



Impact of intermittent and deficit irrigation practices in subsurface drip systems on yield and morphological traits of black cumin (*Nigella sativa* L.)

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Abstract

In this study, the effects of intermittent and deficit irrigation applications in subsurface drip irrigation system on the yield and some development parameters of black cumin (*Nigella sativa* L.) plant were investigated. Four irrigation water levels and three interval treatments were applied in the study. According to the results obtained in the study, the effect of intermittent irrigation practices was found to be statistically significant on yield, plant weight, number of branches, and average capsule diameter parameters of black cumin. The lowest and highest black cumin yields were obtained in irrigation treatments S0 and S1 with 566.0 and 18,883.4 kg ha⁻¹, respectively. When evaluated according to intermittent applications, it was seen that seed yield increased as the water cut time increased. Accordingly, the average yield values in F0 (continuous irrigation), F1 (the treatment where water is applied once interrupted), and F2 (the treatment where water is applied twice interrupted) treatments were obtained as 1163.5, 1282.5, and 1204.8 kg ha⁻¹, respectively. While the interaction of irrigation level and interval number was found to be significant only in the average capsule diameter, the lowest and highest capsule diameters were obtained from treatments S0F2 and S1F1 with 8.9 and 12.8 mm, respectively. The two-year average lowest and highest plant water consumption values were obtained from treatments S0 and S1F2 with 253.7 and 418.6 mm, respectively. As a result, it was revealed that increasing the on–off period in intermittent irrigation applications in clayey soils may have positive effects on plant development and productivity.

Keywords Subsurface drip irrigation · Intermittent irrigation · Water efficiency · Black cumin · Deficit irrigation

Introduction

The use of medicinal and aromatic plants dates back to ancient times (Giannenas et al. 2020; Ahad et al. 2021). Globally, the economic value of medicinal plant products is estimated to be around 400 billion dollars, and it is expected to grow annually at a rate of 15–25% (Asigbaase et al. 2023). In terms of increasing the yields of medicinal and aromatic

plants through cultivation, researching water yield functions and enhancing studies in this direction are of significant importance for producers. From past to present, various methods have been implemented in agricultural irrigation to meet the water needs of plants. Research is being conducted to ensure more efficient use of existing water resources in agriculture due to increasing population and global warming (Nhemachena et al. 2020; Zhang et al. 2020; Srivastav et al. 2021). A significant portion of the water required to achieve optimal yield in agricultural production cannot be utilized by the plant, and water losses occur due to various reasons during the transmission of water to the plant root zone. To minimize these losses to the lowest levels, it is necessary to prevent water from evaporating from the soil, infiltrating deeply, and flowing on the surface to the highest possible extent. In this regard, subsurface drip irrigation system, which has become widely used, also has some shortcomings. Particularly, limitations arising from adhesion force in the lateral movement of water, and the problems of

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water reaching the soil surface through capillary rise can be listed as significant challenges. Various techniques have been applied in subsurface drip irrigation to address these issues (Noguchi et al. 2021; Thebaldi et al. 2021; Karimi and Karimi 2022; Gültekin and Ertek 2023).

The fact that many medicinal and aromatic plants are either harvested from the wild or that optimal production techniques for cultivated varieties have not yet been determined reduces the possibility for industrialists to obtain products that comply with standards. Despite the existing production potential in Turkey, inadequate efforts in cultivation, low yields per unit area due to rainfed agriculture, and the increasing demand, particularly in the food and health sectors, lead to insufficient production of plants like black cumin and necessitate their importation. Therefore, it is essential to establish a more precise irrigation program for black cumin, similar to other cultivated crops, based on clearer data. Determining an appropriate irrigation program for black cumin will address the research need in this field by achieving high and quality yields with less input costs per unit area.

In this study, the intermittent irrigation method, commonly used in furrow irrigation, was employed in subsurface drip irrigation, and it was also tested in conjunction with deficit irrigation. The research determined plant height, number of branches, number of capsules per plant, number of seeds per capsule, capsule diameter, thousand-seed weight, and seed yield in black cumin.

Material and method

Site description

The research was conducted at Ankara University, Faculty of Agriculture, Haymana Research and Application Farm, located approximately 45 km away from Ankara, Türkiye

at latitude 39°36'43.06" North and longitude 32°41'11.60" East. In Ankara province, rainfall mostly occurs during the winter months, falling as snow and occasionally as rain. The highest precipitation is typically received in May and December. The average annual total precipitation is 391 mm, with July and August being the hottest and driest months. The annual average temperature is 12.0 °C.

The analysis results for the soil of the experimental area are presented in Table 1, and the analysis results for the irrigation water used in the research are provided in Table 2. The soil in the experimental area is characterized by clay texture. Soil clay content varies between 53.3% and 63.6%. The organic matter content of the surface soil (0–0.3 m) in the experimental area was determined to be 1.28%. The irrigation water used in the research was obtained from the pond located at the experimental area site. In terms of irrigation water quality classification, it belonged to Class C2S1 (Richards 1954).

The climate data covering the planting and harvesting seasons were obtained from the meteorological station located in the experimental area. Monthly temperature (average, minimum and maximum) and monthly total precipitation data measured during the plant vegetation periods in both years of the study are presented in Fig. 1.

In the first year of the experiment, 127.8 mm of rainfall occurred, while a total of 198 mm of rainfall occurred in the second year.

Experimental design and cultural practices

In the study, Çameli variety of black cumin (*Nigella sativa* L.), which was registered by the Transitional Zone Agricultural Research Institute in 2014, was used as the material. Black cumin seeds were sown in plots with a width of 3.5 m and a length of 5.0 m, with inter-row spacing of 0.25 m and intra-row spacing of 0.10 m. Prior to sowing, the experimental area was plowed with a plow, and then prepared for

Table 1 Some important properties for the experimental area soil

Soil depth	Sand	Clay	Silt	Texture	Bulk Density	Field Capacity	Wilting Point	Organic Matter	EC	pH	Cation Exchange Capacity (CEC)
(m)	%	%	%		(g cm ⁻³)	%	%	%	dSm ⁻¹	Ext	me100g ⁻¹
0–0.3	27	56.1	16.9	C	1.16	39.8	21.4	1.28	0.73	7.45	49.6
0.3–0.6	26	53.3	20.7	C	1.16	39.7	21.51	0.64	0.67	7.60	48.7
0.6–0.9	24.2	63.6	12.2	C	1.13	38.4	21.46	0.66	1.27	7.39	45.8

Table 2 Some important properties of irrigation water

pH	EC dSm ⁻¹	Cations (meL ⁻¹)				Total	Anions (meL ⁻¹)				Boron (ppm)	Class
		Na ⁺	K ⁺	Ca ⁺⁺	Mg ⁺⁺		CO ₃ ⁻	HCO ₃ ⁻	Cl ⁻	SO ₄ ⁼		
8.2	0.59	1.55	0.11	2.15	2.55	6.36	0.38	4.79	0.73	0.46	0.25	C ₂ S ₁

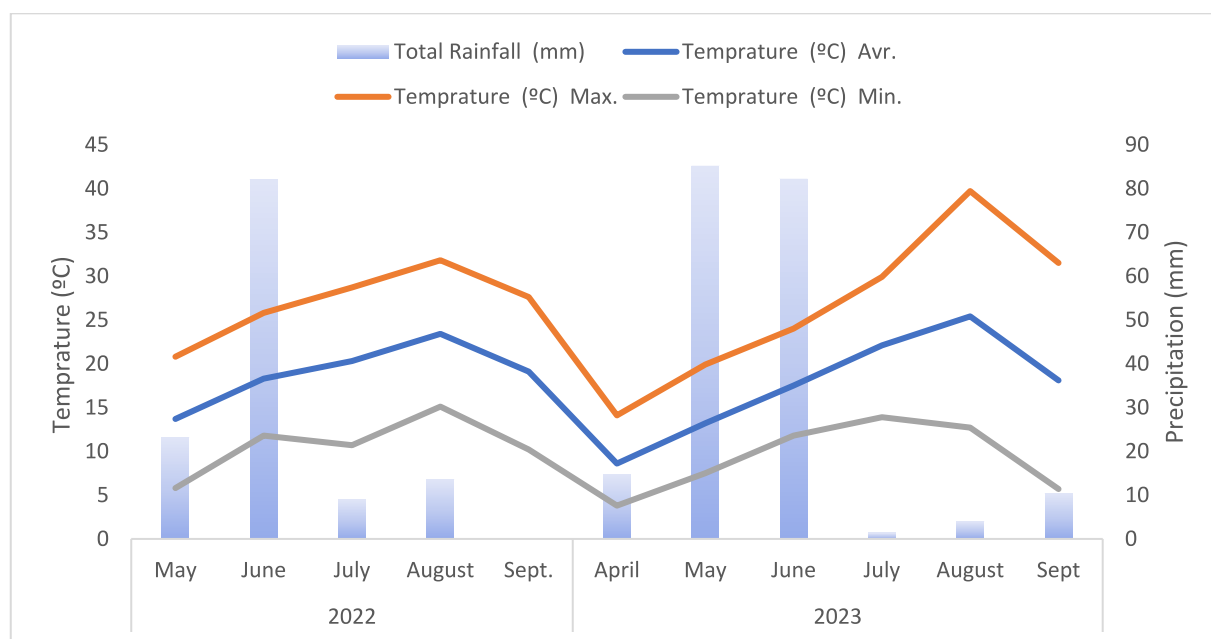


Fig. 1 Temperature and rainfall information for the research periods

seeding using a harrow and rake to create seed beds. The experiment was conducted according to a factorial experimental design within randomized complete blocks, consisting of 4 irrigation levels, 3 intermittent irrigation treatments, and 3 replications.

Irrigation

Subsurface drip irrigation system was utilized for irrigation. The irrigation water was sourced from the reservoir located in the experimental area. The irrigation systems in the experimental area comprised a pump, hydrocyclone, injection pump, screen filter, pressure gauges, pressure regulator, main valve, control valves for each plot, water meters, manifold pipelines, and drip irrigation pipelines equipped with internal pressure regulators. Laterals were installed at a depth of 0.35 m below the soil surface with lateral spacings set at 0.7 m intervals (Kanber 2010). In the conducted study, the calculation of irrigation water considered the soil depth of 0–0.6 m. Irrigation commenced when plants emerged and reached the 3–4 leaf stage, and irrigation was terminated when green seeds were observed in the capsules after flowering (Bannayan et al. 2008). Soil moisture content was determined using a neutron meter at depths of 0–0.3, 0.3–0.6, and 0.6–0.9 m in the soil. Prior to commencing irrigation, neutron meter readings taken at the same depths were graphically calibrated against values obtained using the gravimetric method to establish calibration equivalence.

Irrigation main and sub-topics were created as follows;

Main treatment: Deficit Irrigation.

- S1: Irrigation up to field capacity for 0.6 m soil depth.
- S2: Applying 66% of the water given to treatment S1.
- S3: Applying 33% of the water given to treatment S1.
- S0: Rain-based (non-irrigated) treatment.

Subtopics: Intermittent Irrigation.

- F0-The treatment where water is provided without interruption.
- F1-The treatment where the water is cut off once (intermittently).
- F2-The treatment where the water is cut off twice (with two intervals).

In the intermittent irrigation treatments, the duration of flow and interruption periods were kept equal to each other. For instance, if 30 mm of irrigation water was to be applied, in the case of the F1 staged treatment, 15 mm of water was provided, followed by an equal duration of interruption, and then the remaining 15 mm of water was applied (Elneer et al. 2015; Gültekin and Ertek 2023).

The calculation of the irrigation water applied to the plots was based on the following equation. Firstly, the volumetric soil water content was determined using a neutron probe for each soil depth being monitored with the following equation.

$$\theta h = a + b(SO) \quad (1)$$

In the equation: θh represents the volumetric soil water content (%); a is the calibration curve constant, b is the slope of the calibration curve; SO is the count ratio ($SO = S/SS$); S represents the neutron meter count-reading value; SS represents the standard count value. The volumetric water content obtained was converted to mm for each soil depth (0–0.3, 0.3–0.6, 0.6–0.9 m) as follows:

$$AM = \theta h \times \gamma_t \times D / 100 \quad (2)$$

In the equation: AM represents the actual soil moisture (mm); γ_t represents the bulk density of the soil (g cm^{-3}); D represents the depth of wetted soil (mm). The amount of irrigation water applied for each depth is calculated using Eq. 3.

$$I = \frac{FC - AM}{100} \times P \times I_c \quad (3)$$

In the equation: I : Net irrigation water amount (mm), FC : Field capacity (mm), AM : Actual soil moisture (mm), I_c : Irrigation coefficient, 1.0 for the S1 treatment, 0.66 for the S2 and 0.33 for the S3 treatment, P : Wetted area ratio (%).

The wetting ratio (P) was obtained by dividing the lateral spacing by the measured wetting diameter after irrigation at field capacity at the beginning of the experiment. Accordingly, the wetting ratio was determined as 0.7 for both years of the experiment. Plant water consumption for the experimental treatments is calculated using Eq. 4 based on the water budget, taking into account the measured soil moisture values before each irrigation application (Allen et al. 1998).

$$ET = I + P \pm DSW - DP - RO \quad (4)$$

where: ET : Crop water consumption, mm, I : Applied irrigation water, mm, P : Effective precipitation, mm, DP : Deep percolation, mm, DSW : Change in soil water content in the soil profile, mm, and RO : Surface runoff, mm.

Subsurface drip irrigation system was used in the study. During the vegetation period, the instantaneous rainfall amount was below 20 mm. Therefore, no surface runoff occurred due to irrigation water and rainfall. Water use efficiency (WUE) and irrigation water use efficiency ($IWUE$) were determined based on the ratio of crop water consumption to irrigation water application, using equations proposed by Howell et al. (1990).

$$WUE = Y / ET \quad (5)$$

In the equation: WUE : water use efficiency (kg m^{-3}), Y : seed yield (kg ha^{-1}), ET : crop water consumption (mm)

$$IWUE = Y / I \quad (6)$$

In the equation: $IWUE$: irrigation water use efficiency (kg m^{-3}), Y : seed yield (kg ha^{-1}).

In the research, the agricultural land requirement (ALR) required by different irrigation levels and intermittent numbers according to unit yield was calculated. For this purpose, equation number 7 was developed.

$$ALR = A / Y_a \quad (7)$$

In equality;

ALR : Agricultural land requirement for 1 ton of yield (ha).

A : Production area (taken as 1 ha).

Y_a : Actual yield amount (t ha^{-1}).

Statistical analysis

The data obtained from the study were analyzed with JMP v.17 computer software. ANOVA test was applied for variance analysis, while Tukey's multiple comparison test was applied for statistical differences between treatments.

Results and discussion

Irrigation

In both years of the research, all trial plots were first irrigated to field capacity level. Then, irrigation was applied five times throughout the vegetation period, according to the irrigation treatments. The detailed results of the study on the effect of intermittent and deficit irrigation practices on soil water distribution are presented in Gültekin et al. (2025). The water consumption values of the black cumin plant for the trial years are presented in Table 3. The graph showing the response of crop yield to irrigation water level is presented in Fig. 2.

Irrigations were conducted when 50% of the available water in the 0–60 cm soil profile was depleted. The S1F0 (continuous irrigation) treatment was considered as the control application. Thus, in the treatment without interruption (S1F0), irrigation was performed whenever the soil moisture value decreased by 50%. In intermittent irrigation, a waiting period equal to the time required for irrigation in each interval was applied. For example, in the S1F2 treatment, if a total of 30 mm of irrigation water was to be applied, 10 mm of water was applied first, followed by a waiting period equivalent to the time required for the 10 mm application. Then, another 10 mm of water was applied, and the process continued until the total of 30 mm was applied. At the end of the study, the average irrigation duration for each intermittent irrigation treatment is presented in Table 3. As seen in Table 3, the irrigation duration significantly increased with the number of intervals.

Table 3 Black cumin water consumption amounts (mm) for the years 2022 and 2023

Treatments	Irrigation (mm)	Rainfall (mm)	ΔS (mm)	ET (mm)	Yield (kg ha ⁻¹)	IWUE (kg m ⁻³)	WUE (kg m ⁻³)	ALR (ha)	AIDI (minutes)	ATID (minutes)
<i>Year 2022</i>										
S ₁ F ₀	238.2	127.8	-39.4	405.4	1967	0.83	0.49	0.51	392	392
S ₁ F ₁	238.2	127.8	-44.7	410.7	2223	0.93	0.54	0.45	196	588
S ₁ F ₂	238.2	127.8	-46.7	412.7	2034	0.85	0.49	0.49	131	654
S ₂ F ₀	165.7	127.8	-59.9	353.4	1449	0.87	0.41	0.69	225	225
S ₂ F ₁	165.7	127.8	-56.3	349.8	1428	0.86	0.41	0.70	113	338
S ₂ F ₂	165.7	127.8	-66.0	359.5	1617	0.98	0.45	0.62	75	375
S ₃ F ₀	95.4	127.8	-68.9	292.1	993	1.04	0.34	1.01	113	113
S ₃ F ₁	95.4	127.8	-73.2	296.4	1131	1.19	0.38	0.88	56	169
S ₃ F ₂	95.4	127.8	-63.9	287.1	1005	1.05	0.35	1.00	38	188
S ₀	15.0	127.8	-77.8	220.6	607	4.05	0.28	1.65	-	-
<i>Year 2023</i>										
S ₁ F ₀	254.5	198.0	35.2	417.2	1769	0.7	0.42	0.57	383	383
S ₁ F ₁	254.5	198.0	36.7	415.8	1896	0.75	0.46	0.53	192	575
S ₁ F ₂	254.5	198.0	27.9	424.6	1821	0.72	0.43	0.55	128	639
S ₂ F ₀	183.7	198.0	-16.0	397.7	1241	0.68	0.31	0.81	220	220
S ₂ F ₁	183.7	198.0	-16.8	398.4	1297	0.71	0.33	0.77	110	330
S ₂ F ₂	183.7	198.0	-21.3	402.9	1266	0.69	0.31	0.79	73	367
S ₃ F ₀	114.9	198.0	-28.1	341.0	962	0.84	0.28	1.04	110	110
S ₃ F ₁	114.9	198.0	-37.9	350.9	1141	0.99	0.33	0.88	55	165
S ₃ F ₂	114.9	198.0	-36.4	349.3	983	0.85	0.28	1.02	37	183
S ₀	46.2	198.0	-42.7	286.8	526	1.14	0.18	1.90	-	-

S₁: Irrigation at field capacity level, S₂: 66% of the water given to S₁, S₃: %33% of the water given to S₁, S₀: Rain-fed treatment, F₀: Treatment with continuous water application, F₁: Treatment where water is cut once, F₂: Treatment where water is cut twice, ΔS : Soil moisture difference, ET: Evapotranspiration, WUE: Water use efficiency, IWUE: Irrigation water use efficiency, ALR: Agricultural land requirement for 1 ton of yield, AIDI: Average irrigation duration per intermittent, ATID: Average total irrigation duration

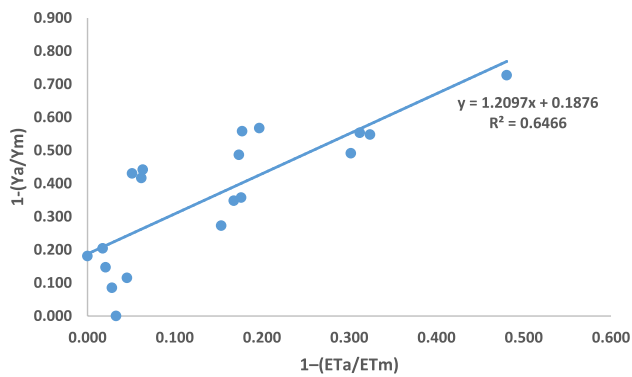


Fig. 2 Crop yield response factor (Cy). Ya: actual yield, Ym: Maximum yield, Eta: actual evapotranspiration, ETm: maximum evapotranspiration, Cy: Crop yield response factor

In the first year of the study, 238.2 mm of irrigation water was applied under full irrigation (S1), while in the second year, 254.5 mm of irrigation water was applied under full irrigation. In the second year of the experiment, due to sufficient soil moisture during the planting period, no supplementary irrigation was required. However, after plant emergence and when the plants reached a height of 4–5 cm, it was observed that the soil moisture level was much lower compared to the first year. Therefore, a much higher amount of irrigation water was applied to bring the soil moisture level to field capacity. It was determined that the ratio of the wetting diameter measured in the soil to the lateral spacing was approximately 0.7 after irrigation at field capacity level performed at the beginning of the experiment, and this value was used as the wetting ratio in irrigation applications.

In the first year of the study, the highest crop water consumption value of 412.7 mm was recorded in the S1F2 treatment, where irrigation was interrupted twice. The highest ET (evapotranspiration) value in the S2 treatment was observed at 359.5 mm in the S2F2 treatment, again where irrigation was interrupted twice. For the S3 irrigation treatment, the highest ET value was 296.4 mm, achieved in the S3F1 application. In the second year of the experiment, the highest ET values were obtained as 424.6, 402.9, and 350.9 mm for the S1F2, S2F2, and S3F1 treatments, respectively. Considering the ET values obtained over both years, it can be said that cutting irrigation twice in treatments at field capacity (FC) level and at 66% of FC increased the plant water consumption needs relatively. On the other hand, under deficit irrigation conditions where only 33% of FC was applied, cutting irrigation once (S3F1) relatively increased the plant water consumption amount compared to the other treatments.

In both years of the study, the water use efficiency (WUE) increased inversely with the irrigation level. The highest WUE values in both years were obtained with the S1F1 treatment, reaching 0.54 and 0.46 kg m⁻³, respectively. The lowest WUE values were observed in the rainfed (S0)

treatment. When examined in terms of area-based agricultural productivity, it was found that under irrigation levels without water stress (S1), the agricultural land requirement to achieve one ton of yield with the intermittent irrigation application (F1), where irrigation water was cutted once, was the lowest in both years. This indicates that under conditions of sufficient water resources, applying water in one interval requires less agricultural land, thus contributing to more environmentally friendly agricultural areas. This trend was generally consistent with deficit irrigation practices as well.

Research on regular irrigation practices using subsurface drip irrigation systems in black cumin (*Nigella sativa* L.) is quite limited. Literature reviews indicate that irrigations are typically applied either as supplementary irrigation without specifying any amount or are conducted in a limited number during critical periods of the plant. In addition, there are only a few studies aimed at determining plant water consumption and irrigation water requirements. In a study conducted in Iran, the water use efficiency of black cumin under furrow and drip irrigation systems was investigated. The study concluded that the average crop water consumption for black cumin over two years was reported to be 724 mm (Ghamarnia et al. 2014). In another study conducted in Iran, irrigation was applied to black cumin using drip irrigation. The study reported that irrigation was applied at weekly intervals, totaling 280 mm of irrigation water, and the ET (evapotranspiration) value was calculated as 660 m³ ha⁻¹ in the first year and 1549 m³ ha⁻¹ in the second year (Merajipoor et al. 2020). Şenyiğit and Arslan (2018) investigated the effects of different irrigation intervals on yield and quality parameters of black cumin crop under the conditions of Afyonkarahisar, using drip irrigation. In their study, they reported that the highest amount of irrigation water was approximately 255 mm at irrigation intervals of 5 and 10 days. They also found the highest and lowest ET (evapotranspiration) amounts to be at 387.6 mm for a 3-day irrigation interval and at field capacity (FC) level irrigation, and 166.9 mm for the rainfed condition, respectively. In a study conducted in Salamiyah, Iran, during 2018–2019, the highest average crop water consumption value, 440.3 mm, was obtained under full irrigation treatment (Yaghi et al 2024). In a study conducted in Kayseri, Turkey, in 2022, it was reported that the evapotranspiration (ET) value of black cumin under different levels of water restriction ranged between 182 and 425 mm (Irik et al. 2024). The ET values obtained in the study were found to be lower than those reported in some other research findings. One of the primary reasons for this is the use of a subsurface drip irrigation system, which significantly reduces evaporation. Additionally, the crop water consumption values and irrigation water amounts obtained in the study are similar to those reported by Şenyiğit and Arslan (2018), Merajipoor et al. (2020),

Irik et al (2024) and Yaghi et al (2024) while being lower than those found in other research findings. The irrigation water requirement for black cumin is influenced by various factors, including precipitation, soil properties, irrigation method, irrigation interval, plant variety characteristics, and other climatic features. When considering the water use efficiency (WUE), the obtained WUE values were found to be similar to Şenyiğit and Arslan 2018, but notably higher, especially in full irrigation treatments, compared to other literature findings (Ghamarnia 2010; Yousuf et al. 2021). In similar studies, the limited number of irrigation applications in black cumin, often conducted during phenological periods or as supplementary irrigation, has been considered a significant factor. Additionally, the variety characteristics of black cumin used in the study, as well as climate and soil properties, can also be considered as important factors influencing water and irrigation efficiency.

Plants like black cumin, which are naturally adapted to wild environments and rely on rainfall for growth, are generally expected to have low interaction with irrigation. However, when examining Fig. 2, which illustrates the water yield response factor, it is observed that the R^2 value is close to 1.00. Therefore, under conditions where irrigation facilities are available, cultivation of black cumin with irrigation is recommended.

Black cumin yield and some growth characteristics measurements

In order to determine the effect of intermittent irrigation practices on plant yield and physiological parameters, measurements were conducted at harvest in the study. Measurements were taken on two rows at the center of each experimental plot, with 20 plants measured from each plot. Accordingly, measurements were taken on parameters including Plant weight, Plant height, Number of branches, Number of capsules per plant, Number of seeds per capsule, Capsule diameter, Thousand-seed weight, and Seed yield in black cumin plants. The obtained values were subjected to statistical analysis. A literature review did not reveal any studies examining the effect of intermittent subsurface drip irrigation practices on yield and quality parameters of black cumin. Therefore, the yield and morphological parameters obtained in the study were evaluated solely in relation to irrigation levels. The variance analysis of the crop measurements is presented in Table 4.

When examining the variance analysis table for two years, it was found that the differences in the number of branches, number of seeds per capsule, and thousand grain weight were statistically significant across years, and evaluations for these parameters were made separately for each year. The interaction between irrigation and the number of intervals had a significant effect only on the average capsule diameter.

It was determined that intermittent irrigation practices alone impacted yield and the number of branches on the plant. It was identified that irrigation levels had a significant effect on all plant parameters.

Black cumin seed yield

Duncan grouping showing the effect of irrigation levels on black cumin seed yield is given in Table 5, and Duncan grouping for yield values obtained under interval applications is presented in Table 6.

In the variance analysis of seed yield in black cumin plants, no difference was found between the years. While the effect of irrigation treatments on black cumin yield was significant at the 1% error level ($p < 0.01$), the effect of intermittent treatments on seed yield was found to be significant at the 5% error level ($p < 0.05$). The interaction between irrigation and interval treatments on seed yield was found to be insignificant. Accordingly, it can be said that the effect of irrigation levels on seed yield is quite significant. The highest seed yield was obtained from the plot with the highest irrigation water (S1), reaching $1883.3 \text{ kg ha}^{-1}$, indicating a linear relationship between irrigation level and seed yield. Intermittent treatments showed a higher impact on seed yield compared to continuous irrigation practices. The highest seed yield was achieved in the F1 treatment, where water was cutted once, reaching $1282.5 \text{ kg ha}^{-1}$. Based on the findings, it can be concluded that providing irrigation water at certain intervals rather than continuously may significantly increase black cumin seed yield to meet plant water requirements. When comparing the obtained yield values with the literature, the obtained yield values were found to be similar to the findings of Yılmaz et al. (2020), Ürüsan (2016), and Şenyiğit and Arslan (2018), while they were higher than the findings of Yousuf et al. (2021) and Koşar and Özel (2018). It can be said that the differences in seed variety characteristics, climate, and irrigation practices used in the study have an impact on yield.

Average crop weight

In the variance analysis, plant weight showed significance at the 1% error level ($p < 0.001$) for irrigation treatments, and the year $\times$ intermittent irrigation relationship was significant at the 5% error level ($p < 0.05$). Duncan grouping for plant weights based on irrigation treatments is presented in Table 7, and Duncan grouping for the year $\times$ intermittent irrigation interaction is shown in Table 8.

When examining the effect of irrigation levels on plant weight, it can be observed that there is a linear relationship between irrigation amount and plant biomass. Each irrigation treatment formed a separate group in the statistical grouping. The highest average plant weight of 19.6 g was

Table 4 Variance analysis of black cumin plant

Source of Variation	df	Yield	Plant Weight	Plant Height	Number of Branches	Number of Capsules per Plant	Average Capsule Diameter	Number of Seeds per Capsule	Thousand Seed Weight
Year (Y)	1	ns	ns	ns	**	ns	ns	**	**
Irrigation (S)	3	**	**	**	**	**	**	**	**
Intermittent (F)	2	*	ns	ns	**	ns	ns	ns	ns
Y x S	3	ns	ns	ns	**	ns	ns	**	ns
Y x F	2	ns	*	ns	ns	ns	ns	ns	ns
S x F	6	ns	ns	ns	ns	ns	**	ns	ns
Error	71	188,182.6	2182.9	1679.3	122.5	4821.5	130.4	30,239.9	10.9
CV(%)		13.3	14.1	7.0	9.7	18.0	4.7	10.7	10.9

ns: not statistically significant; * Significant at the 5% level; ** Significant at the 1% level

Table 5 Statistical grouping of black cumin seed yield by irrigation treatments

Irrigation treatments	Average yields (kg ha ⁻¹)
S ₀	566.0 d ± 79.4
S ₁	1883.4 a ± 242.8
S ₂	1382.4 b ± 182.7
S ₃	1035.8 c ± 136.9

S₁: Irrigation at field capacity level, S₂: 66% of the water given to S₁, S₃: %33% of the water given to S₁, S₀: Rain-fed treatment

Table 6 Statistical grouping of black cumin seed yield by interval treatments

Intermittent treatments	Average yields (kg ha ⁻¹)
F ₀	1163.5 b ± 442.5
F ₁	1282.5 a ± 523.0
F ₂	1204.8 ab ± 526.1

F₀: Treatment with continuous water application, F₁: Treatment where water is cut once, F₂: Treatment where water is cut twice

obtained in the S1 irrigation treatment, while the weight of 6.0 g obtained in the rainfall-based treatment was the lowest. In the first year of the study, the highest plant biomass value in intermittent irrigation treatments was obtained in the F1 treatment (13.5 g), where water was cut once, followed by 12.4 g in the F2 treatment, where water was cut twice. The plant biomass value obtained in the F0 treatment represented the lowest group. In the second year of the study, the highest plant biomass value was 13.3 g in the F0 treatment, followed by 13.1 g in the F0 treatment. The plant weight values obtained in the study were found to be similar to those of El-Leithy et al. (2019), higher than those of Hosseini et al. (2018), and lower than those of Pavankumar et al. (2018). The differences in black cumin variety characteristics as well

Table 7 Duncan grouping for plant weights according to irrigation treatments

Irrigation treatments	Average plant weight (g)
S ₀	6.0 d ± 0.4
S ₁	19.6 a ± 2.9
S ₂	15.0 b ± 2.1
S ₃	9.9 c ± 1.6

S₁: Irrigation at field capacity level, S₂: 66% of the water given to S₁, S₃: %33% of the water given to S₁, S₀: Rain-fed treatment

as the variations in irrigation and fertilization practices used in the study have influenced the obtained results.

Plant height

In the variance analysis, only the effect of irrigation levels was found to be significant on plant height ($p < 0.001$). Accordingly, Duncan grouping table based on irrigation levels is provided in Table 9.

When examining the values related to plant height, it was observed that up to 33% deficit irrigation in black cumin did not create a statistically significant difference in plant height compared to full irrigation. The 66% water deficit application resulted in a plant height statistically similar to the rainfall-based treatment, and these two treatments were placed in the same group. Accordingly, the highest average plant height of 52.0 cm was obtained in the S1 treatment, while the lowest average plant height of 42.3 cm was obtained in the S0 treatment. When comparing the plant height values obtained in the study with the literature, the findings were similar to those of Muhammad et al. (2017) and Can et al. (2021), while they were lower than those of Koşar and Özel (2018), Kılıç and Arabacı (2016), and Kizilyildirim and

Table 8 Duncan grouping for Year×intermittent irrigation interaction

Year	Intermittent treatments	Plant weight (g)
2022	F ₀	10.8 b ± 4.0
	F ₁	13.5 a ± 5.3
	F ₂	12.4 ab ± 5.9
2023	F ₀	13.3 a ± 5.6
	F ₁	13.1 a ± 5.5
	F ₂	12.8 ab ± 5.3

F₀: Treatment with continuous water application, F₁: Treatment where water is cut once, F₂: Treatment where water is cut twice

Table 9 Duncan grouping for plant height according to irrigation levels

Irrigation treatments	Average plant height (cm)
S ₀	42.3 b ± 1.5
S ₁	52.0 a ± 4.1
S ₂	49.4 a ± 1.8
S ₃	44.3 b ± 3.2

S₁: Irrigation at field capacity level, S₂: 66% of the water given to S₁, S₃: %33% of the water given to S₁, S₀: Rain-fed treatment

Osman (2021). The differences in black cumin variety and genotype characteristics, as well as variations in fertilizer and irrigation practices, along with climatic conditions, may have contributed to the differences in the findings obtained in the study.

Number of branches

In the two-year variance analysis, significant differences were found between the years regarding the number of branches per plant. Therefore, variance analyses and Duncan grouping for each experimental year were conducted separately. Accordingly, the Duncan grouping for the effect of irrigation levels on the number of branches is presented in Table 10, while the Duncan grouping for the effect of cropping on the number of branches is presented in Table 11.

When evaluating the results of the variance analysis conducted for each year regarding the number of branches per plant, it was found that the effects of irrigation levels and intermittent treatments were significant on the number of branches in the 2022 data ($p < 0.001$). However, in the second year of the study, only the effect of irrigation levels was found to be significant ($p < 0.001$). Upon examining the Duncan groupings, in the first year of the study, irrigation levels S₁ and S₂ constituted the treatments with the highest impact on the number of branches. Regarding intermittent treatments, the effects of treatments F₁ and F₂ were found

Table 10 Number of branches per plant according to irrigation levels

Irrigation treatments	Number of branches per plant	
	Year 2022	Year 2023
S ₀	4.9 c ± 0.4	4.6 d ± 0.4
S ₁	7.0 a ± 0.9	8.2 a ± 0.5
S ₂	6.9 a ± 0.8	7.2 b ± 0.5
S ₃	5.9 b ± 0.4	6.3 c ± 0.9

S₁: Irrigation at field capacity level, S₂: 66% of the water given to S₁, S₃: %33% of the water given to S₁, S₀: Rain-fed treatment

Table 11 Number of branches per plant according to intermittent treatments

Intermittent treatments	Number of branches per plant	
	Year 2022	Year 2023
F ₀	5.7 b ± 0.6	6.4 ± 1.3
F ₁	6.5 a ± 1.1	6.5 ± 1.5
F ₂	6.5 a ± 1.2	6.8 ± 1.5

F₀: Treatment with continuous water application, F₁: Treatment where water is cut once, F₂: Treatment where water is cut twice

to be the most significant on the number of branches. In the second year of the study, the effect of each irrigation treatment on the number of branches was distributed across different importance groups. It was determined that as the irrigation level increased, the number of branches also significantly increased. The effect of intermittent treatments on the number of branches in the 2023 data was not statistically significant. In the literature review, the number of branches per plant obtained in the study was found to be similar to the findings of Ürüşan (2016) and Tulukçu (2015), while higher than the results of Can et al. (2021) and Yılmaz et al. (2020), and lower than the findings of Kizilyildirim and Osman (2021). The differences in the varieties of black cumin used in the research and the variations in the research methodology are considered to have an impact on the number of branches per plant obtained.

Capsule number per plant

The variance analysis revealed that only the effect of irrigation levels was significant on the number of capsules per plant ($p < 0.001$). Duncan grouping according to irrigation levels is provided in Table 12.

The variance analysis results regarding the average number of capsules per plant found the effect of irrigation levels to be statistically significant. As irrigation levels increased, the average number of capsules also increased. In the Duncan grouping, each irrigation level formed a separate group, with the highest average number of capsules per plant

obtained in the S1 irrigation treatment, with an average of 30.3 capsules per plant.

When the obtained values for the number of capsules per plant in the study were compared with the literature, it was observed that the values obtained, especially for the S1 and S2 irrigation levels, were significantly similar to the findings of Kizilyildirim and Osman (2021) and Aysabar and Gedik (2022), while higher values were obtained compared to Keser and Gedik (2021), Mengistu et al. (2021) and Yilmaz et al., (2020) research findings. Due to limited studies on the effect of irrigation treatments on physiological parameters of black cumin plants and the fact that the studies in the literature were conducted under limited irrigation treatments, it can be said that these differences indicate that irrigation treatments increased the number of capsules in black cumin.

Capsule diameter

The interaction between irrigation level and number of intervals was found to be significant ($p < 0.001$) in the variance analysis conducted on capsule diameter. The Duncan grouping for the mean capsule diameter obtained according to irrigation levels and number of intervals is presented in Table 13.

In the variance analysis conducted for both years of the study, the effect of irrigation water level and applied intermittent irrigation levels on capsule diameter in *Nigella sativa* L. was found to be statistically significant. The highest capsule diameter value of 12.8 mm was obtained in the S1F1 treatment. Additionally, as the amount of irrigation water applied increased, a significant increase in capsule diameter was observed. In the S2 irrigation level, where 66% of the required water was applied, an increase in the number of intermittent irrigation intervals led to higher capsule diameter, indicating that shorter intervals between watering resulted in larger capsules. Specifically, in the S2F2 treatment under this deficit irrigation level, a higher capsule diameter (11.6 mm) was achieved compared to other intermittent irrigation treatments. Moreover, under the higher

water constraint of the S3 irrigation level, continuous irrigation contributed to a larger capsule diameter compared to intermittent irrigation treatments. This suggests that reducing the interruption duration or adopting continuous irrigation practices could be more beneficial, especially under deficit irrigation conditions. Studies investigating the impact of irrigation practices on black cumin and those focusing on determining capsule diameter are indeed scarce. The capsule diameter values obtained in this study were found to be higher compared to the findings of Yousuf et al. (2021), Hosseini et al. (2018), and Ali et al. (2016). This variance can be attributed to differences in the characteristics of the *Nigella sativa* varieties used in the study, as well as differences in climate, irrigation, and fertilization practices. The influence of these factors suggests that agricultural outcomes, such as capsule diameter in black cumin plants, can vary significantly based on environmental conditions and cultivation practices. This emphasizes the importance of considering local conditions and varietal characteristics when optimizing cultivation practices for the best yield and quality outcomes.

Number of seeds per capsule

Since the differences between years in the average number of seeds were found to be statistically significant, variance analyzes and Duncan grouping for each trial year were performed separately. In the first year of the experiment, the statistical grouping of irrigation level $\times$ intermittent interaction is presented in Table 14, while the Duncan grouping for the effect of irrigation levels on number of seeds per capsule in the second year of the experiment is provided in Table 15.

Table 12 Number of capsules per plant according to irrigation levels

Irrigation treatments	Number of capsules per plant
S ₀	12.3 d $\pm$ 0.8
S ₁	30.3 a $\pm$ 6.6
S ₂	25.8 b $\pm$ 3.7
S ₃	17.4 c $\pm$ 3.5

S₁: Irrigation at field capacity level, S₂: 66% of the water given to S₁, S₃: %33% of the water given to S₁, S₀: Rain-fed treatment

Table 13 Effect of irrigation level $\times$ intermittent irrigation levels interaction on capsule diameter

Irrigation level $\times$ Intermittent treatments interaction (S $\times$ F)	Capsule diameter (mm)
S ₀ F ₀	9.3 ef $\pm$ 0.3
S ₀ F ₁	9.1 ef $\pm$ 0.6
S ₀ F ₂	8.9 f $\pm$ 0.7
S ₁ F ₀	12.3 ab $\pm$ 0.3
S ₁ F ₁	12.8 a $\pm$ 0.7
S ₁ F ₂	12.0 ab $\pm$ 0.3
S ₂ F ₀	10.5 d $\pm$ 0.5
S ₂ F ₁	10.8 cd $\pm$ 0.6
S ₂ F ₂	11.6 bc $\pm$ 0.4
S ₃ F ₀	10.5 d $\pm$ 0.5
S ₃ F ₁	10.0 de $\pm$ 0.8
S ₃ F ₂	10.0 de $\pm$ 0.2

S₁: Irrigation at field capacity level, S₂: 66% of the water given to S₁, S₃: %33% of the water given to S₁, S₀: Rain-fed treatment, F₀: Treatment with continuous water application, F₁: Treatment where water is cut once, F₂: Treatment where water is cut twice

When evaluating the results of the variance analysis conducted for each year regarding the average seed number per capsule, it was found that the irrigation level x intermittent irrigation interaction had a statistically significant effect on the seed number per capsule in the year 2022 ($p < 0.001$), while in the second year of the study, the effect of irrigation levels was found to be significant ($p < 0.001$). Upon examining the Duncan grouping, in the first year of the study, the highest seed number per capsule was obtained in the full irrigation treatments, and water was cut once and twice (S1F1, S1F2) with 117.1 and 117.3, respectively. Similarly, it was observed that intermittent irrigation practices significantly increased the seed number per capsule compared to continuous irrigation practices in deficit irrigation applications where 66% of the water requirement was met. In the S3 treatment, where 33% of the water requirement was met, continuous irrigation and one-time cutted (F1) irrigation practices were found to have a more significant effect on seed number per capsule compared to two-times cutted (F2) irrigation. When the effect of irrigation levels on seed number per capsule in black cumin crop was examined in the second year of the study, it was observed that the seed number per capsule increased significantly with the increase in irrigation levels. In the S1 irrigation level where water scarcity was not applied, approximately 25% more seeds per capsule were obtained compared to the S2 application, approximately 46% more compared to the S3 application, and approximately 75% more compared to the S0 application. In the study, it can be said that the seed number per capsule obtained is higher than the values reported in the literature (Hosseini et al. 2018; Ali et al. 2016; Şenyiğit and Arslan 2018; Pavankumar et al. 2018). Particularly in irrigation treatments without water stress (S1), the seed number per capsule was found to be significantly higher. The limited findings in the literature related to the cultivation of black cumin based on irrigation methodology, as well as morphological characteristics of the plant variety and climatic conditions, can be considered as factors influencing the seed number per capsule.

Thousand-seed weight

Due to statistically significant differences between years in the average thousand-seed weight as determined by the variance analysis, variance analyses and Duncan grouping were conducted separately for each trial year. The Duncan grouping for thousand-seed weight according to irrigation levels for both years of the trial is provided in Table 16.

In the two-year field trial conducted, variance analyses for both research years found the effect of irrigation levels on the thousand-seed weight to be statistically significant.

Table 14 Effect of irrigation level x intermittent interaction on average seed number per capsule in 2022

Irrigation level x Intermittent treatments (S x F)	Average seed number per capsule
S ₁ F ₀	107.4 a-c ± 5.3
S ₁ F ₁	117.1 a ± 6.1
S ₁ F ₂	117.3 a ± 5.8
S ₂ F ₀	90.3 c-d ± 4.3
S ₂ F ₁	102.9 a-c ± 3.7
S ₂ F ₂	114.8 a-b ± 9.8
S ₃ F ₀	94.2 b-c ± 8.5
S ₃ F ₁	93.4 b-c ± 3.8
S ₃ F ₂	87.2 c-d ± 3.0
S ₀ F ₀	69.2 d ± 3.2
S ₀ F ₁	69.3 d ± 2.5
S ₀ F ₂	69.3 d ± 2.9

S₁: Irrigation at field capacity level, S₂: 66% of the water given to S₁, S₃: %33% of the water given to S₁, S₀: Rain-fed treatment, F₀: Treatment with continuous water application, F₁: Treatment where water is cut once, F₂: Treatment where water is cut twice

Table 15 Effect of irrigation levels on the average number of seeds per capsule in 2023

Irrigation level	Average seed number per capsule
S ₀	65.9 c ± 3.0
S ₁	115.2 a ± 15.8
S ₂	91.9 b ± 12.8
S ₃	79.1 b-c ± 11.8

S₁: Irrigation at field capacity level, S₂: 66% of the water given to S₁, S₃: %33% of the water given to S₁, S₀: Rain-fed treatment

In 2022 and 2023, the highest thousand-seed weight values were obtained in the S1 treatment, with 3.14 and 3.23 g, respectively. In the statistical analysis for the first year of the study, although the highest thousand-seed weight value was achieved at the S1 irrigation level, it was determined to be statistically in the same group as the S2 and S3 treatments. In the statistical analysis for the second year of the study, the S1 treatment had the highest thousand-seed weight and was determined to be significantly higher than the other treatments on its own. The other treatments were in the same group, showing that the differences between them were similar in terms of significance levels. When comparing the thousand-seed weight results obtained in this study with the literature, the findings were significantly similar to those of Pavankumar et al. (2018), while they were higher than the findings of Bannayan et al.

(2008), Yousuf et al. (2021), and Kizilyildirim & Osman (2021). The differences in irrigation methodology, climatic conditions, and varietal characteristics used in these studies are considered to be significant factors influencing the results obtained.

Correlation and principal component analysis

The effect of irrigation levels intermittent numbers applied in the research on the physiological parameters of the black cumin plant was evaluated by Principal Component Analysis (PCA). Additionally, the relationship between plant physiological parameters was revealed by correlation analysis. The Biplot chart for Principal Component Analysis is given in Fig. 3 and the Correlation matrix is given in Fig. 4.

Evaluating the relationship between irrigation and interval applications with the physiological parameters of black cumin (*Nigella sativa*) using PCA analysis and a biplot graph has yielded significant findings. The first two principal components explain 97.5% of the total variance, indicating that these components effectively summarize the majority of the variation in the analyzed parameters. PC1 represents high positive loadings for parameters such as yield (YLD), plant weight (CW), plant height (PH), number of branches (NB), number of capsules per plant (NC), number of seeds per capsule (NSC), and thousand-seed weight (TSW). These parameters exhibit similar patterns of variation and are strongly correlated with PC1. Capsule diameter (CD), while also positively loaded, shows a relatively lower correlation compared to the other parameters on PC1.

Examining the irrigation and interval applications, the combination of full irrigation (S1) and one-time water cut (F1) is strongly associated with high yield and favorable physiological parameters. This combination stands out as the optimal irrigation and interval strategy for enhancing the physiological performance of black cumin plants. In the biplot graph, parameters under the S1F1 application are aligned with the vectors indicating positive loadings, demonstrating the beneficial effects of this combination on plant health and yield. Similarly, the combination of full

irrigation (S1) and two-time water cut (F2) also shows high performance. This combination is strongly associated with the physiological parameters that have high positive loadings on PC1, suggesting that S1F2 can also enhance yield and quality in black cumin production. Lower irrigation levels such as S2 (66% of S1) and S3 (33% of S1), as well as rain-fed (S0) applications, are situated near vectors with negative loadings in the biplot graph. This indicates that S3 and S0 irrigation practices result in significantly reduced yield and unfavorable physiological parameters. Optimal growth conditions, as supported by the findings of this study, involve irrigation at field capacity levels (S1) with intermittent irrigation strategies such as S1F1 and S1F2. These approaches maximize yield and enhance plant health, as evidenced by the significant positive correlations observed between yield and plant physiological traits like capsule diameter and weight. Darakeh et al. (2021) reported that black cumin plants produce higher yield and quality seeds under optimal growth conditions. Similarly, a study by Aryafar et al. (2021) highlighted the positive effects of regular irrigation and water stress management on black cumin yield. These studies support the notion that full irrigation and strategic water cuts can positively influence plant health and yield. Additionally, a study by Ozer et al. (2020) demonstrated that water stress significantly reduces yield and quality parameters in black cumin plants. In conclusion, PCA analysis and the biplot graph clearly illustrate the impact of irrigation and interval applications on the physiological parameters of black cumin plants. Optimal irrigation management and water cut strategies play a crucial role in enhancing plant health and yield. These findings underscore the importance of careful planning of irrigation strategies in agricultural practices to optimize black cumin production through effective water management.

Correlation analysis between plant parameters reveals the strength and direction of relationships between specific variables. When the correlation matrix is examined, it is seen that there are high correlations between some plant parameters. Firstly, a strong positive correlation was observed between YLD (yield) and CW (capsule weight) ($r=0.85$). This indicates that as capsule weight increases, plant yield also increases. Capsule weight emerges as an important determinant of yield, suggesting that practices aimed at increasing capsule weight could positively impact yield. This relationship is supported by the literature, where Yousuf et al. (2018) found that increasing capsule weight led to higher plant yield. Similarly, Day et al. (2023) highlighted the direct impact of capsule weight on yield. Additionally, there is a high positive correlation between NC (number of capsules) and NB (number of capsules per plant) ($r=0.80$), demonstrating that an increase in the number of capsules per plant directly relates to an increase in the total number of capsules. This relationship underscores the importance of

Table 16 Effect of irrigation levels on black cumin thousand grain weight in 2022 and 2023

Irrigation level	Average thousand grain weight in 2022 (g)	Average thousand grain weight in 2023 (g)
S ₀	2.69 b ± 0.21	2.37 b ± 0.19
S ₁	3.14 a ± 0.14	3.23 a ± 0.35
S ₂	2.98 a-b ± 0.26	2.73 b ± 0.46
S ₃	2.80 a-b ± 0.14	2.51 b ± 0.27

S₁: Irrigation at field capacity level, S₂: 66% of the water given to S₁, S₃: %33% of the water given to S₁, S₀: Rain-fed treatment

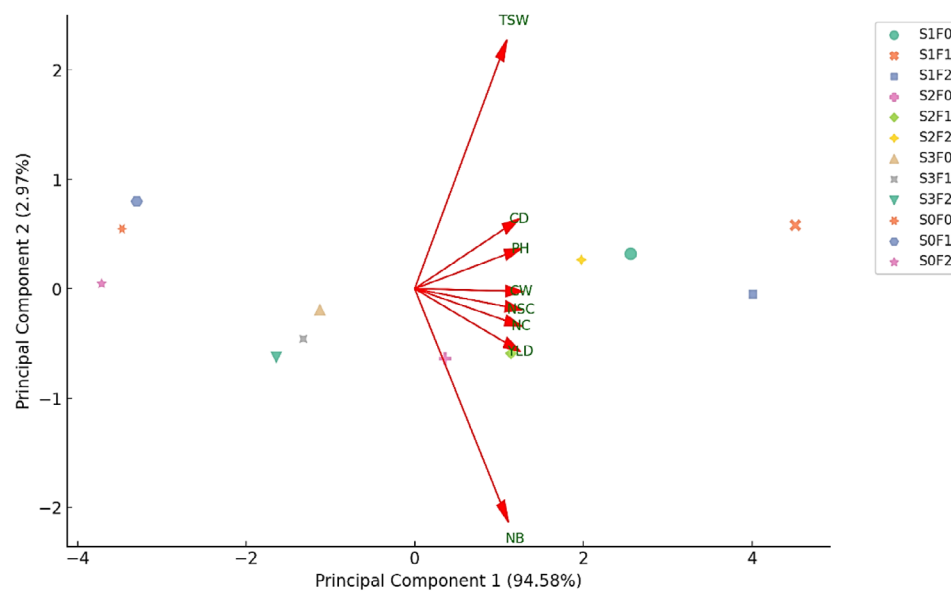


Fig. 3 Biplot of black cumin physiological parameters. S_1 : Irrigation at field capacity level, S_2 : 66% of the water given to S_1 , S_3 : 33% of the water given to S_1 , S_0 : Rain-fed treatment, F_0 : Treatment with continuous water application, F_1 : Treatment where water is cut once, F_2 : Treatment where water is cut twice, YLD: Yield, PW: Plant weight, PH: Plant height, NB: Number of branches, NC: Number of capsules per plant, CD: Capsule diameter, NSC: Number of seeds per capsule, TSW: Thousand-seed weight

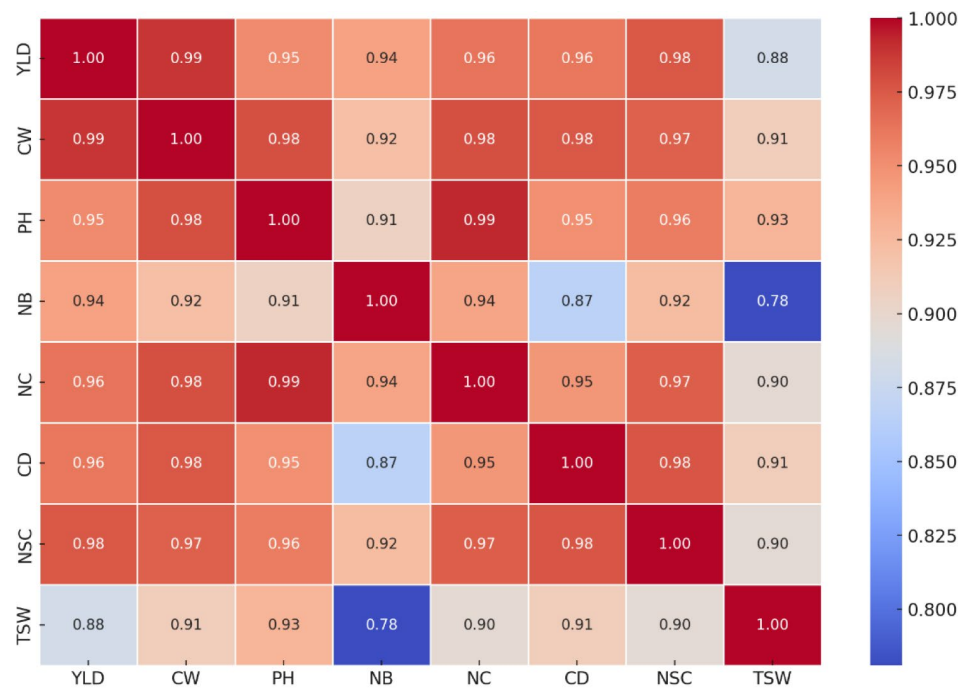


Fig. 4 Correlation matrix between black cumin physiological parameters. YLD: Yield, PW: Plant weight, PH: Plant height, NB: Number of branches, NC: Number of capsules per plant, CD: Capsule diameter, NSC: Number of seeds per capsule, TSW: Thousand-seed weight

plant density and capsule formation on overall yield. This finding aligns with the study by Karim et al. (2017), which showed that increasing the number of capsules per plant directly affects the total capsule count. A significant positive correlation between PH (plant height) and NSC (number of nodes) ($r=0.78$) was also found. As plant height increases, the number of nodes also increases, indicating the influence of plant height on node formation during the growth process. This strong relationship provides important insights into the effects of plant morphology on yield and other agronomic traits. Reaz (2016) similarly observed that as plant height increased, so did the number of nodes, emphasizing the impact of plant height on node formation. Lastly, there is a high positive correlation between CD (capsule diameter) and CW (capsule weight) ($r=0.77$). As capsule diameter increases, so does capsule weight, highlighting the critical role of capsule size in determining capsule weight. Practices aimed at increasing capsule diameter could be effective in enhancing capsule weight and, consequently, plant yield. This relationship is supported by Ozer et al. (2020), who found that increasing capsule diameter significantly affects capsule weight and yield.

Conclusion

In a two-year field experiment conducted under Ankara conditions, it was observed that irrigation levels created statistically significant differences in all physiological parameters, particularly yield, of black cumin. With an increase in irrigation water amount, both yield and physiological parameters of black cumin showed a significant increase. When the effects of irrigation intervals were examined, statistically significant differences were observed in seed yield, number of branches, biomass, and capsule diameter parameters. This study revealed that intermittent irrigation applications are effective in improving black cumin yield compared to continuous irrigation. Specifically, the highest yield and favorable physiological parameters were observed when soil moisture content was maintained between 80 and 100% of field capacity under the S1 (full irrigation) treatments. The S1F1 and S1F2 applications optimized yield and critical physiological parameters such as capsule diameter (Tables 4 and 13). For areas where drip irrigation is not feasible, these findings emphasize the importance of maintaining optimal soil moisture levels through alternative methods such as manual or furrow irrigation.

When examining the effect of intermittent irrigation levels under different irrigation water levels on plant water consumption, it was observed that each irrigation level exhibited quite similar water consumption values within itself. This indicates that the effect of intermittent irrigation application on plant water consumption is relatively low under a

certain irrigation water level application. On the other hand, considering the agricultural land requirement (ALR) necessary for one ton of product, it was found that generally lower agricultural land requirement was observed in the F1 application, where the waiting period between two irrigations was the longest. In this regard, intermittent irrigation application may indirectly contribute positively by reducing the agricultural land requirement.

Drip irrigation with both deficit and intermittent irrigation applications was tested in black cumin plants as a unique study aimed at increasing water use efficiency in agriculture. The level of increase in yield and morphological parameters with irrigation may vary for medicinal and aromatic plants. Black cumin is an important agricultural crop both as an oil-seed and a spice plant in Turkey and worldwide. Especially, the changes in yield and quality with irrigation for newly registered varieties are open topics for research. Economic analysis approaches (irrigation costs, income from the crop) for irrigation application in black cumin should be considered as subjects open to research. Although intermittent irrigation application increases water use efficiency, it also significantly prolongs the irrigation duration. Therefore, it is advisable to automate intermittent irrigation practices in drip irrigation. Furthermore, developing irrigation practices supported by artificial intelligence integrated with soil physiology presents some research opportunities in this field.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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