır: %100 ($I_{1.0}$: tam sulama), %70 ($I_{0.7}$: hafif stres), %30 ($I_{0.3}$: şiddetli stres) ve %0 ($I_{0.0}$: yalnızca yağışa dayalı sulama). Bitkilerin su stresine karşı morfolojik, fizyolojik ve biyokimyasal tepkileri incelenmiş; özellikle flavonoid, antosiyanin ve fenolik bileşik birikimi gibi biyokimyasal özellikler üzerinde durularak adaptasyon kapasiteleri ve besin kaliteleri değerlendirilmiştir. Veriler, su açığı arttıkça verimin önemli ölçüde azaldığını göstermiştir. Tam sulama uygulamasında 2021 yılında 1514,2 g bitki^{-1} ve 2022 yılında 1252,6 g bitki^{-1} ile en yüksek verim

Tarımsal Yapılar ve Sulama

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Anahtar Kelimeler
Kırmızı lahana,
Su stresi,
Biyokimyasal bileşim,
İklim değişikliği]

elde edilmiştir; bu da yeterli su temininin verimlilik üzerindeki olumlu etkisini ortaya koymuştur. En düşük verim ise sulama yapılmayan (yağışa bağlı) koşullarda kaydedilmiştir. Ancak, verim değerlerinin aksine, su kısıtlaması biyoaktif bileşiklerin birikimini artırmıştır. Sulama azaldıkça flavonoid, fenolik, antosiyanin düzeyleri ve antioksidan aktivite (DPPH ve CUPRAC testleriyle ölçülen) anlamlı şekilde artmıştır. En yüksek antosiyanin içeriği (1,31 mg g^{-1}) ve antioksidan aktivite, şiddetli stres koşullarında belirlenmiştir. Bu bulgular, su stresinin verimi olumsuz etkilediğini, ancak ikincil metabolit sentezini güçlü bir şekilde uyararak ürünün besinsel ve fonksiyonel kalitesini artırdığını göstermektedir. Dolayısıyla, kontrollü veya orta düzeyde su stresi, özellikle suyun sınırlı olduğu tarımsal sistemlerde kırmızı lahananın biyokimyasal kalitesini artırmak amacıyla sürdürülebilir bir tarımsal uygulama olarak stratejik biçimde kullanılabilir. Elde edilen sonuçlar, gelecekteki iklim değişikliği senaryoları altında ürün verimi ve kalitesini sürdürebilmek için etkin sulama yönetimi ve adaptif stratejilerin önemini vurgulamaktadır.

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INTRODUCTION

The potential impacts of climate change on agriculture and water conservation have made ensuring food security increasingly important. Therefore, in this critical period characterized by diminishing water resources and rising food demand, studying the effects of water stress conditions on plants has become highly significant (Youssef et al., 2023). Climate change is expected to adversely affect the agricultural sector and agricultural development by altering vegetation patterns (Ektiren & Değirmenci, 2018). Plant production is increasingly exposed to environmental constraints that exert serious pressure on growth and development, thereby threatening global food production and food security (IPCC, 2014; Dewedar, 2021). Understanding the projected impacts of climate change on crop production is therefore essential for developing effective mitigation strategies (Kumar, 2016; Lipovac, 2018).

The quality and productivity of plants are directly influenced by environmental conditions. Adverse changes in environmental factors trigger morphological, physiological, and biochemical stress responses in plants, leading to significant yield losses (Levitt, 1980; Yıldız & Terzi, 2007). While unfavorable environmental conditions are defined as "stress," the ability of plants to adapt to these conditions is referred to as "stress resistance" (Levitt, 1980). Abiotic stresses such as drought, salinity, extreme temperatures, and chemical toxicity threaten agricultural lands worldwide and account for more than 50% reductions in crop productivity (Wang et al., 2004). Among these factors, drought stress is considered one of the most complex abiotic stresses, as it induces profound physiological and biochemical alterations in plants (Şahin et al., 2018).

Plant water uses and water relations must be understood within the framework of whole-plant interactions, particularly those associated with nutrient uptake and transport. The internal circulation of water and minerals through the xylem and phloem determines transpiration rates and water potential gradients, while also mediating hormonal signaling from roots under soil water deficit conditions. Water is indispensable for plant metabolism, as it participates directly in biochemical reactions and plays a central role in maintaining cellular structure and membrane integrity (Schulze, 1991).

Water stress has therefore become a major focus of plant science research, especially amid global warming, population growth, and dwindling freshwater resources (Yang et al., 2024). In plants, insufficient water availability disrupts the balance between transpiration and root water uptake, triggering morphological, physiological, and biochemical responses that ultimately result in yield and quality losses. Studies on Brassica oleracea cultivars have demonstrated that drought stress significantly affects plant morphology, nutritional composition, and biochemical properties (Yan, 2015; Beacham et al., 2017; Şahin et al., 2018; Yıldırım et al., 2019; Haghighi et al., 2020; Shinde et al., 2020). Generally considered a cool-season crop, cabbage exhibits reduced yield and quality under water-deficit conditions (Beacham et al., 2017; Yıldırım et al., 2019), while drought stress has also been

associated with increased antioxidant enzyme activities and accumulation of osmotically active compounds, particularly under saline environments (Şahin et al., 2018).

Red cabbage (Brassica oleracea var. capitata f. rubra), in particular, is distinguished by its high anthocyanin content and high yield potential per unit area (Wiczkowski et al., 2013; Ahmadiani et al., 2014). Research has shown that irrigation level plays a decisive role in red cabbage plant development and productivity, with excessive water stress negatively affecting morphology and yield, and that water availability exhibits a linear relationship with biomass accumulation (Yıldırım et al., 2019). Similarly, studies on cauliflower have demonstrated that the effects of water stress vary with developmental stage, being limited during early vegetative growth but more pronounced during reproductive development (Kuzucu et al., 2016).

Flavonoids and other phenolic compounds, owing to their antioxidant, antiallergic, antiplatelet, anti-inflammatory, antitumor, and antiviral properties, protect plant and human tissues against oxidative damage caused by free radicals. These compounds also regulate plant growth, development, and stress responses (Cheynier et al., 2013; Shahidi & Yeo, 2018). For instance, gallic acid exhibits anticancer activity by inhibiting cell proliferation, inducing apoptosis, and suppressing angiogenesis in various cancer types (Kaur et al., 2009; Veluri et al., 2006).

Red cabbage is a highly adaptable species rich in pigments and secondary metabolites, making it a valuable crop both nutritionally and pharmacologically. Identifying and characterizing these metabolites is essential for understanding plant stress physiology and for developing strategies to minimize yield and quality losses in agricultural systems increasingly constrained by water scarcity (Alper & Ozay, 2022).

The aim of this study is therefore to determine the biochemical changes occurring under water stress in the Integra red cabbage variety during the 90-day period from transplanting to harvest maturity. Specifically, the study evaluates the effects of water stress on anthocyanin content, phenolic compounds, and antioxidant capacity.

MATERIAL and METHOD

The field experiment was conducted at the Dardanos Agricultural Research Station of Çanakkale Onsekiz Mart University, located in Çanakkale (Dardanelles), Turkey. The site is situated at an elevation of 3 m above sea level, and the study was carried out during the 2021 and 2022 growing seasons. As plant material, the *Integra* red cabbage variety—reaching harvest maturity 90 days after transplanting was used. Each treatment was implemented under field conditions with three replications. Each replication consisted of four rows of plants, with 10 plants per row, for a total of 40 plants per replication. After eliminating border effects, 16 plants from the inner rows were sampled to evaluate yield, quality parameters, and biochemical changes. The soil at the experimental site was classified as clay loam, with a pH of 7.07 and an electrical conductivity (ECe) of 0.62 mS cm^{-1}. Each plot was treated with the same fertilizer dose (20-20-20 plus trace elements). The first fertilizer was applied at the time of seedling transplanting, and the second 20 days later, with the fertilizer evenly distributed across all treatments. Four irrigation treatments were applied:

- $I_{1.0}$ = the treatment in which the plant water requirement was fully met and named as Control (full irrigation),
- $I_{0.7}$ = the treatment in which 70% of the plant water requirement was met (mild stress),
- $I_{0.3}$ = the treatment in which 30% of the plant water requirement was met (severe stress),
- $I_{0.0}$ = rainfed irrigation (no water).

In the control treatment, evaporation measurements taken every 4 days from the Class-A pan in the experimental area were used to determine plant water consumption. The amount of irrigation water applied was calculated based on Class-A pan evaporation using the following equation:

$I = Epan \times Kp \times Kc \times A$

where I is the irrigation water amount (mm), Epan is the cumulative pan evaporation (mm), Kp is the pan coefficient, Kc is the crop coefficient, and A is the plot area (m^2). In this study, the pan coefficient (Kp) was set to 0.81, and the crop coefficients (Kc) were taken as kc1=0.55, kc3=1.03, and kc4=0.92 for Canakkale, as given in Anonymous (2017), depending on the growth stage.

For the full irrigation treatment ($I_{1.0}$), 100% of the calculated irrigation water was applied, while 70% and 30% of this amount were applied in $I_{0.7}$ and $I_{0.3}$ treatments, respectively. Soil moisture content was determined gravimetrically at two soil depths (0–30, 30–60cm). Based on these values, the irrigation duration was calculated, and irrigation water was applied to the plants' root zones using a drip irrigation system. Additionally, soil samples were taken every week using the gravimetric method. Based on undisturbed soil samples collected prior to the experiment, field capacity, wilting point, and available water-holding capacity of the experimental site were determined using a PF device.

After transplanting, all plots received equal irrigation until the seedlings were fully established. Once the plants had adapted to the soil, the water restriction treatments were initiated and maintained until harvest.

Yield and quality parameters:

Crown height and diameter were measured with a caliper (accuracy 0.01 mm). Yield per unit area and per plant were determined using an electronic balance with 0.01 g precision. Soluble solid content was determined using a digital hand refractometer (Atago PAL 1 model).

Analysis of some biochemical properties

Analysis of Antioxidant Content

Determined using DPPH and CUPRAC methods.

DPPH Method:

The methods of Brand-Williams et al. (1995) and Ak & Türker (2018) were used to analyze the effects of the extracts on 1,1-diphenyl-2-picrylhydrazyl (DPPH). 1 mg mL^{-1} of the samples was diluted in methanol and mixed with DPPH solution. After thorough mixing, they were left to react at room temperature for 30 minutes. Using a UV-Vis spectrophotometer (Thermo Aquamate), absorbance was measured at 515 nm. The following equation was used to estimate the DPPH percentage, the concentration of compounds inhibiting 50% of total DPPH radicals (IC_{50} inhibition value). Lower IC_{50} values indicate higher antioxidant activity. Butylated hydroxytoluene (BHT) was included in the experiment as a positive control.

$$DPPH\ (\%) = [(A_{control}\text{-}A_{sample})/A_{control}] \times 100$$

CUPRAC Method:

The copper (II) ion reducing antioxidant capacity (CUPRAC) test, developed by Apak et al. (2004), is based on the electron transfer ability of plant extracts to reduce Cu^{2+} ions. For this, 40 µL of extract was mixed with 1 mL of 0.01 M $CuCl_2$, 1 mL of 7.5×10^{-3} neocuproine, 1 mL of 1 M ammonium acetate buffer (pH 7), and 1060 µL of distilled water, making a final volume of 4100 µL. Absorbance was measured at 450 nm after incubation at 20 °C for 30 minutes. Results for antioxidant activity were reported as Trolox equivalents (mg Trolox 100 g^{-1} fresh weight) based on a standard calibration curve.

Total Phenolic Content (Folin–Ciocalteu Method)

The total phenolic content of the extracts was determined using the Folin-Ciocalteu reagent method as described by Türker et al. (2012) and developed by Djeridane et al. (2006). 0.2 mL of 500 mg mL^{-1} of the original plant extract was mixed and vortexed with 0.5 mL of distilled water and 0.5 mL of Folin-Ciocalteu reagent. After one minute, 0.8 mL of sodium carbonate solution (7.5%) was added to the mixture and shaken intermittently for 30 minutes. Absorbance readings were obtained at 760 nm with a UV-Vis spectrophotometer. Total phenolic content was reported as mg gallic acid equivalents per 100 g fresh weight (mg GAE 100 g^{-1} FW).

Anthocyanin Content

The total anthocyanin content of the plant extracts was determined using the pH differential method described by Giusti & Wrolstad (2001) and Benvenuti et al. (2004). 0.025 M potassium chloride and 0.4 M sodium acetate were used as buffer systems for anthocyanin extraction. Extracts (1 mL) obtained from each red cabbage sample were diluted with pH 1.0 buffer, and the process was repeated with pH 4.5 buffer. The solutions were transferred to 100 mL test tubes, mixed, and allowed to equilibrate at room temperature for 20 minutes. Absorbance was measured at 520 and 700 nm with the abovementioned spectrophotometer.

To estimate the anthocyanin content, the following equations were used:

$$A = (A520 - A700)\ pH1.0 - (A520 - A700)\ pH4.5$$

$$\text{Monomeric anthocyanin pigment (mg/L)} = (A \times MW \times DF \times 1000) / (\varepsilon \times 1)]$$

In the equation, *A* stands for 'absorbance of the diluted sample', *MW* for 'molecular weight', *DF* for 'dilution factor', ε for 'molar absorptivity'. MW = 449.2 and ε = 26,900 were used for cyanidin-3-glucoside.

Statistical Analysis

Statistical analyses were performed using Duncan's Multiple Range Test. Statistics were considered significant at the 5% probability level ($p < 0.05$). Data analysis was done using the SPSS statistical software package.

RESULTS and DISCUSSION

Irrigation Water Amount Applied According to Different Irrigation Treatments

The amount of water applied for irrigation during the cultivation period (2021 and 2022) is presented in Table 1. Climatic parameters recorded by the State Meteorological Service during 2021-2022are presented in (Table 2 (MGM, 2021-2022).

Table 1. Amounts of irrigation water applied in the experimental treatments during 2021 and 2022.
Tablo 1. 2021–2022 yıllarında deneme konularına uygulanan sulama suyu miktarları.

Treatment (mm)	2021	2022
$I_{1.0}$	433.0	495.0
$I_{0.7}$	303.1	346.5
$I_{0.3}$	129.9	148.5
$I_{0.0}$	42.0	56.0

Table 2. Climatic parameters for 2021 and 2022.
Tablo 2. 2021 ve 2022 yıllarına ait iklim parametreleri.

Month	Average Temperature (°C)		Rain (mm)		Evaporation (mm)	
	2021	2022	2021	2022	2021	2022
August	28.3	26.2	0.0	111.6	479.2	491.9
September	23.1	22.0	8.9	1.2	359.7	400.5
October	18.1	17.6	75.9	0.6	206.0	301.3
November	15.8	14.8	26.7	33.2	156.2	276.8
December	12.2	11.5	121.0	43.2	211.1	209.2

Yield and Quality Parameters

The yield and quality parameters obtained in 2021 (Table 3) and 2022 (Table 4) demonstrate how irrigation constraints influenced red cabbage yield and quality. Red cabbage is considered moderately tolerant to water stress (Nortje et al., 1996), and autumn–winter cultivation is typically supported by supplemental irrigation (Xu & Leskovar, 2014). Previous studies reported significant increases in cabbage yield with combined water and nitrogen applications (Sanchez et al., 1994). Wurr et al. (2002) found that broccoli plants subjected to full or near-full irrigation treatments had greener leaves and higher turgor pressure, whereas severe water stress conditions (-0.6 MPa) caused morphological deformation and yield reduction.

In the first year of the experiment (Table 3), the highest average head weight was observed in the control plants that received 100% irrigation water. Among the water-restricted treatments, the average head weights were 1076.0 g and 942.7 g for the 70% and 30% irrigation treatments, respectively, with no statistically significant difference between them. The lowest average head weight was observed in the 0% irrigation (no-water) treatment.

Regarding yield amounts, one of the most notable results from the first year was the 554.3 g yield recorded in the non-irrigated treatment. Tiwari et al. (2003) reported that the seasonal water requirement of cabbage averages around 400 mm, and under full irrigation via drip systems, the maximum yield was 106 t ha^{-1}. Furthermore, with 20% and 40% water savings, yields were 105.5 t ha^{-1} and 101.5 t ha^{-1}, respectively.

Table 3. Yield and quality parameters of experimental treatments during the 2021 growing season.
Tablo 3. 2021 yetiştirme sezonunda deneme konularının verim ve kalite parametreleri.

Treatment	Head Weight (g)	Diameter x (cm)	Diameter y (cm)	Height (cm)	Circumference (cm)	Leaf Number	SSC*	Dry Weight (%)
$I_{1.0}$	1514.2±32.77a	12.8± 1.2a	12.59±1.58a	16.5±2.85a	45.7 ±3.65 a	29.4±4.20a	8.77 ns	9.2±1.80a
$I_{0.7}$	1076.0±22.01b	10.8±1.59b	10.43±2.25b	13.9±1.98b	38.7 ± 4.38 b	27.4±3.82ab	9.22 ns	8.9±1.72a
$I_{0.3}$	942.7±21.54b	10.9±1.82b	10.69±2.02b	14.6±1.82b	40.1 ± 3.84 b	25.3±3.55ab	9.36 ns	10.8±2.05a
$I_{0.0}$	554.3± 15.88c	8.78±0.93c	8.82± 1.84c	11.9±0.96c	31.9 ± 3.65 c	24.6± 2.88 b	10.4 ns	14.3±1.94b
p	0.010	0.010	0.022	0.025	0.021	0.035	0.850	0.030

*SSC –Soluble solid content
(Means bearing different letters within the same column are significantly different at $p<0.05$; ns = not significant.)

When the quality parameters such as head diameter (x and y), height, circumference, and number of leaves measured after harvest were evaluated, it was observed that these values decreased with decreasing irrigation water levels (Table 3). The reduction in red cabbage head size directly affected its weight and, consequently, its yield.

The increase in soluble solid content (SSC) and dry matter under water stress conditions can be explained not only by the concentration effect resulting from reduced water content in plant tissues, but also by physiological adaptation mechanisms. Under water deficit, plants tend to accumulate osmolytes such as soluble sugars, proline, and other compatible solutes to maintain cell turgor and metabolic activity. This osmotic adjustment contributes to increases in SSC and dry matter content, reflecting the plant's adaptive response to water stress. The dry weight percentages of the harvested red cabbage heads were calculated. Statistical analysis showed that the dry weight percentages of the control (100%), 70%, and 30% irrigation treatments were similar, while the non-irrigated (0%) treatment formed a statistically distinct group (Table 3).

The morphological parameters of red cabbage under water stress treatments during the 2022 season are given in Table 4. The results showed patterns similar to those observed in the first year. The highest yield was obtained from the 100% irrigation (full irrigation) treatment. Among the water-restricted treatments, a decrease in yield was observed in plants exposed to mild (70%) and severe (30%) water stress; however, the difference between these two treatments was not statistically significant. The lack of statistically significant differences between the I0.7 and I0.3 treatments for certain parameters may be attributed to red cabbage's relatively high tolerance to moderate water stress. In addition, climatic conditions during the growing seasons, particularly rainfall distribution and temperature patterns, may have partially mitigated the effects of water deficit. As a result, plants under both deficit irrigation levels may have exhibited similar physiological responses, leading to comparable yield and quality outcomes. The lowest yield was recorded in the 0% irrigation treatment. In the second year, red cabbages from the non-irrigated treatment had head weights below 100 g. While marketable-sized heads were obtained from the non-irrigated plots in the first year, in the second year only very small heads were harvested. This difference can be attributed entirely to variations in climatic parameters. In 2021, the high autumn rainfall in Çanakkale (Table 2) compensated for much of the irrigation water requirement of red cabbage. Therefore, it was determined that under the 2021 conditions, even in the non-irrigated (0%) treatment, marketable red cabbage heads could be obtained. The pronounced differences in yield between the 2021 and 2022 growing seasons, particularly under rainfed conditions (I0.0), can be explained not only by total rainfall amounts but also by the temporal distribution of precipitation. In 2021, the substantial rainfall recorded in October (75.9 mm) likely coincided with the critical head-formation stage of red cabbage, providing an essential water supply and supporting plant development. In contrast, despite higher total rainfall during certain months in 2022, the lack of well-distributed precipitation during key growth stages may have limited plant performance. This finding highlights that not only the quantity but also the timing of rainfall is crucial for crop productivity. Moreover, this situation underscores that, under climate change scenarios, irregularities in precipitation patterns—rather than solely temperature increases—can have dramatic impacts on crop yield and agricultural sustainability.

Table 4. Yield and quality parameters of experimental treatments during the 2022 growing season.
Tablo 4. 2022 yetiştirme sezonunda deneme konularının verim ve kalite parametreleri.

Treatment	Head Weight (g)	Diameter x (cm)	Diameter y (cm)	Height (cm)	Circumference (cm)	Leaf Number	SSC*	Dry Weight (%)
$I_{1.0}$	1252.6±25.52a	14.0±1.42a	13.96±2.35a	15.3±1.09a	41.96±3.25a	31.4±3.80a	8.77±0.54b	9.26±1.35b
$I_{0.7}$	930.4±21.48 b	11.7±1.86 a	11.11±2.80a	14.0±1.96a	38.00 ± 3.02a	33.7±1.57a	9.00±0.74b	10.6±1.68b
$I_{0.3}$	841.6±15.24 b	10.2±0,95a	10.27±1.88a	12.8±0.52a	37.12 ± 2.52 a	31.3±1.86a	9.83±0.82b	19.1±1.86b
$I_{0.0}$	90.7 ± 12.68 c	4.83±0,62b	4.87 ± 0.52 b	6.28±0.64b	16.95 ± 1.28 b	25.4±0.95b	13.0±1.02a	24.8±2.18±a
p	0.010	0.028	0.025	0.030	0.025	0.020	0.040	0.025

*SSC –Soluble solid content
(Means bearing different letters within the same column are significantly different at $p<0.05$; ns = not significant.)

The quality parameters obtained from the second year of the experiment are presented in Table 4. It was determined that red cabbage head size decreased with reduced irrigation water across the different treatments. Head diameter, height, circumference, and number of leaves all declined as irrigation water levels decreased. According to the statistical analysis, the differences among heads obtained from the control, 70%, and 30% irrigation treatments were not statistically significant, while the non-irrigated (0%) treatment formed a separate statistical group distinct from the others.

In contrast to the other quality parameters, the soluble solid content (SSC) and dry weight percentages increased as the amount of irrigation water decreased. Thus, while physical growth parameters decreased with water restriction, SSC and dry matter ratios increased, indicating higher concentrations of soluble and structural compounds under water-stress conditions.

Biochemical Responses to Water Stress

The biochemical parameters determined after harvest at the end of the 2021 growing season are presented in

Tables 5 and 6.

Organic acids play significant roles as flavor enhancers and natural antimicrobials. They also influence vegetable color, as many pigments act as natural pH indicators (Sinha et al., 2011). According to Fortier et al. (2010,) phenolic compounds increased in water-stressed broccoli plants. Similarly, Oh et al. (2009) reported that exposure of plants to biotic and abiotic stress can enhance the synthesis of bioactive compounds. Elavarasan et al. (2015) found that the ascorbic acid content of cabbage varies depending on the growing environment: cabbages cultivated in high-altitude regions had significantly higher ascorbic acid content (42.6 mg 100 g^{-1}) compared to those grown in lowland areas (12.92 mg 100 g^{-1}).

In the first year of the study, flavonoid contents in red cabbage under water restriction treatments ranged from 0.25 to 0.54 mg g^{-1} at harvest. Results indicated that flavonoid levels increased as irrigation water decreased.

Secondary metabolites such as ascorbic acid, benzoic acids, carotenoids, cinnamic acids, flavonoids, folic acid and tocopherols are produced by plants as antioxidants for their own nutritional and protective needs (Ghasemzadeh et al., 2010). After two years of research, it was confirmed that flavonoid content increased in red cabbage plants exposed to water stress.

The total phenolic content also increased with the degree of water restriction in 2021. Statistical analyses revealed that each irrigation treatment belonged to distinct significance groups, indicating clear and meaningful differences. According to the results of phenolic content analysis, the highest phenolic accumulation (1.823 mg g^{-1}) was found in the non-irrigated (0%) treatment, while the lowest accumulation occurred in the fully irrigated (100%) control.

Leja et al. (2010) reported that the total phenolic content varied greatly among four red cabbage cultivars and two double-haploid (DH) lines (one white, one red). Although there was no significant difference between red and white cabbage types overall, significant variation was observed among the red cabbage cultivars. In their study, total phenolic contents ranged from 209.6 to 288.3 mg 100 g^{-1} FW in the first year and 116.8 to 248.8 mg 100 g^{-1} FW in the second year.

Table 5. Biochemical parameter results for 2021.
Tablo 5. 2021 yılı biyokimyasal parametre sonuçları.

Treatment	Flavonoid	Phenolic	CUPRAC	DPPH	Anthocyanin
$I_{1.0}$	0.25 ± 0.02 b	0.726 ± 0.08 d	0.72 ± 0.06 d	2.14 ± 0.14 a	1.63 ± 0.24 b
$I_{0.7}$	0.32 ± 0.03 ab	0.996 ± 0.06 c	0.99 ± 0.05 c	1.72 ± 0.20 b	1.96 ± 0.18 a
$I_{0.3}$	0.35 ± 0.03 ab	1.244 ± 0.12 b	1.24 ± 0.08 b	1.43 ± 0.18 c	2.0 ± 0.22 a
$I_{0.0}$	0.54 ± 0.08a	1.823 ± 0.15 a	1.82 ± 0.12 a	1.08 ± 0.09 d	2.2 ± 0.25 a
p	0.010	0.001	0.002	0.002	0.025

In the second year of the study (2022), several biochemical analyses were conducted on the samples collected from each treatment, as shown in Table 7. It was observed that flavonoids, phenolic compounds, antioxidant levels (CUPRAC and DPPH), and anthocyanins, the pigments responsible for the red coloration in cabbage, increased as irrigation water decreased.

The increases observed in flavonoids, total phenolic content, anthocyanins, and antioxidant activity (DPPH and CUPRAC) under water stress conditions indicate a strong physiological relationship among these parameters. In particular, the substantial increase in anthocyanin content under severe stress conditions may be a major contributor to the enhancement of antioxidant capacity. For instance, the nearly threefold increase in anthocyanin content under severe stress conditions can be associated with the approximately 2.5-fold increase in CUPRAC values, as anthocyanins are known to be powerful antioxidants. These results suggest that the enhancement of antioxidant activity is largely driven by the accumulation of phenolic compounds, especially anthocyanins, as part of the plant's defense mechanism against oxidative stress.

When all parameters were evaluated together, it was determined that when the water requirements of red cabbage were not fully met, the plant increased the synthesis of biochemicals as a response to water stress.

Table 6. Biochemical parameter results for 2022.
Tablo 6. 2022 yılı biyokimyasal parametre sonuçları.

Treatment	Flavonoid	Phenolic	CUPRAC	DPPH	Anthocyanin
$I_{1.0}$	0.47 ± 0.05 b	0.84 ± 0.15b	1.38 ± 0.22 b	2.81 ± 0.52 a	0.5 ± 0.01 c
$I_{0.7}$	0.52 ± 0.05 b	0.84 ± 0.12 b	1.45 ± 0.35 b	2.64 ± 0.68 b	0.78 ± 0.03 b
$I_{0.3}$	0.55 ± 0.08 b	1.23 ± 0.09 b	1.76 ± 0.28 b	2.59 ± 0.42b	1.20 ± 0.08 a
$I_{0.0}$	0.86 ± 0.06 a	1.76 ± 0.26a	2.20 ± 0.45 a	2.55 ± 0.55 b	1.31 ± 0.10 a
p	0.025	0.020	0.018	0.020	0.032

According to the research findings, statistically significant differences were also observedine anthocyanin content. The highest anthocyanin level (1.31 mg g^{-1}) was observed in the non-irrigated (0%) treatment, consistent with the results for other biochemical parameters. The lowest anthocyanin content was found in red cabbages from the fully irrigated (100%) control plots.

When all biochemical compounds were considered together, it was determined that the reduction in irrigation water led to a significant increase in the synthesis of these substances within the plant. Among them, anthocyanins showed the highest proportional increase, approximately threefold.

Therefore, water restriction in red cabbage, particularly at the 70% irrigation level, can be considered an effective strategy for promoting anthocyanin accumulation, thereby enhancing its biochemical composition and antioxidant capacity.

CONCLUSION

This study demonstrated how climate change–driven increases in temperature and declines in precipitation affect red cabbage growth, yield, and biochemical composition. Over the past 30 years, the study region has experienced a temperature rise of 1.5–2°C and a 22–28% reduction in annual rainfall, underscoring the growing importance of efficient irrigation management.

Across the two-year experiment, reduced irrigation consistently decreased yield while enhancing biochemical constituents such as flavonoids, phenolics, antioxidants, and anthocyanins. Under full irrigation, mean head weights reached 1514.2 g in 2021 and 1252.6 g in 2022, whereas severe water stress lowered yields by up to 40%. Despite this decline, controlled water limitation promoted the synthesis of health-promoting compounds, indicating a trade-off between yield and biochemical quality.

Water stress stimulated the accumulation of flavonoids and anthocyanins, which contribute to both antioxidant capacity and plant stress tolerance. These findings suggest that a moderate water deficit, corresponding to the 70% irrigation regime ($I_{0.7}$) may be a balanced strategy, especially in water-scarce regions. This level of stress improved nutritional and functional quality while avoiding the substantial yield losses observed under more severe deficit treatments. The $I_{0.7}$ irrigation treatment appears to represent a balanced strategy between yield and quality parameters. Although the highest biochemical responses were generally observed under more severe water stress ($I_{0.3}$), this treatment also resulted in a considerable reduction in yield. In contrast, $I_{0.7}$ provided significant improvements in quality-related parameters compared to full irrigation ($I_{1.0}$), while limiting yield losses to a moderate level. For example, anthocyanin content increased from 1.63 to 1.96 in 2021, while yield decreased from 1514 g to 1076 g. This indicates that $I_{0.7}$ can be considered an effective irrigation strategy for achieving yield–quality optimization, particularly under conditions of limited water availability.

Overall, the results highlight the potential of deficit irrigation as a climate-smart practice in water-limited environments. Implementing moderate, regulated water stress can reduce irrigation demand, maintain acceptable yield levels, and enhance biochemical quality. In the context of ongoing climate change and increasing water scarcity, adaptive irrigation strategies such as these will be essential for sustaining productivity, improving crop quality, and ensuring food security.

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Contribution Rate Statement Summary of Researchers

The authors declare that they have contributed equally to the article.

Conflict of Interest

We declare no conflict of interest between us as the article's authors.

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