BIOLOGICA NYSSANA
17 (1) June 2026:
DOI: 10.46793/BiolNyss.17.1.9G

The deficit irrigation affects productivity, essential oil content, and phenolic compounds accumulation in basil varieties

Original Article

Erdinç Günay
Fruit Research Institute, Isparta, Türkiye
ORCID: 0009-0000-3352-3009
erdinc.gunay@tarimorman.gov.tr (Corresponding author)

Melih Aydinli
Fruit Research Institute, Isparta, Türkiye
ORCID: 0000-0002-1166-5791

Received: September 11, 2025
Revised: March 05, 2026
Accepted: March 15, 2026

Abstract:

In recent years, the increasing severity of drought has emphasized the importance of deficit irrigation (DI) for sustainable agricultural production. Basil (*Ocimum basilicum*), a plant with high water requirements, necessitates meticulous evaluation under conditions of limited water availability. This study examined the morphological, physiological, and biochemical responses of two commercial basil varieties, "Moonlight" and "Midnight," to DI applications (DI_{100} as the control, DI_{80}, DI_{60}, and DI_{40}) at two different harvest stages. The highest essential oil content in both varieties at both harvest stages was obtained under the DI_{80} treatment. Linalool content decreased, whereas methyl chavicol content increased with increasing water stress. Notably, total phenolic and flavonoid content significantly increased in the Moonlight under DI_{60}. Furthermore, the Moonlight exhibited higher drought tolerance, likely due to the activation of non-enzymatic antioxidant mechanisms. The study found that irrigating at 60% of field capacity positively affected the examined characteristics of the basil.

Key words:
Basil, deficit irrigation, essential oil content, phenolic compounds, antioxidant activity

Apstrakt:

Deficitarno navodnjavanje utiče na produktivnost, sadržaj etarskog ulja i akumulaciju fenolnih jedinjenja kod sorti bosiljka

Poslednjih godina, sve izraženija ozbiljnost suše naglasila je značaj deficitarnog navodnjavanja (DI) za održivu poljoprivrednu proizvodnju. Bosiljak (*Ocimum basilicum*), biljka sa visokim potrebama za vodom, zahteva pažljivu procenu u uslovima ograničene dostupnosti vode. Ova studija je ispitivala morfološke, fiziološke i biohemijske odgovore dve komercijalne sorte bosiljka, „Moonlight" i „Midnight", na primenu deficitarnog navodnjavanja (DI_{100} kao kontrola, DI_{80}, DI_{60} i DI_{40}) u dve različite faze berbe. Najveći sadržaj etarskog ulja kod obe sorte, u obe faze berbe, dobijen je pri tretmanu DI_{80}. Sadržaj linalola se smanjivao, dok se sadržaj metil-čavikola povećavao sa porastom vodenog stresa. Značajno je da su se ukupni sadržaj fenolnih jedinjenja i flavonoida značajno povećali kod sorte Moonlight pod tretmanom DI_{60}. Pored toga, sorta Moonlight pokazala je veću toleranciju na sušu, verovatno zahvaljujući aktivaciji neenzimskih antioksidativnih mehanizama. Studija je pokazala da navodnjavanje na 60% poljskog vodnog kapaciteta pozitivno utiče na ispitivane karakteristike bosiljka.

Ključne reči:
Bosiljak, deficitarno navodnjavanje, sadržaj etarskog ulja, fenolna jedinjenja, antioksidativna aktivnost

Introduction

Water scarcity, considered the most significant environmental stressor affecting agricultural production worldwide (Cattivelli et al., 2008), has become increasingly prevalent in many regions due to global climate change. In the Mediterranean region, in particular, areas allocated to irrigated agriculture are increasingly affected by severe droughts linked to climate change. Furthermore, agriculture in the Mediterranean region consumes substantial amounts of water, and effective irrigation management could mitigate the loss of freshwater resources (Hajlaoui et al., 2022). Given current water scarcity, a potential strategy to reduce water consumption in irrigated agriculture is deficit irrigation, in which less water is supplied than the full crop requirement (Abdelfattah & Mostafa, 2024). The objective of this approach is

© 2026 Günay & Aydinli. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and build upon your work non-commercially under the same license as the original.

to maximise yield and product quality by making the most efficient use of limited water resources.

Herbaceous plants typically contain 85–90% water by weight, which is essential for growth, development, and metabolic processes. However, providing water at suboptimal levels through deficit irrigation (DI) subjects plants to drought stress, a major limiting factor for agricultural productivity worldwide (Abdelfattah & Mostafa, 2024). Drought stress can adversely affect numerous physiological and biochemical processes, leading to significant reductions in the growth, development, and yield of various economically important crops, such as field crops, fruit trees, and aromatic plants (Chen et al., 2022; Carvalho et al., 2023; Hassan et al., 2025).

Basil (*Ocimum basilicum* L.) is an erect, herbaceous annual plant belonging to the Lamiaceae family. It is one of the most important aromatic plants and typically grows to 30–60 cm in height (Gürgan & Adiloğlu, 2021; Fathi et al., 2023). It can be consumed fresh or dried, and its essential oils are widely used in perfumery, cosmetics, pharmaceuticals, and agriculture (Bekhradi et al., 2015; Dorni et al., 2017; Acosta-Pérez et al., 2020). However, its primary economic value lies in its use as a seasoning and aromatic herb, with fresh leaves being particularly valuable (Bekhradi et al., 2015; Carvalho et al., 2023). Basil exhibits significant morphological diversity, with notable variation in leaf and flower size, shape, colour, and aroma (Radácsi et al., 2020). Furthermore, basil is a rich source of various biochemical compounds, and its secondary metabolite and essential oil profiles differ significantly among chemotypes. For instance, Telci et al. (2006) reported essential oil content ranging from 0.4 to 1.5 mL 100 g^{-1} in local cultivars. To date, around 140 different volatile compounds have been identified in basil (Hiltunen & Holm, 2006). The major constituents of the essential oil include linalool, methyl chavicol, 1,8-cineole, methyl eugenol, limonene, and citral (Simon et al., 1999; Kumar et al., 2018; Kalamartzis et al., 2020). Phytochemical analyses further reveal that basil is also rich in other secondary compounds, including total phenolics, flavonoids, flavones, and anthocyanins (Dhama et al., 2021). While the biosynthesis of these secondary metabolites is primarily governed by genetic factors, environmental conditions can also significantly influence their content (Amani et al., 2023; Qasem et al., 2023). Additionally, the concentration and composition of these compounds may vary with harvest time (Rahimi et al., 2023).

Like many other crops, basil requires an adequate water supply for optimal production and undergoes various morphological, physiological, and biochemical changes under water deficit conditions. For example, Ekren et al. (2012) observed reductions in plant height and in fresh and dry herbaceous yields under deficit irrigation. Similarly, Damalas (2019) reported decreases in plant weight, height, leaf relative water content, and chlorophyll index in basil subjected to limited irrigation. Sarayer et al. (2023) reported consistent findings, documenting reductions in plant height, dry leaf yield, and SPAD values under DI conditions. Changes in basil under drought stress are not limited to morphological traits or photosynthetic pigments: variations in essential oil content and composition, as well as in non-enzymatic antioxidant levels, have also been reported. Radácsi et al. (2020) found that drought stress resulted in genotype-dependent increases in essential oil yield, with the contents of 1,8-cineole, linalool, and α-cadinol either increasing or decreasing. In contrast, Sarayer et al. (2023) found that linalool and 1,8-cineole contents decreased under limited irrigation. As an important source of polyphenols, basil has also been shown to increase in total phenolic and flavonoid content under DI (Zulfiqar et al., 2021; Rahimi et al., 2023).

Adequate irrigation is essential for maximising the yield and quality of basil cultivation (Günay, 2025). Nevertheless, deficit irrigation is increasingly recognised as a vital strategy for conserving freshwater resources and promoting agricultural sustainability. Given basil's high water requirements, it is important to understand how the plant responds to water-deficit conditions in terms of yield and quality to ensure sustainable production. Furthermore, since basil can be harvested multiple times during a growing season, it is important to determine whether environmental factors can lead to variations in yield and quality between successive harvests. The present study, therefore, aims to evaluate how different basil cultivars respond to deficit irrigation, determine the extent to which yield and quality are affected, and identify potential variations between harvest periods.

Materials and methods

Plant materials, growing conditions and deficit irrigation treatments

The study was conducted on *O. basilicum* L., using the green-leaved Moonlight and the purple-leaved Midnight cultivars, at the Fruit Research Institute located in Eğirdir district, Isparta province (37°54'1.22" N, 30°44'0.43" E), at an altitude of approximately 922 m above sea level. The study was conducted during the 2021 growing season under high tunnel conditions. Seeds of the basil (*O. basilicum*) varieties "Moonlight" and "Midnight" were obtained from Anadolu Seed Company. They were sown in early April into pots (42 mm

diameter, 60 mm depth) filled with peat:perlite:soil (2:1:1). Uniform seedlings were transplanted on May 20 into 18 L pots containing a peat:sand:soil mixture. Four irrigation regimes were applied: DI_{100} (100% field capacity, control), DI_{80} (80% field capacity), DI_{60} (60% field capacity), and DI_{40} (40% field capacity). As only leaves were evaluated, developing generative organs were removed throughout the experiment. Since basil is a multi-harvest crop, two harvests were performed. Deficit irrigation treatments started 10 days before each harvest and continued until harvest, while plants were otherwise irrigated at field capacity. Harvesting was carried out by cutting above the first pair of true leaves. For both harvests, mature leaves were sampled for essential oil and biochemical analyses. Samples were collected homogenously, frozen, and stored at –80 °C until analysis. The experiment was arranged in a randomized design with three replicates and five plants per replicate, for a total of 120 potted basil plants.

Morpho-physiological traits

Plant height (cm), canopy diameter (mm), fresh plant weight (g), fresh leaf weight (g), and chlorophyll content (SPAD value; SPAD-502, Konica Minolta, Tokyo, Japan) were evaluated. Plant height, canopy diameter, and SPAD values were measured immediately before each harvest. Fresh plant weight was recorded directly after harvest, while fresh leaf weight was determined by separating the leaves from stems following plant weight measurement.

Relative water content

Before harvest, fully developed, mature leaves were collected, and their fresh weights (FW) were recorded. Subsequently, the leaves were immersed in distilled water for 24 hours, and their weights were measured again. The leaves were then dried at 72 °C for 48 hours, and their dry weights (DW) were measured again. RWC% was calculated using the formula provided below (Barrs & Weatherley, 1962).

RWC (%) = 100*(FW-DW)/(TW-DW).

Essential oil content

Dried leaf samples were subjected to hydrodistillation for 150 min using a Clevenger-type apparatus. The volume of essential oil collected in the graduated burette of the system was recorded, and the results were expressed as mL 100 g^{-1} dry weight.

Composition of essential oil

Essential oil components were analyzed at the West Mediterranean Agricultural Research Institute using GC/GC-MS (Gas Chromatography, Agilent 7890A coupled with mass detector, (Agilent 5975C) equipped with a capillary column (HP Innowax Capillary; 60.0 m × 0.25 mm × 0.25 µm). Essential oil samples were diluted 1:100 with hexane. Helium was used as the carrier gas at a flow rate of 0.8 mL min^{-1}, and samples were injected with a split ratio of 40:1 at 1 µL. The injector temperature was maintained at 250 °C. The column temperature program was set as follows: 60 °C for 10 min, increased from 60 °C to 220 °C at 4 °C min^{-1}, and held at 220 °C for 10 min, resulting in a total analysis time of 60 min. For the mass detector, the scan range was m/z 35–450 with electron impact ionization at 70 eV. Identification of essential oil components was performed using WILEY and OIL ADAMS libraries. Component percentages were determined by the FID detector, and component identification was performed by the MS detector.

Total phenolic compounds

The determination of total phenolic compounds (TPCs) was carried out using the method of Singleton and Rossi (1965). A 0.5 g sample of freeze-dried leaves was homogenized with 5 mL of 80% MeOH containing 1% HCl at room temperature for 15 min using a mechanical shaker at 200 rpm. The mixture was then centrifuged at 3 000 rpm at 22 °C. An aliquot of 0.2 mL from the upper phase was mixed with 1.5 mL of Folin reagent and 1.5 mL of sodium bicarbonate, and the absorbance was read at 765 nm. A standard solution of gallic acid with different concentrations was used, and the results were expressed as mg GAE g^{-1} DW (dry weight).

Total flavonoid content

The Total flavonoid content (TFC) in the leaves was measured according to the method of Zhishen et al. (1999). Briefly, 1 g of freeze-dried leaf sample was extracted with an 80% MeOH solution. From the extracted plant material, 1 mL was taken and diluted with 4 mL of distilled water. Immediately after, 5% $NaNO_2$ was added, and after 5 min, $AlCl_3$ was introduced. At the 6-min mark, 2 mL of 1 M NaOH was added, and the mixture was diluted to 10 mL with distilled water. Rutin was used as a standard, and the results were expressed as mg RUTIN g^{-1} DW by measuring absorbance at 510 nm.

Statistical analysis

The study was conducted using a factorial experimental design in randomized complete blocks with three replications, and five plants were used per replication. Statistical analyses were performed using JMP 11 software. Differences between treatments were determined using the LSD Multiple Comparison Test. Significant differences were accepted at $p<0.05$, and represented by different letters.

Results and discussions

Effects of deficit irrigation on growth parameters in basil varieties

During the first harvest period, deficit irrigation had a negative impact on all growth parameters except plant height (**Tab. 1**). During the second harvest period, variations in growth parameters were observed across varieties. Canopy diameter significantly decreased under the DI_{60} and DI_{40} treatments in both basil varieties during the first harvest. However, no statistically significant reduction was observed under the DI_{80} treatment. In the second harvest period, a significant difference among treatments was observed only under the DI_{60} treatment. When fresh plant weight was examined, the Midnight variety was more affected by deficit irrigation treatments than the Moonlight variety. The fresh plant weight of the Moonlight variety significantly decreased under the DI_{40} (189.9 g) treatment during the first harvest period. In the Midnight variety, significant differences were observed between the DI_{60} (161.28 g) and DI_{40} (91.68 g) treatments and the control plants during the first harvest period, while all deficit irrigation treatments showed significant differences during the second harvest period. Another growth parameter, fresh leaf weight, was significantly affected by deficit irrigation treatments in the Moonlight variety during the first and second harvest periods. Fresh leaf weight notably decreased under the DI_{60} and DI_{40} treatments compared to the control plants in both harvest periods. In the Midnight variety, a reduction in fresh leaf weight was observed under deficit irrigation treatments in both harvest periods, with significant differences detected between the DI_{60} and DI_{40} treatments and the control plants. In the Moonlight cultivar, dry plant weight significantly decreased under both DI_{60} and DI_{40} treatments in both harvest periods. However, no statistical difference was found between the DI_{80} treatment and the control plants. In the Midnight cultivar, dry plant weight was significantly reduced across all deficit irrigation treatments. When examining dry leaf weight, similar trends to those observed for dry plant weight were observed. In the Moonlight cultivar, significant differences were identified between the DI_{60} and DI_{40} treatments and the other treatments in both periods. In the Midnight cultivar, statistically significant differences among treatments were detected in both periods, with the lowest dry leaf weight recorded under the DI_{40} treatment. Deficient irrigation negatively affects vegetative growth in plants (Biswas et al., 2025). Basil, being sensitive to abiotic stresses, is known

Table 1. Changes in certain growth parameters of Moonlight (green) and Midnight (purple) basil varieties under deficit irrigation

Harvest time	Varieties	Treatment	Plant height (cm)	Canopy diameter (cm)	Fresh plant weight (g)	Fresh leaf weight (g)	Dry plant weight (g)	Dry leaf weight (g)
1st harvest	Moonlight	DI_{100} (CT)	29.91^{ns}	35.81^{a}	318.98^{a}	210.67^{a}	89.31^{a}	58.59^{a}
		DI_{80}	29.71	33.26^{a}	310.36^{a}	199.55^{ab}	79.92^{a}	51.56^{ab}
		DI_{60}	28.96	28.83^{b}	251.23^{ab}	147.1^{bc}	49.94^{b}	28.82^{b}
		DI_{40}	28.72	23.51^{c}	189.9^{b}	125.6^{c}	35.06^{c}	23.58^{c}
	Midnight	DI_{100}	34.48^{ns}	36.72^{a}	225.67^{a}	128.84^{a}	57.41^{a}	33.34^{a}
		DI_{80}	33.78	33.44^{ab}	192.41^{ab}	112.65^{ab}	43.79^{b}	25.5^{b}
		DI_{60}	33.67	30.08^{b}	161.28^{b}	95.12^{b}	30.59^{c}	17.8^{c}
		DI_{40}	31.83	23.94^{c}	91.68^{c}	52.69^{c}	15.36^{d}	8.85^{d}
2nd harvest	Moonlight	DI_{100}	27.22^{a}	32.36^{a}	234.89^{ns}	147.67^{a}	40.74^{a}	65.27^{a}
		DI_{80}	26.67^{ab}	31.56^{a}	214.66	139.58^{ab}	36.1^{ab}	55.27^{ab}
		DI_{60}	24.75^{bc}	30.94^{a}	193.14	119.58^{b}	23.49^{b}	37.82^{c}
		DI_{40}	23.72^{c}	27.83^{b}	143.33	91.9^{c}	17.09^{c}	26.9^{d}
	Midnight	DI_{100}	33.78^{ns}	38.78^{a}	182.13^{a}	147.67^{a}	30.97^{a}	46.88^{a}
		DI_{80}	33.74	38.26^{a}	152.8^{b}	95.54^{b}	21.73^{b}	34.59^{b}
		DI_{60}	33.44	38.06^{a}	131.5^{b}	83.37^{c}	15.64^{bc}	24.51^{c}
		DI_{40}	30.94	34.36^{b}	75.78^{c}	63.24^{d}	10.55^{c}	12.07^{d}

to exhibit restricted growth under limited water supply (Ekren et al., 2012; Carvalho et al., 2023). Previous studies have reported reductions in plant height (Ekren et al., 2012; Biswas et al., 2024), stem diameter (Farajnia et al., 2025), plant biomass (Khakdan et al., 2016), and leaf weight (Rahimi et al., 2023) under deficit irrigation. Similarly, our study revealed that vegetative growth parameters were adversely affected by DI treatments. In the "Moonlight" variety, DI_{60} and DI_{40} negatively impacted growth factors, whereas DI_{80} showed no significant effect. Khalid (2006) reported that 75% of field capacity represents the optimum irrigation level for basil, which aligns with our findings. As observed in many plant species, drought tolerance varies among basil varieties. For instance, three basil varieties grown in Iran exhibited differential responses to deficit irrigation, with one variety showing higher tolerance (Khakdan et al., 2016). In our study, varietal differences in response to water stress were also evident, and vegetative parameters indicated that "Moonlight" (green-leafed) was more tolerant than "Midnight." Ekren et al. (2012) noted that purple basil is sensitive to water stress and irrigation levels, whereas Rahimi et al. (2023) exposed four varieties, including a purple variety, to deficit irrigation and found them to be more tolerant. However, the "Midnight" variety's tolerance was not evaluated in their study. The frequency of cutting in basil increases the utilization of total fresh and dry biomass (Günay, 2025). The cut-and-come-again (CC) harvesting strategy allows for multiple harvests, with at least two harvests in temperate European regions (Corrado et al., 2020). Successive harvests generally reduce fresh leaf weight and harvest index in green basil (Corrado et al., 2020). In our study, the "Moonlight" variety showed reduced fresh and dry biomass and leaf weight at the second harvest under DI treatments. Conversely, Ekren et al. (2012) reported higher fresh and dry herbage yields in purple basil during the second and third harvests under deficit irrigation. In our experiment, while there were varietal and treatment-dependent differences, the vegetative parameters of the "Midnight" variety were generally higher during the first harvest.

Effects of deficit irrigation on leaf relative water content in basil varieties

Deficit irrigation treatments significantly reduced the leaf relative water content (RWC) of the Moonlight variety during the first harvest period, with the lowest RWC observed in the DI_{60} (83.9%) and DI_{40} (83.67%) treatments (**Fig. 1a**). Additionally, the lowest LWC was detected under the DI_{40} treatment in both harvest periods. In the second harvest period, a significant reduction in RWC was observed under the DI_{60} and DI_{40} treatments, while no difference was found between the control and DI_{80} treatments. Deficit irrigation treatments significantly reduced RWC in the Midnight variety in both harvest periods (**Fig. 1b**). Statistically significant differences in LWC were observed among treatments in both periods. The lowest RWC value in both harvest periods was determined in the DI_{40} treatment. RWC is an important physiological parameter that reflects a plant's overall water status (Aydınlı et al., 2025). Additionally, the RWC contents indicate healthy plant status (Verslues et al., 2006). However, relative water content (RWC) decreases under various environmental factors, including drought stress

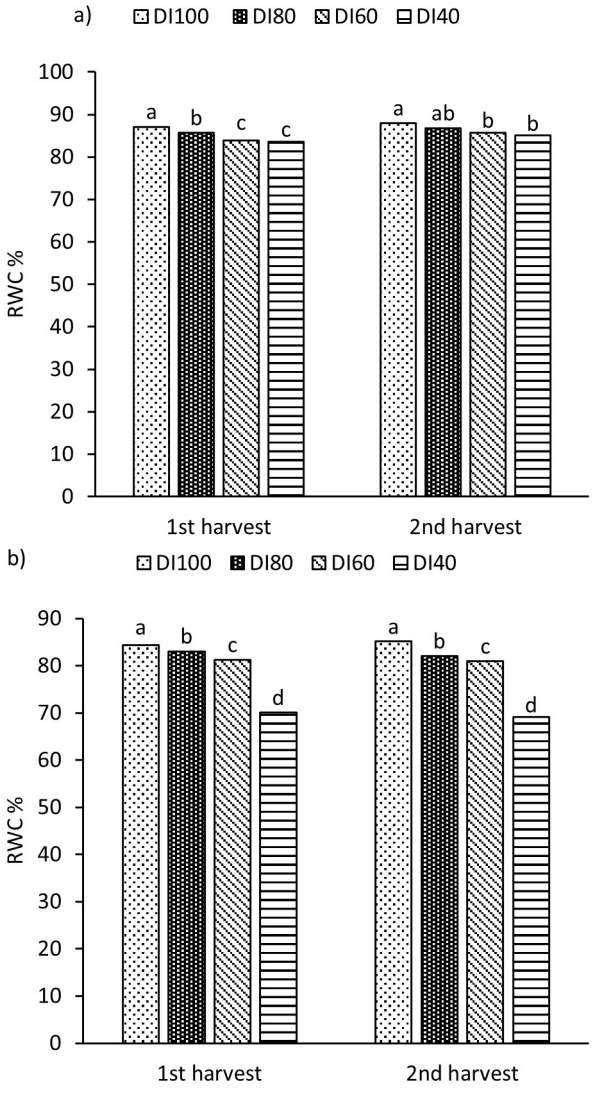


Fig. 1. Variations in the leaf relative water content (RWC) of Moonlight (green) (**a**) and Midnight (purple) (**b**) basil varieties under different deficit irrigation treatments. Different lowercase letters indicate significant differences within different deficit irrigation treatments (p<0.05).

(Farouk & Omar, 2020). In basil, RWC has been reported to decline under deficit irrigation (Damalas, 2019). In our study, RWC was significantly reduced under DI treatments, particularly DI_{60} and DI_{40}. Additionally, varietal differences in RWC are known, with drought-tolerant varieties exhibiting smaller changes (Khakdan et al., 2016). Consistent with the literature, our results indicated that the "Midnight" variety, considered more sensitive to drought stress, showed a greater reduction in RWC. This change is likely associated with cell wall elasticity and the succulent nature of the plant tissue (Jones, 2007; Hessini et al., 2009).

Effects of deficit irrigation on SPAD value in basil varieties

In both basil varieties, deficit irrigation treatments did not affect SPAD values during the first harvest period (**Fig. 2a** and **Fig. 2b**). In the second harvest period, SPAD values in the Moonlight variety were found to decrease under DI_{60} (33.03) and DI_{40} (31.14) treatments compared to the control (36.61) plants (**Fig. 2a**). In the second harvest period of the Midnight variety, SPAD values significantly decreased under the DI_{60} (40.54) and DI_{40} (38.45) deficit irrigation treatments (**Fig. 2b**). No difference in SPAD values was observed between the control (43.91) plants and the DI_{80} (43.43) deficit irrigation treatment. Leaf chlorophyll concentration is a key physiological trait associated with photosynthetic performance and is influenced by various environmental factors (Damalas, 2019). Studies on basil under deficit irrigation have reported decreases in chlorophyll content and/or SPAD values, with responses varying among varieties (Zulfiqar et al., 2021; Fathi et al., 2023; Burbulis et al., 2023). In our study, SPAD values decreased under DI_{60} and DI_{40} treatments during the second harvest in both varieties, with a more pronounced reduction observed in the "Moonlight" variety, which is considered more drought-tolerant. Contrary to some reports, this finding may be explained by Radácsi et al. (2020), who noted that higher SPAD readings do not necessarily indicate higher chlorophyll content.

Deficit irrigation treatments could affect the essential oil content of basil varieties

The essential oil content of basil varieties was significantly altered under deficit irrigation conditions (**Fig. 3a** and **3b**). Deficit irrigation treatments led to a significant increase in the essential oil content of the Moonlight variety, especially in the first harvest period (**Fig. 3a**). Deficit irrigation treatments enhanced the essential oil content of the Moonlight variety in the first harvest period. In the second harvest period, however, the DI_{60} (0.25 mg $100g^{-1}$) and DI_{40} (0.28 mg $100g^{-1}$) treatments reduced the essential oil content. On the other hand, the highest essential oil content in both harvest periods was observed under the DI_{80} treatment (0.53 mg $100g^{-1}$ and 0.49 mg $100g^{-1}$, respectively). A comparable trend was also observed in the Midnight variety (**Fig. 3b**). Essential oil content was enhanced by deficit irrigation during the first harvest period, but decreased under the DI_{40} (0.24 mg $100g^{-1}$) treatment in the second harvest period. Additionally, the highest essential oil content was determined in the DI_{80} (0.47 mg $100g^{-1}$ and 0.36 mg $100g^{-1}$, respectively)

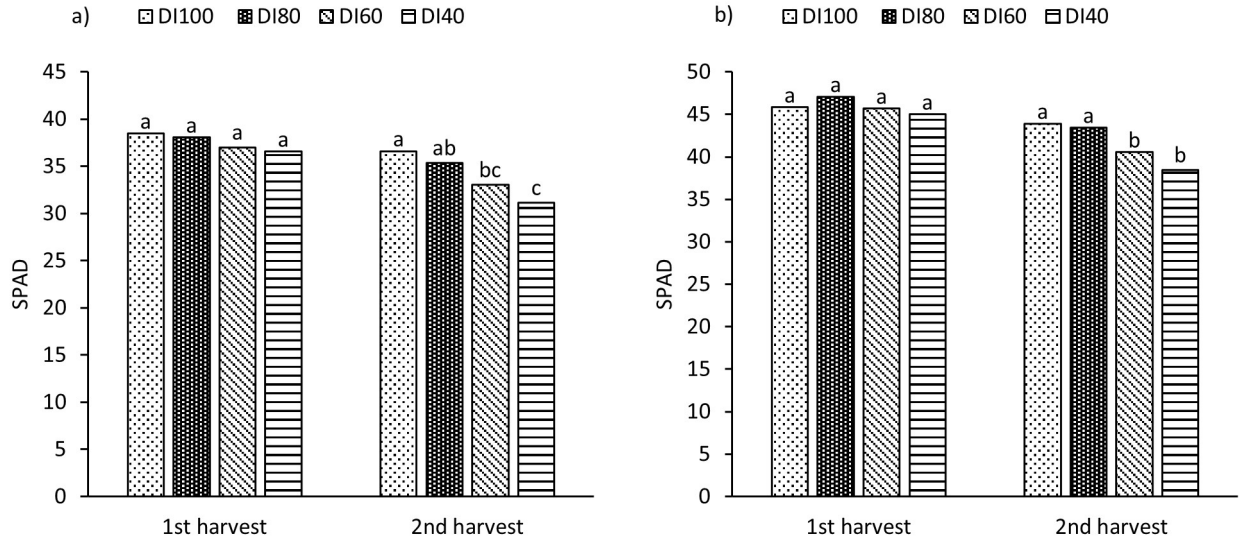


Fig. 2. Variations in the SPAD value of Moonlight (green) (**a**) and Midnight (purple) (**b**) basil varieties under different deficit irrigation treatments. Different lowercase letters indicate significant differences within different deficit irrigation treatments (p<0.05).

treatment in both harvest periods. On the other hand, the essential oil content was higher in the first harvest period for both the Moonlight and Midnight varieties. Khalid (2006) reported that essential oil content in plants is influenced by various factors and moderately affected by environmental conditions. Under drought stress, increases in essential oil content may be associated with a higher number of glandular trichomes (Bistgani et al., 2017). Studies on basil have shown that deficit irrigation alters essential oil content, with responses varying among varieties and either increasing or decreasing (Ekren et al., 2012; Fathi et al., 2023; Rahimi et al., 2023). Sayarer et al. (2023) reported that severe water stress (25% field capacity) increased essential oil content in basil. In our study, deficit irrigation increased essential oil content in both varieties during the first harvest, and DI_{80} enhanced it across both harvests. It is known that harvest number can affect essential oil content under optimal conditions, with terpenoid levels increasing during the second harvest (Corrado et al., 2020). However, Ekren et al. (2012) could not clearly determine the effect of harvest number on essential oil content in purple basil under deficit irrigation. In our experiment, essential oil content decreased during the second harvest, which may be attributed to ecological factors, varietal differences, and the applied stress conditions.

Deficit irrigation treatments could affect the essential oil composition of basil varieties

Under deficit irrigation, the Moonlight cultivar exhibited significant variations in the concentrations of key volatile compounds, including oxygenated monoterpenes (1,8-cineole, linalool), sesquiterpenes (α-bergamotene, τ-cadinol), and the phenylpropene derivative methyl-chavicol (**Fig. 4a** and **Fig. 4b**). The content of 1,8-cineole, linalool, methyl-chavicol, and τ-cadinol showed a similar trend in both harvest periods. A significant reduction in cineole content was observed under the DI_{40} treatment. Linalool content showed a significant reduction in both DI_{60} (28.26%) and DI_{40} (21.98%) treatments compared with the control (37.48%) and DI_{80} (36.57%) treatments. The methyl-chavicol content increased significantly under both DI_{60} and DI_{40} treatments compared to the other treatments. The highest τ-cadinol content was recorded in the DI_{60} treatment, showing statistically significant differences compared to other treatments. The highest α-bergamotene content was detected in the DI_{40} treatment during both harvest periods. In the second harvest period, α-bergamotene content was also found to increase significantly in the DI_{60} treatment (**Fig. 4b**). The main constituents of basil essential oil are linalool, methyl chavicol, 1,8-cineole, methyl eugenol, methyl cinnamate, and citral (Simon et al., 1999; Kumar et al., 2012). The content of these compounds can vary under different stress factors, including deficit irrigation (Khakdan et al., 2016; Farsaraei et al., 2020; Tursun & Telci, 2020; Sayarer et al., 2023). Ekren et al. (2012) reported that linalool content generally increased under deficit irrigation in basil, whereas Radácsi et al. (2020) observed that drought effects were variety-dependent, and Sayarer et al. (2023) found a generally decreasing trend under limited irrigation. In our study, linalool content remained unchanged under DI_{80} in both varieties but decreased under more

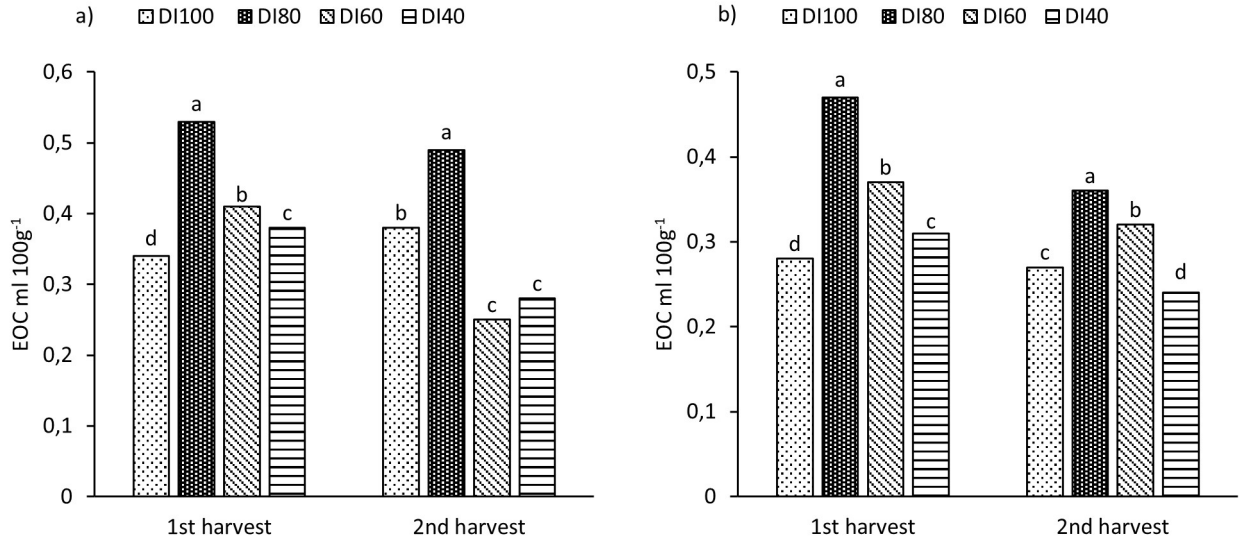


Fig. 3. Variations in the essential oil content (EOC) of Moonlight (green) (**a**) and Midnight (purple) (**b**) basil varieties under different deficit irrigation treatments. Different lowercase letters indicate significant differences within different deficit irrigation treatments (p<0.05).

severe stress levels. Regarding methyl chavicol, Ekren et al. (2012) reported low levels in purple basil and a decline with increasing drought severity, whereas Khakdan et al. (2016) observed an increase under deficit irrigation. In our study, methyl chavicol content in the "Moonlight" variety increased with the severity of deficit irrigation, reaching the highest levels under DI_{40} for both harvests. In contrast, methyl chavicol was not detected in the "Midnight" variety. In the Midnight variety subjected to deficit irrigation, linalool was the most abundant essential oil component among those examined in the study (**Fig. 5a** and **5b**). A statistically significant reduction in linalool content was observed under the DI_{60} and DI_{40} treatments during both harvest periods. A similar trend was observed in cineole content, which also decreased under the DI_{60} and DI_{40} treatments during both harvest periods. The content of β-myrcene significantly increased under all deficit irrigation treatments compared to the control. The content of dauca-4,8-diene was found to significantly increase under the DI_{60} and DI_{40} treatments.

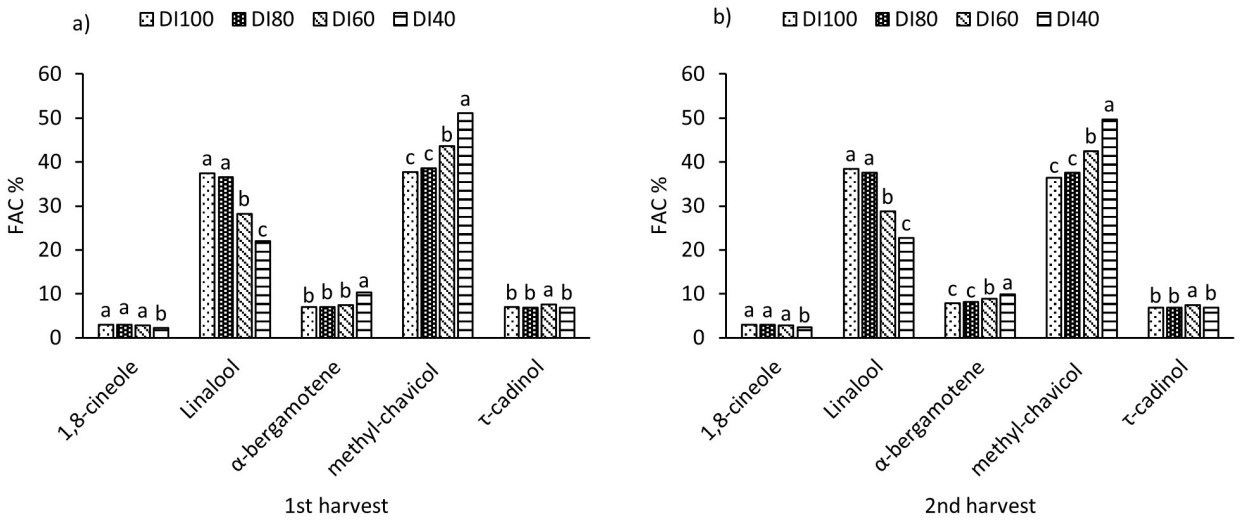


Fig. 4. Variations in the essential oil composition (EOC) of Moonlight (green) basil varieties under different deficit irrigation treatments. **a**) indicates the first harvest period, while **b**) indicates the second harvest period. Different lowercase letters indicate significant differences within different deficit irrigation treatments (p<0.05).

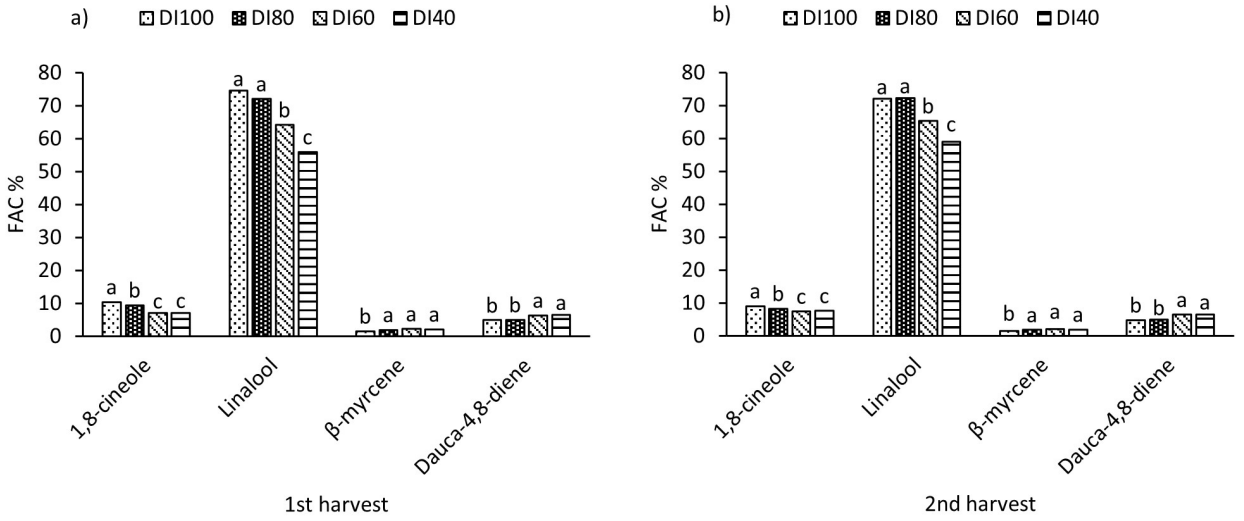


Fig. 5. Variations in the essential oil composition (EOC) of Midnight (purple) basil varieties under different deficit irrigation treatments. **a**) indicates the first harvest period, while **b**) indicates the second harvest period. Different lowercase letters indicate significant differences within different deficit irrigation treatments (p<0.05).

Phenolic compounds may act as defense components in basil under deficit irrigation conditions

Deficit irrigation treatments had a significant contribution to the accumulation of total phenolic compounds, especially in the Moonlight variety (**Fig. 6a**). In the Moonlight variety, the DI_{80} (35.02 mg g^{-1}) and DI_{60} (37.53 mg g^{-1}) treatments significantly increased the total phenolic compound content during the first harvest period. In the second harvest period, total phenolic content significantly increased under all deficit irrigation treatments compared with the control. In the Midnight variety, the total phenolic compound content did not differ among treatments during the first harvest period, whereas it significantly increased under the DI_{60} (72.34 mg g^{-1}) treatment in the second harvest period (**Fig. 6b**). Basil, an important source of secondary metabolites, is rich in total phenolics, phenolic acids, and flavonoids, which contribute to its antioxidant capacity (Javanmardi et al., 2002; Kanmaz et al., 2023). The content of these compounds varies across varieties (Bajomo et al., 2022), stress types (Biswas et al., 2025; Yolcu & Yilmaz, 2025), and stress severities (Rahimi et al., 2023). Biswas et al. (2024) reported that total phenolic and flavonoid contents increased with the severity of deficit irrigation in basil. Similarly, Šerbo et al. (2024) found the highest total phenolic and flavonoid contents in green basil under moderate drought stress. Rahimi et al. (2023) observed that total phenolic content increased with stress level in 22 basil varieties, whereas total flavonoid content varied depending on the variety. In our study, total phenolic and flavonoid contents generally increased with stress severity, reaching the highest values under DI_{60} treatment, while decreasing under the most severe stress (DI_{40}). These findings are consistent with previous reports. The changes in total flavonoid content in basil varieties resulting from deficit irrigation are presented in **Fig. 7**. During the first harvest period, a significant increase of total flavonoid content in the Moonlight variety was observed particularly under the DI_{60} (12.88 mg g^{-1}) treatment, while a decrease was noted under the DI_{40} (10.67 mg g^{-1}) treatment; however, the content remained higher than in the other treatments (**Fig. 7a**). During the second harvest period, total flavonoid content increased under all deficit irrigation treatments, and similar to the first harvest period, the highest content was recorded under the DI_{60} (12.88 mg g^{-1}) treatment. In the Midnight variety, total flavonoid content was not affected by the deficit irrigation treatments (**Fig. 7b**).

Conclusion

In this study, morphological, physiological, and biochemical responses of green ("Moonlight") and purple ("Midnight") basil varieties under deficit irrigation were evaluated across two harvest times. Morphological traits in "Moonlight" were not affected by DI_{80}, whereas increasing stress intensity led to reductions in "Midnight." Relative water content (RWC) generally decreased under deficit irrigation, with a more pronounced decline in "Midnight." SPAD values remained stable during the first harvest but decreased under DI_{60} and DI_{40} in the second harvest for both varieties. Essential oil content was higher under DI_{80} in both varieties.

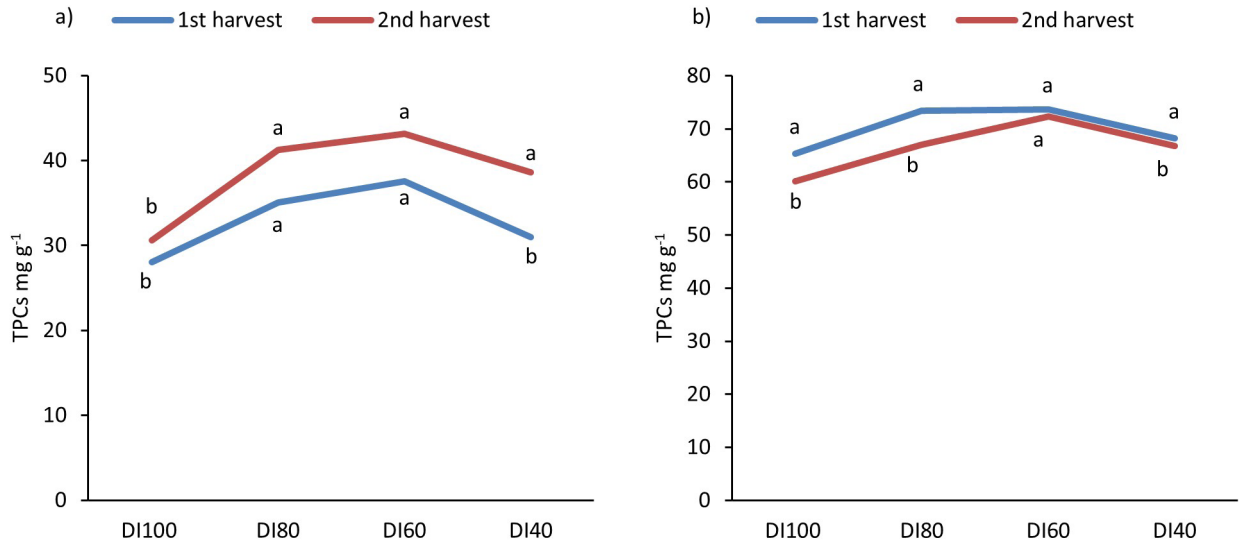


Fig. 6. Variations in the total phenolic compounds (TPCs) of Moonlight (green) (**a**) and Midnight (purple) (**b**) basil varieties under different deficit irrigation treatments. Different lowercase letters indicate significant differences within different deficit irrigation treatments (p<0.05).

Linalool content decreased under DI_{60} and DI_{40}, while methyl chavicol content increased with increasing stress. Total phenolic and flavonoid contents were highest under DI_{60} in both varieties and harvests. Additionally, non-enzymatic antioxidant activity significantly increased under deficit irrigation in the "Moonlight" variety. Overall, the results indicate that "Moonlight" is more drought-tolerant. Moreover, in the context of climate change and increasing drought stress in the Mediterranean region, irrigation at 60% of field capacity does not adversely affect basil yield and may enhance its biochemical properties.

Conflict of interest. The authors have no conflicts of interest regarding this manuscript.

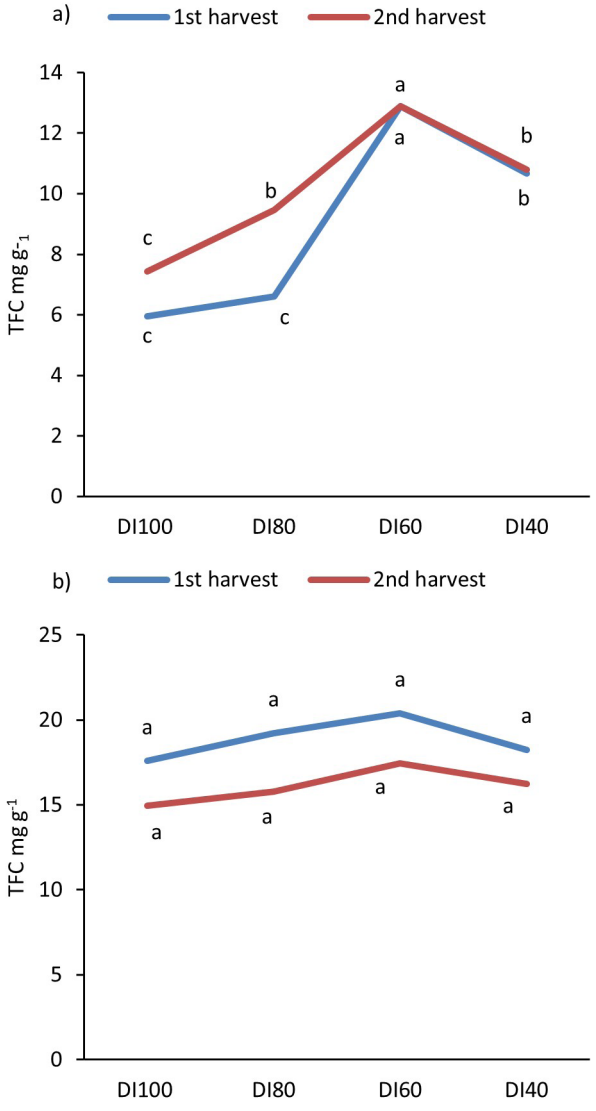


Fig. 7. Variations in the total flavonoid content (TFC) of Moonlight (green) (**a**) and Midnight (purple) (**b**) basil varieties under different deficit irrigation treatments. Different lowercase letters indicate significant differences within different deficit irrigation treatments (p<0.05).

Funding. This study was supported by the Republic of Turkey Ministry of Agriculture and Forestry, General Directorate of Agricultural Research and Policies.

References

Abdelfattah, A., & Mostafa, H. (2024). Potential of soil conditioners to mitigate deficit irrigation impacts on agricultural crops: A review. *Water Resources Management, 38*(8), 2961–2976. https://doi.org/10.1007/s11269-024-03800-4

Acosta-Pérez, P., Camacho-Zamora, B. D., Espinoza-Sánchez, E. A., Gutiérrez-Soto, G., Zavala-García, F., Abraham-Juárez, M. J., & Sinagawa-García, S. R. (2020). Characterization of trehalose-6-phosphate synthase and trehalose-6-phosphate phosphatase genes and analysis of its differential expression in maize (*Zea mays*) seedlings under drought stress. *Plants, 9*(3), 315. https://doi.org/10.3390/plants9030315

Amani, M., Sabzi-Nojadeh, M., Alizadeh Salteh, S., Younessi Hamzekhanlu, M., Farmani, B., Hatef Heris, H., Mohammadian, S., & Piretarighat, S. (2023). Improving the antioxidant activities of sweet basil (*Ocimum basilicum* L.) under the influence of different species of mycorrhiza under water stress. *Journal of Horticultural Science, 37*(2), 377–389. https://doi.org/10.22067/jhs.2022.76064.1157

Aydınlı, M., Yıldırım, F., Kaçal, E., Önder, S., Altındal, M., & Karakurt, Y. (2025). Role of enzymatic antioxidants on salinity tolerance of some rootstocks used in European pear (*Pyrus communis* L.) cultivation. *Spanish Journal of Agricultural Research, 23*(2), 20795. https://doi.org/10.5424/sjar/2025232-20795

Barrs, H. D., & Weatherley, P. E. (1962). A re-examination of the relative turgidity technique for estimating water deficits in leaves. *Australian Journal of Biological Sciences, 15*(3), 413–428.

Bajomo, E. M., Aing, M. S., Ford, L. S., & Niemeyer, E. D. (2022). Chemotyping of commercially available basil (*Ocimum basilicum* L.) varieties: Cultivar and morphotype influence phenolic acid composition and antioxidant properties. *NFS Journal, 26*, 1–9. https://doi.org/10.1016/j.nfs.2022.01.001

Bekhradi, F., Luna, M. C., Delshad, M., Jordan, M. J., Sotomayor, J. A., Martínez-Conesa, C., & Gil, M. I. (2015). Effect of deficit irrigation on

the postharvest quality of different genotypes of basil including purple and green Iranian cultivars and a Genovese variety. *Postharvest Biology and Technology, 100*, 127–135. https://doi.org/10.1016/j.postharvbio.2014.09.017

Bistgani, Z. E., Siadat, S. A., Bakhshandeh, A., Pirbalouti, A. G., & Hashemi, M. (2017). Morpho-physiological and phytochemical traits of *Thymus daenensis* Celak. in response to deficit irrigation and chitosan application. *Acta Physiologiae Plantarum, 39*(10), 231. https://doi.org/10.1007/s11738-017-2526-2

Biswas, A., Ullah, H., Himanshu, S. K., Garcia-Caparros, P., Chungloo, D., Praseartkul, P., Tisarum, R., Cha-um, S., & Datta, A. (2024). Morpho-physio-biochemical responses of sweet basil plants to integrated application of silicon and salicylic acid under water supply restrictions. *Silicon, 16*(16), 5841–5854. https://doi.org/10.1007/s12633-024-03123-4

Biswas, A., Ullah, H., Himanshu, S. K., Praseartkul, P., Tisarum, R., Cha-um, S., & Datta, A. (2025). Biostimulant enhances growth, herbage yield, and physio-biochemical characteristics of sweet basil plants under drought stress. *Russian Journal of Plant Physiology, 72*(1), 4. https://doi.org/10.1134/S1021443724608711

Burbulis, N., Deveikytė, J., Baltušnikienė, A., & Blinstrubienė, A. (2023). Effect of phenylalanine and tryptophane on chlorophyll and phenolic content, and the antioxidant activity of sweet basil (*Ocimum basilicum* L.) under drought conditions. *Zemdirbyste-Agriculture, 110*(4). https://doi.org/10.13080/z-a.2023.110.038

Carvalho, B. L., Aires, E. S., Rodrigues, J. D., & Ono, E. O. (2023). Use of plant regulators for activation of antioxidant enzymes in basil plants under water deficit conditions. *Stresses, 3*(1), 282–301. https://doi.org/10.3390/stresses3010021

Cattivelli, L., Rizza, F., Badeck, F. W., Mazzucotelli, E., Mastrangelo, A. M., Francia, E., Marè, C., Tondelli, A., & Stanca, A. M. (2008). Drought tolerance improvement in crop plants: An integrated view from breeding to genomics. *Field Crops Research, 105*(1–2), 1–14. https://doi.org/10.1016/j.fcr.2007.07.004

Chen, X., Qi, Z., Gui, D., Sima, M. W., Zeng, F., Li, L., Li, X., Feng, S., & Feng, S. (2022). Responses of cotton photosynthesis and growth to a new irrigation control method under deficit irrigation. *Field Crops Research, 275*, 108373. https://doi.org/10.1016/j.fcr.2021.108373

Corrado, G., Chiaiese, P., Lucini, L., Miras-Moreno, B., Colla, G., & Rouphael, Y. (2020). Successive harvests affect yield, quality and metabolic profile of sweet basil (*Ocimum basilicum* L.). *Agronomy, 10*(6), 830. https://doi.org/10.3390/agronomy10060830

Damalas, C. A. (2019). Improving drought tolerance in sweet basil (*Ocimum basilicum*) with salicylic acid. *Scientia Horticulturae, 246*, 360–365. https://doi.org/10.1016/j.scienta.2018.11.005

Dhama, K., Sharun, K., Gugjoo, M. B., Tiwari, R., Alagawany, M., Iqbal Yatoo, M., Thakur, P., Iqbal, H. M., Chaicumpa, W., & Michalak, I. (2021). A comprehensive review on chemical profile and pharmacological activities of *Ocimum basilicum*. *Food Reviews International, 36*, 190–230. https://doi.org/10.1080/87559129.2021.1900230

Dorni, A. C., Amalraj, A., Gopi, S., Varma, K., & Anjana, S. N. (2017). Novel cosmeceuticals from plants—An industry guided review. *Journal of Applied Research on Medicinal and Aromatic Plants, 7*, 1–26. https://doi.org/10.1016/j.jarmap.2017.05.003

Ekren, S., Sönmez, Ç., Özçakal, E., Kurttaş, Y. S. K., Bayram, E., & Gürgülü, H. (2012). The effect of different irrigation water levels on yield and quality characteristics of purple basil (*Ocimum basilicum* L.). *Agricultural Water Management, 109*, 155–161. https://doi.org/10.1016/j.agwat.2012.03.004

Farajnia, H., Majnooni-Heris, A., Bolandnazar, S., & Rezaverdinejad, V. (2025). Biochar and irrigation effects on sweet basil growth and water use efficiency in greenhouse. *Journal of Soil Science and Plant Nutrition*, 1–13. https://doi.org/10.1007/s42729-025-02576-9

Farouk, S., & Omar, M. M. (2020). Sweet basil growth, physiological and ultrastructural modification, and oxidative defense system under water deficit and silicon forms treatment. *Journal of Plant Growth Regulation, 39*(3), 1307–1331. https://doi.org/10.1007/s00344-020-10071-x

Farsaraei, S., Moghaddam, M., & Pirbalouti, A. G. (2020). Changes in growth and essential

oil composition of sweet basil in response to salinity stress and superabsorbents application. *Scientia Horticulturae, 271*, 109465. https://doi.org/10.1016/j.scienta.2020.109465

Fathi, S., Bolandnazar, S., Alizadeh-Salteh, S., & Zaare-Nahandi, F. (2023). Effects of biological fertilizers on some physiological traits of sweet basil under water deficit stress. *Journal of Medicinal Plants and By-Products, 12*(4), 365–374. https://doi.org/10.22092/jmpb.2022.356634.1424

Günay, E. (2025). *Development of basil (Ocimum basilicum L.) lines with high essential oil and citral yield by selection breeding and determination of their yield and quality characteristics* (Doctoral dissertation, University of Isparta Applied Sciences). https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp

Gürgan, M., & Adiloğlu, S. (2021). Increasing concentrations of iron fertilizer affect antibacterial activity of basil (*Ocimum basilicum* L.). *Industrial Crops and Products, 170*, 113768. https://doi.org/10.1016/j.indcrop.2021.113768

Hajlaoui, H., Maatallah, S., Guizani, M., Boughattas, N. E. H., Guesmi, A., Ennajeh, M., Dabbou, S., & Lopez-Lauri, F. (2022). Effect of regulated deficit irrigation on agronomic parameters of three plum cultivars (*Prunus salicina* L.) under semi-arid climate conditions. *Plants, 11*(12), 1545. https://doi.org/10.3390/plants11121545

Hassan, I. F., Ajaj, R., Abd El-Khalek, A. F., Alam-Eldein, S. M., Gaballah, M. S., Athar, H. U. R., & Hatterman-Valenti, H. M. (2025). Effects of deficit irrigation on growth, yield, and quality of pomegranate (*Punica granatum*) grown in semi-arid conditions. *Horticulturae, 11*(1), 101. https://doi.org/10.3390/horticulturae11010101

Hessini, K., Martínez, J. P., Gandour, M., Albouchi, A., Soltani, A., & Abdelly, C. (2009). Effect of water stress on growth, osmotic adjustment, cell wall elasticity and water-use efficiency in *Spartina alterniflora*. *Environmental and Experimental Botany, 67*(2), 312–319. https://doi.org/10.1016/j.envexpbot.2009.06.010

Hiltunen, R., & Holm, Y. (1999). Essential oil of *Ocimum*. In *Basil* (pp. 83–116). CRC Press.

Javanmardi, J., Khalighi, A., Kashi, A., Bais, H. P., & Vivanco, J. M. (2002). Chemical characterization of basil (*Ocimum basilicum* L.) found in local accessions and used in traditional medicines in Iran. *Journal of Agricultural and Food Chemistry, 50*(21), 5878–5883.

Jones, H. G. (2007). Monitoring plant and soil water status: Established and novel methods revisited and their relevance to studies of drought tolerance. *Journal of Experimental Botany, 58*(2), 119–130. https://doi.org/10.1093/jxb/erl118

Kalamartzis, I., Dordas, C., Georgiou, P., & Menexes, G. (2020). The use of appropriate cultivar of basil (*Ocimum basilicum*) can increase water use efficiency under water stress. *Agronomy, 10*(1), 70. https://doi.org/10.3390/agronomy10010070

Kanmaz, H., Gokce, Y., & Hayaloglu, A. A. (2023). Volatiles, phenolic compounds and bioactive properties of essential oil and aqueous extract of purple basil (*Ocimum basilicum* L.) and antidiabetic activity in streptozotocin-induced diabetic Wistar rats. *Food Chemistry Advances, 3*, 100429. https://doi.org/10.1016/j.focha.2023.100429

Khakdan, F., Ranjbar, M., Nasiri, J., Ahmadi, F. S., Bagheri, A., & Alizadeh, H. (2016). The relationship between antioxidant compounds contents and antioxidant enzymes under water-deficit stress in the three Iranian cultivars of basil (*Ocimum basilicum* L.). *Acta Physiologiae Plantarum, 38*(9), 226. https://doi.org/10.1007/s11738-016-2241-4

Khalid, K. A. (2006). Influence of water stress on growth, essential oil, and chemical composition of herbs (*Ocimum* sp.). *International Agrophysics, 20*(4).

Kumar, R. R., Reddy, L. P. A., & Patel, R. P. (2012). Genetic association for oil yield and its component traits in different *Ocimum* species. *Electronic Journal of Plant Breeding, 3*(2), 794–799.

Qasem, A., Assaggaf, H., Mrabti, H. N., Minshawi, F., Rajab, B. S., Attar, A. A., Alyamani, R. A., Hamed, M., Mrabti, N. N., Baaboua, A. E., Omari, N. E., Alshahrani, M. M., Awadh, A. A. A., Sheikh, R. A., Ming, L. C., Goh, K. W., & Bouyahya, A. (2023). Determination of chemical composition and investigation of biological activities of *Ocimum basilicum* L. *Molecules, 28*(2), 614. https://doi.org/10.3390/molecules28020614

Radácsi, P., Inotai, K., Sárosi, S., Hári, K., Seidler-Lozykowska, K., Musie, S., & Zámboriné, É. N.

(2020). Effect of irrigation on the production and volatile compounds of sweet basil cultivars (*Ocimum basilicum* L.). *Herba Polonica, 66*(4). https://doi.org/10.2478/hepo-2020-0021

Rahimi, M., Mortazavi, M., Mianabadi, A., & Debnath, S. (2023). Evaluation of basil (*Ocimum basilicum*) accessions under different drought conditions based on yield and physio-biochemical traits. *BMC Plant Biology, 23*(1), 523. https://doi.org/10.1186/s12870-023-04554-8

Sayarer, M., Aytaç, Z., & Kürkçüoğlu, M. (2023). The effect of irrigation and humic acid on the plant yield and quality of sweet basil (*Ocimum basilicum* L.) with mulching application under semi-arid ecological conditions. *Plants, 12*(7), 1522. https://doi.org/10.3390/plants12071522

Šerbo, A., Avdić, J., Pustahija, F., Murtić, M. S., & Murtić, S. (2024). Physiological response of basil plants (*Ocimum basilicum* L.) to drought. *Agriculture & Forestry/Poljoprivreda i šumarstvo, 70*(3).

Simon, J. E., Morales, M. R., Phippen, W. B., Vieira, R. F., & Hao, Z. (1999). Basil: A source of aroma compounds and a popular culinary and ornamental herb. *Perspectives on New Crops and New Uses, 16*, 499–505.

Simon, J. E., Quinn, J., & Murray, R. G. (1990). Basil: A source of essential oils. In J. Janick & J. E. Simon (Eds.), *Advances in new crops* (pp. 484–489). Timber Press.

Singleton, V. L., & Rossi, J. A. Jr. (1965). Colorimetry of total phenolics with phosphomolybdic–phosphotungstic acid. *American Journal of Enology and Viticulture, 16*(3), 144–158. https://doi.org/10.5344/ajev.1965.16.3.144

Telci, I., Bayram, E., Yılmaz, G., & Avcı, B. (2006). Variability in essential oil composition of Turkish basils (*Ocimum basilicum* L.). *Biochemical Systematics and Ecology, 34*(6), 489–497. https://doi.org/10.1016/j.bse.2006.01.009

Tursun, A. O., & Telci, I. (2020). The effects of carbon dioxide and temperature on essential oil composition of purple basil (*Ocimum basilicum* L.). *Journal of Essential Oil Bearing Plants, 23*(2), 255–265. https://doi.org/10.1080/0972060X.2020.1741452

Verslues, P. E., Agarwal, M., Katiyar-Agarwal, S., Zhu, J., & Zhu, J. K. (2006). Methods and concepts in quantifying resistance to drought, salt and freezing: Abiotic stresses that affect plant water status. *The Plant Journal, 45*(4), 523–539. https://doi.org/10.1111/j.1365-313X.2005.02593.x

Yolcu, M. S., & Yilmaz, A. (2025). Biostimulant-driven enhancement of bioactive compounds in salt-stressed sweet basil (*Ocimum basilicum* L.). *South African Journal of Botany, 178*, 318–329. https://doi.org/10.1016/j.sajb.2025.01.037

Zhishen, J., Mengcheng, T., & Jianming, W. (1999). The determination of flavonoid contents in mulberry and their scavenging effects on superoxide radicals. *Food Chemistry, 64*(4), 555–559. https://doi.org/10.1016/S0308-8146(98)00102-2

Zulfiqar, F., Chen, J., Finnegan, P. M., Younis, A., Nafees, M., Zorrig, W., & Hamed, K. B. (2021). Application of trehalose and salicylic acid mitigates drought stress in sweet basil and improves plant growth. *Plants, 10*(6), 1078. https://doi.org/10.3390/plants10061078