RESEARCH

Open Access

Potential use of crop water stress index (CWSI) and spectral vegetation indices for black cumin under deficit irrigation

Hasan Ali Irik[1*], Engin Kaymaz[2], Pembe Saban Polu[3], Erman Beyzi[4], İhsan Serkan Varol[1], Ali Unlukara[1] and Halil Kirnak[5]

Abstract

This study was carried out in 2022 to examine the yield, yield components and changes in crop water stress index (CWSI) and vegetation index in black cumin with deficit irrigation. Five different irrigation water levels (I_0, I_{25}, I_{50}, I_{75}, I_{100}) were used. The amount of irrigation water applied changed between 20 and 276 mm. Plant water consumption (ET) values varied between 182 and 425 mm. The highest seed yields were obtained from I_{100} treatments (692 t ha^{-1}) and the lowest from I_0 treatments (25 t ha^{-1}). Biological yield, plant height, stem diameter, first capsule height, number of capsules per plant, number of branches per plant, number of seeds per capsule and 1000-seed weight of black cumin were affected by deficit irrigation. CWSI lower limit equation to be used in irrigation scheduling was identified Tc−Ta = − 1.7524 × VPD + 0.7698 (R^2 = 0.54) and the upper limit 10.9 ℃. For black cumin plants, irrigation is recommended when the CWSI value is between 0.08 and 0.12. 9 different spectral vegetation indices were evaluated in this study. It has been determined that there are significant correlations between yield, yield components and CWSI and spectral vegetation indices.

Keywords Black cumin, Deficit irrigation, CWSI, Vegetation indices

Introduction

Droughts emerge as the most important effects of global climate change on terrestrial ecosystems. It is also an important environmental abiotic stress factor that has reduced crop yields worldwide in recent years [1]. Agricultural drought not only indicates soil water status but also can be used to reflect the degree of soil water deficiency, plant growth and morphology, as well as plant water needs [2]. Therefore, accurate monitoring and assessment of crop water stress is not only the key to scientific countermeasures to reduce adverse effects but also fundamental research in terms of monitoring, warning and evaluation of agricultural drought [3].

Traditional methods for monitoring crop water stress are largely dependent on soil moisture measurements or the determination of matric potential in the effective root zone [4]. However, it is often difficult to account for soil heterogeneity in the field and in addition, soil water status is an indirect way of determining true crop water status [5]. Remote sensing methods such as spectral vegetation indices and infrared thermometers have been actively used in the monitoring of plant water stress in recent years due to their reliability, data collection speed and no damage to the plant [6].

*Correspondence:
Hasan Ali Irik
haliirik42@gmail.com
[1] Department of Biosystems Engineering, Faculty of Agriculture, University of Erciyes, Kayseri, Türkiye
[2] Department of Research and Development, Kayseri Sugar Beet Factory, Kayseri, Türkiye
[3] Department of Biosystems Engineering, Institute of Graduate School of Natural and Applied Sciences, University of Erciyes, Kayseri, Türkiye
[4] Department of Field Crops, Faculty of Agriculture, University of Erciyes, Kayseri, Türkiye
[5] Department of Construction Technology, Vocational School, University of Cukurova, Adana, Türkiye

Irik *et al. Environmental Sciences Europe*   (2024) 36:93

Page 2 of 14

Generally, field-based spectro-radiometry techniques and remote monitoring and evaluation studies cover the structural and biochemical contents of the plant such as chlorophyll, nitrogen content and water content. Among these, it makes important contributions to the remote estimation of vegetation water content, determination of the physiological state of the vegetation, decision of irrigation time and drought assessment [7–9].

Canopy temperature is used as the most practical way to learn about plant water status. Plant stomata close up, transpiration and photosynthesis decrease and plant canopy temperature rises in response to soil moisture depletion. Therefore, plants under water stress will generally have less transpiration and higher leaf temperatures than plants that are not stressed [10]. Crop water stress index (CWSI), calculated with the use of the difference in plant canopy temperature and air temperature and the vapor pressure deficit, has gained importance in recent years [11–13].

Black cumin (*Nigella sativa* L.) is an annual herb native to Egypt and the Eastern Mediterranean, mostly grown in arid and semi-arid areas. Nigella sativa is highly popular as a spice in culinary and foodstuffs. It is also commonly used in traditional medicine and industrial pharmacology. It is now widely used in traditional medicine for asthma, bronchitis, rheumatism, headaches and backaches, and hypertension, as well as in the treatment of skin and eczema diseases [14]. Black cumin essential oil is used in cosmetics and pharmacy.

As it was in other parts of the world, most of the medicinal and aromatic plants are collected from their natural habitats in Türkiye and they are not cultivated [15]. It is expected that the cultivation of black cumin, which has a high export potential, and increasing the amount of production with irrigated agriculture will meet the demands of both domestic and foreign markets and bring significant income to the farmers [16].

This study was conducted to (1) investigate the effects of different irrigation water levels on yield and quality parameters of black cumin, (2) determine the potential use of CWSI value in irrigation scheduling and threshold value in irrigation, (3) determine the potential use of vegetation indices in the estimation of plant characteristics through the reflections at different irrigation water levels.

Material and method
Experimental area
This study was carried out over the experimental fields of Erciyes University Agricultural Research Center (ERU-TAM) in 2022. Experimental fields are located in Kayseri province between 35° 30' east longitudes and 38°41´ north latitudes and have an altitude of 1084 m. The experimental area has a dominant terrestrial climate with hot-dry summers and cold-snowy winters. According to long-term meteorological data, Kayseri province has an average annual temperature of 10.7 °C, the average temperature of the coldest month (January) is − 1.7 °C and the temperature difference (Tmax−Tmin) is 28.9 °C. The hottest month is July with an average temperature of 30.6 °C and a temperature difference of 18.7 °C. Climate data for the year 2022 are provided in Table 1.

Soil samples were taken from 0 to 30, 30 to 60, 60 to 90 and 90 to 120 cm depths of 3 different locations representing the entire trial area. Soil texture, electrical conductivity (EC), field capacity (FC), permanent wilting point (PWP), bulk density, organic matter, lime, nitrogen, phosphorus and potassium contents were determined. Analysis results are provided in Table 2. The soil texture was generally loamy and there was no salinity problem. EC values varied between 0.173 and 0.258 dS m^{-1} and pH values varied between 8.13 and 8.17.

Infiltration tests were conducted at 3 different locations with a double-ring infiltrometer to determine the soil infiltration rates. Infiltration tests revealed the stable infiltration rate of the soil as 23.3 mm/h.

Irrigation water quality parameters (electrical conductivity, anion, and cation contents) were determined with the use of the methods specified in Tüzüner et al. [17]. Irrigation water samples were taken from the well and analysis results are given in Table 3. Irrigation water

Table 1 Climate data for the year 2022

Years	Months	T_{min} (°C)	T_{max} (°C)	T_{avr} (°C)	RH_{min} (%)	RH_{max} (%)	RH_{avr} (%)	u_2 (m s^{-1})	Precipitation (mm)
2022	April	6.45	20.78	13.61	28.25	68.40	48.32	2.59	15.2
	May	7.25	19.44	13.34	26.17	46.13	36.15	1.93	77.8
	June	13.71	27.29	20.50	36.90	82.34	59.62	1.99	54.5
	July	13.42	29.79	21.61	28.38	74.57	51.47	2.26	0.3
	August	16.90	33.95	25.42	22.85	62.29	42.57	1.84	0
	September	9.82	26.59	18.20	27.83	76.30	52.07	1.63	58.1
	October	4.86	19.85	12.36	37.44	95.31	66.37	0.99	17.9

Irik *et al. Environmental Sciences Europe* (2024) 36:93

Page 3 of 14

Table 2 Soil physical and chemical properties

Depth (cm)	Texture	EC (dS m^{-1})	pH	FC (%) P$_w$	PWP (%) P$_w$	Bulk density (g cm^{-3})	Organic matter (%)	Lime (%)	N (kg da^{-1})	P$_2$O$_5$ (kg da^{-1})	K$_2$SO$_4$ (kg da^{-1})
0–30	Loam	0.220	8.13	25.5	10.7	1.27	1.25	2.5	2.15	2.05	27.16
30–60	Loam	0.173	8.17	23.3	11.4	1.24	1.05	5.8	1.05	1.15	37.64
60–90	Clay Loam	0.258	8.14	26.0	9.4	1.22	0.69	3.2	0.4	0.6	31.01
90–120	Loam	0.191	8.23	25.0	9.4	1.28	0.73	6.2	0.4	0.2	31.01

FC field capacity, *PWP* permanent wilting point, *EC* electrical conductivity

Table 3 Irrigation water quality parameters

pH	EC (µS)	Na + (mg ha^{-1})	K + (mg ha^{-1})	Ca + 2 (mg ha^{-1})	Mg + 2 (mg ha^{-1})	HCO3 (mg ha^{-1})	CO3-2 (mg ha^{-1})	SAR
7.60	242	11.6	4.57	26.4	6.63	12.2	< 1.0	2.86

quality class was identified as C1S1 without and pH and EC problems.

Experimental design and agronomic practices

Çameli black cumin cultivar registered by Eskişehir Transition Zone Research Institute was used as the plant material of the experiments. Experiments were conducted in randomized block design with 3 replications in the 2022 growing season. Sowing was performed manually to have 25 cm row spacing, 2 cm sowing depth and 2 kg da^{-1} sowing density. Plots were 5 m long and each plot had 6 plant rows. A spacing of 2 m was provided between the plots and 2.5 m between the blocks. Side rows and 0.5 m from the top and bottom of the plots were considered as side effects, observations and measurements were made on middle rows. Based on soil analysis results, N, P and K fertilizers were applied at the dose of 10, 6 and 3 kg da^{-1}, respectively. While phosphorus and potassium fertilizers were applied at once before sowing; half of the nitrogen fertilizer was applied at sowing and the remaining half was applied at the flowering stage of the plants.

Sowing was performed on April 4, 2022. Following the sowing, manual weed control was practiced twice. Due to the differences in irrigation water levels, vegetation periods have changed, so the treatments were not harvested at the same time. Harvest was practiced when the capsules reached sufficient maturity. The earliest harvests were made from I$_0$ treatments with a water stress and the latest from I$_{100}$ treatments without water stress. The I$_0$ treatments were harvested on the 5th of August, I$_{25}$ treatments on the 19th of August, I$_{50}$ treatments on the 2nd of September, I$_{75}$ treatments on the 8th of September and I$_{100}$ treatments on the 16th of September 2022.

Irrigation system and irrigation treatments

The drip irrigation method was used for the irrigation of black cumin plants. Dripper spacing was 0.33 m, dripper discharge was 4 lt/h, the lateral diameter was 20 mm, the manifold pipe diameter was 40 mm and the main pipe diameter was 63 mm. Irrigation schedules were made based on the principle of supplying certain percentages of depleted moisture within the plant root zone. Scheduled irrigations were initiated when 35–40% of available moisture with the effective root zone was depleted. Plant effective root depth was taken as 6 cm [18]. Irrigation

Table 4 Irrigation treatments

Treatments	Irrigation water quantities
I$_{100}$	Full irrigation
I$_{75}$	75% of full irrigation
I$_{50}$	50% of full irrigation
I$_{25}$	25% of full irrigation
I$_0$	Rain-fed (only with emergence irrigation)

treatments used in the present experiments are provided in Table 4.

In full irrigation treatments (I$_{100}$), irrigations were initiated when 35–40% of the available moisture within the effective root zone was depleted and soil moisture was brough to field capacity each time. In deficit irrigations (I$_{75}$, I$_{50}$ and I$_{25}$), a certain percentage of full irrigation was practiced. The amount of irrigation water to be applied (mm) was determined with the use of the following equation:

$$d = \frac{(P_{vFC} - P_{vm})}{100} \times D$$

where; d: Amount of irrigation water to be applied, mm; P$_{vFC}$: Field capacity in percent by volume,%; P$_{vm}$: Soil moisture before irrigation in percent by volume,%; D: Soil depth to be wetted, mm. The resultant value (mm) was multiplied by the area to be irrigated (m^2) to convert the amount of water to be applied into liters (L). The amount of irrigation water calculated for each treatment was separately applied through water meters.

Soil moisture was monitored gravimetrically. Soil samples were taken throughout the effective root zone twice a week and moisture contents were determined accordingly.

Plant water consumptions were determined with the use of water budget equation given in by James [19].

$$ET = I + R + Cr - Dp - Rf \pm \Delta s$$

where; ET; Plant water consumption (mm), I; Irrigation water quantity (mm), R; Effective precipitation (mm), Cr; Capillary rise (mm), Dp; Deep percolation (mm), Rf; Runoff (mm), Δs; Change in soil moisture (mm).

Since the water was applied to bring the depleted moisture to field capacity, deep percolations were assumed to be zero. Since there were buffer zones

Irik *et al. Environmental Sciences Europe*   (2024) 36:93

Page 5 of 14

between the plots and a drip irrigation system was used, runoff was also assumed to be zero. Since there was no groundwater up to 5–6 m depth, capillary rise was not expected. Change in soil moisture was monitored at 60–90 cm depth to see if there were any deep percolations.

Water use efficiencies (water productivity, WP; irrigation water productivity, IWP) were calculated with the following equations given in [20]:

$$WP = \frac{E_Y}{ET}; IWP = \frac{(Ey - Eyo)}{I}$$

where; WP = Water productivity (kg/m^3); Ey = Economical yield (kg/ha); Ey$_0$ = Yield of rainfed treatment (kg/ha); ET = Plant water consumption (mm), IWP = Irrigation water productivity (kg/m^3); I = Irrigation water (mm).

Stewart model [21] was used to assess the relationship between the proportional ET deficit and the proportional yield reduction and the yield-response factor (ky).

$$\left(1 - \frac{Y_a}{Y_m}\right) = k_y\left(1 - \frac{ET_a}{ET_m}\right)$$

where; Y$_a$ = Actual yield (kg/ha); Y$_m$ = Maximum yield (kg/ha); k$_y$ = Yield-response factor; ET$_a$ = Actual plant water consumption (mm); ET$_m$ = Maximum water consumption (mm).

Crop water stress index (CWSI)

Everest 100 L model infrared thermometer (IRT) with an 8–14 μm spectral band range and 4 degrees viewing angle was used to determine the vegetation temperature. Black objects, whose surface temperature can be determined, were used in the calibration of the IRT device [22].

Canopy temperature measurements were made between 13:00 and 14:00 when the weather was completely clear or the clouds did not block the sun. Canopy temperature measurements were made at least 3 days a week, before and after irrigation, when the above-mentioned conditions were met. The average canopy temperature of a plot was found by taking the average of 12 measurements, 3 replicates in each plot, in the direction of diagonals of the plot. Plant canopy temperatures were measured with a portable infrared thermometer (IRT). To keep the soil surface out of the field of view of the IRT, canopy temperature was determined by directing the IRT to the plant surface at an angle of 30-40° with the horizontal. During the measurement of plant canopy temperatures, air temperature and relative humidity values were also recorded.

Crop water stress index (CWSI) was calculated with the use of the following equation given in Idso et al. [23]:

$$CWSI = \frac{[(T_c - T_a) - LL]}{UL - LL}$$

where: Tc, vegetation cover temperature; Ta, air temperature; LL, lower limit of water stress and UL, upper limit of water stress.

Spectral vegetation indices

ASD Hand-Held 2 brand portable handheld spectroradiometer was used to measure spectral reflectance ratios. With the ASD Hand-Held 2 device, measurements can be taken in the wavelength range of 325–1075 nm with 1 nm steps. Before each radiance measurement with a spectroradiometer, irradiance measurements were made with the device using a spectralon panel. By taking the ratio of radiance to irradiance, spectral reflectance values were calculated for each wavelength. Measurements were made twice a week when the weather was cloudless and the sun angle was 45 degrees. In all treatments, readings were taken from 5 plants selected from the plots and each plant in 3 replications. Accordingly, 15 readings were taken from each plot in total, with 5 measurements in each replication. Vegetation indices were calculated with the data obtained through these readings. In the present study, 9 different vegetation indices were used (Table 5).

Morphological observations and measurements

Plant Height, Stem Diameter, First Capsule Height: Measurements were made on 10 randomly selected plants of each harvest plot. Plant height was measured as the distance from the soil surface to the tip of the plant. The stem diameter was measured from the first internode with a digital caliper. The first capsule height was determined as the height of the lowest capsule from the ground.

Number of Branches per Plant, Number of Capsules per Plant, Number of Seeds per Capsule: Ten plants were randomly selected from each plot. A number of branches of each plant was counted and an average of 10 measurements was taken. The same procedures were repeated for many capsules and several seeds.

Thousand-Seed Weight: From each plot, 100 seeds were weighed in replicates. The average of these 4 weights was then multiplied by 10 to get 1000-seed weight.

Statistical analyses

Experimental data were subjected to variance analysis with the use of SAS [32] software. Significant means were compared with the use of Least Square Difference (LSD) test.

Irik *et al. Environmental Sciences Europe*   (2024) 36:93

Page 6 of 14

Table 5 Spectral vegetation indices

Spectral vegetation indices	Equation	References
EVI (Enhanced vegetation index)	$EVI = 2.5 \times \frac{R800-R680}{R800+6\times R680-7.5\times R480+1}$	[24]
NPCI (Normalized pigment chlorophyll index)	$NPCI = \frac{R680-R430}{R680+R430}$	[25]
GNDVI (Green normalized difference vegetation index)	$GNDVI = \frac{R800-R550}{R800+R550}$	[26]
NDVI (Normalized difference vegetation index)	$NDVI = \frac{R800-R680}{R800+R680}$	[27]
MCARI (Modified chlorophyll absorption ratio index)	$MCARI = \left[(R700 - R670) - 0.2 \times (R700 - R550)\frac{R700}{R670}\right]$	[28]
OSAVI (Optimized soil adjusted vegetation index)	$OSAVI = \frac{(1+0.16)(R800-R680)}{(R800+R680+0.16)}$	[29]
SAVI (Soil adjusted vegetation index)	$SAVI = \frac{(1+0.5)(R800-R680)}{(R800+R680+L)}$	[30]
SR (Simple ratio)	$SR = \frac{R900}{R680}$	[31]
WI (Water index)	$WI = \frac{R900}{R970}$	[27]

R680, R800, R480, R430, R550, R970, R700 and R670 express spectral reflectance ratios measured at 680, 800, 480, 430, 550, 970, 700 and 670 nm wavelengths, respectively

Table 6 Effects of different irrigation levels on I, ET, WP, IWUE and yield of black cumin

	I (mm)	ET (mm)	WP (kg m^{-3})	IWP* (kg m^{-3})	Yield (kg ha^{-1})**
I0	20	182	–	–	25c
I25	84	240	1.48	3.94a	356b
I50	148	269	1.73	2.97b	465b
I75	212	370	1.72	2.89b	638a
I100	276	425	1.63	2.42c	692a

** Significant at $p < 0.01$

* Significant at $p < 0.05$

Results and discussion

Irrigation water quantity, plant water consumption (ET), water productivity and yield

Irrigation water quantity (I), plant water consumption (ET), water productivity (WP), Irrigation water productivity (IWP) and yield values of irrigation treatments are provided in Table 6.

Sowing was performed on April 4, 2022 and 20 mm emergence irrigation was practiced to ensure homogeneous emergence. Throughout the growing season, a total of 102.5 mm precipitation was received. Scheduled irrigations were initiated on the 17th of June and the last irrigation was practiced on the 2nd of August. The amount of irrigation water applied to black cumin plants varied between 20 and 276 mm ($I_0 = 20$ mm, $I_{25} = 84$ mm, $I_{50} = 148$ mm, $I_{75} = 212$ mm and $I_{100} = 276$ mm). Ozer et al. [33] conducted a study in Erzurum for irrigation of black cumin plants based on evaporations from Class-A pan and reported the highest irrigation water applications as 230.2 mm in 2014 and 270.3 mm in 2015. Senyıgıt and Arslan [16] reported that the amount of irrigation water applied to black cumin plants varied between 122.5 and 255.6 mm in 2013 and between 97 and 209.2 mm in 2014.

Plant water consumption (ET) values of different irrigation treatments varied between 182 and 425 mm. ET values increased with increasing irrigation water levels. As compared to I_{100} treatments, 12.9, 36.7, 43.5 and 57.2% decreases were seen in I_{75}, I_{50}, I_{25} and I_0 treatments, respectively. Senyıgıt and Arslan [16] conducted a study in Afyonkarahisar in 2014 with the use of a Class-A pan and reported water consumption values of black cumin plants as between 166.9 and 350.5 mm and indicated that ET values decreased with increasing water deficits.

The highest WP (1.73 kg/m^3) was obtained from I_{50} treatments and the lowest (1.48 kg/m^3) from I_{25} treatments. IWP values varied between 2.42 and 3.94 kg/m^3 with the lowest value from I_{100} and the highest from I_{25} treatments (Table 6). Ghamarnia et al. [34] reported the WP value as 1.39 kg/m^3 for 50% water deficit and as 1.10 kg/m^3 for full irrigation treatments. Ghamarnia and Jalili [35] reported WP values as between 0.12 and 1.87 kg/m^3. Ozer et al. [33] reported IWP values of black cumin as between 0.56 and 0.93 kg/m^3 in 2014 and between 0.57 and 0.87 kg/m^3 in 2015. Present differences could be attributed to differences in climate parameters and irrigation programs.

Different irrigation water levels had significant effects on yields ($p < 0.01$). The lowest seed yield (25 kg/ha) was obtained from I_0 treatments and the highest (692 kg/ha) from I_{100} treatments. I_{75} and I_{100} treatments were placed into the same statistical group (Table 6). There was a significant increase in yield with increasing irrigation water levels [35]. Reported average seed yields of black cumin as between 23 and 905 kg/ha in the first year and between 28.5 and 1131 kg/ha in the second year. In other studies, it was reported that black cumin yields increased with increasing irrigation water levels [33, 36, 37].

Effects of irrigation on morphological parameters

Effects of different irrigation water levels on biological yield, plant height, stem diameter, first capsule height, number of capsules per plant, number of branches per plant, number of seeds per capsule and 1000-seed weight of black cumin are provided in Table 7.

Different irrigation water levels had significant effects on the morphological parameters of black cumin ($p < 0.01$) (Table 7). Significant decreases were observed in morphological parameters with increasing water deficits.

Biological yield was significantly affected by irrigation treatments ($p < 0.01$). Increasing values were seen with increasing irrigation water levels. The lowest biological yield (116.7 kg ha^{-1}) was obtained from rain-fed (I_0) treatments and the highest (1680 kg ha^{-1}) from full-irrigation (I_{100}) treatments. As compared to full-irrigation, a 93.1% yield reduction was seen in rain-fed treatments. Ghamarnia et al. [34] reported biological yield as 1050.5 kg ha^{-1} for full-irrigation and 827.4 kg ha^{-1} for 50% water deficit. In another study, it was reported that water stressed reduced the biological yield of black cumin [36]. Sufficient moisture levels maintain a high photosynthetic rate, which can increase cell elongation and proliferation much faster. Drought stress significantly alters photosynthetic pigments and components. Such a case reduces the activities of Calvin cycle enzymes, which in turn results in yield reduction [38, 39].

Irrigation treatments resulted in significant differences in plant heights of black cumin (Table 7). The lowest plant height and stem diameter (26.3 cm and 1.5 mm) were obtained from I_0 treatments and the highest from I_{100} treatments (47.3 cm and 2.3 mm). Both plant height and stem diameter decreased with increasing water stress. Drought stress encountered during vegetative growth reduces cell division and cell elongation [40]. Similar findings were also reported in previous studies for black cumin [16, 33, 41].

Irrigation treatments had highly significant effects on number of branches and number of capsules per plant (Table 7). The highest number of branches was observed in the I_{100} and I_{75} treatments (4.27 and 4.0) and the lowest number of branches was seen in I_0 and I_{25} treatments (1.93 and 2.13). The highest number of capsules per plant was obtained from I_{100} and I_{75} treatments (4 capsules) and the lowest from I_0 treatments (1.93 capsules). Previous studies also reported highly significant effects of irrigations on number of branches and capsules per plant [37, 42, 43]. A high number of branches is desired in black cumin farming since higher number of branches means higher seed yields [44].

The number of seeds per capsule is directly related to seed yield and thus is the most important yield component of black cumin. Drought stress can cause a significant yield loss by affecting the number of seeds. Deficit irrigations had highly significant effects on number of seeds per capsule (Table 7). Significant decreases were seen in some seeds per capsule with increasing water stress. The highest number of seeds per capsule (70 seeds) was obtained from full-irrigation and the lowest (25 seeds) from rain-fed treatments. [33], and [37] indicated that plant water requirements should fully be met to achieve the highest number of seeds per capsule. Negative effects of water stress during the flowering and seed-filling stages are well known and possible drought stress in these stages reduces the number of capsules and seeds, thus generating negative effects on yield [45].

The effect of deficit irrigations on 1000-seed weights was found to be significant ($p < 0.01$). The lowest 1000-seed weight was observed in I_0 (1.66 g) and the highest from I_{75} (2.55 g) treatments. Gutierrez-Prieto and Kirici [46] reported the highest 1000-seed weight for 30% water deficit.

Yield-response factor

The relative yield loss that occurs when the irrigation water requirement of the plant is not met fully is a measure of the response of that plant to water stress. Yield-response factor (ky) is obtained from the relationship established between the relative loss in yield versus the

Table 7 Effects of irrigations on morphological parameters of black cumin

	Biological yield** (kg/ha)	Plant height**	Stem diameter**	Number of capsules per plant**	Number of branches per plant**	Number of seeds per capsule**	1000-seed weight** (gr)
I0	116.7c	26.31d	1.47dc	1.90c	1.93c	25.09c	1.66c
I25	762.7b	35.38c	1.43d	2.10c	2.13c	53.67b	2.35b
I50	1500a	40.87b	1.84bc	3.00b	3.10b	63.00ab	2.39b
I75	1493.3a	42.63ab	2.05ab	4.00a	4.00a	64.67ab	2.55a
I100	1680a	47.33a	2.29a	4.00a	4.27a	70.33a	2.32b

** Significant at $p < 0.01$

Irik *et al. Environmental Sciences Europe*   (2024) 36:93
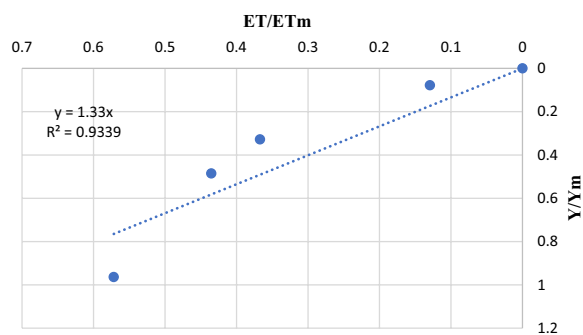
Page 8 of 14

Fig. 1 ky graph of the black cumin plant
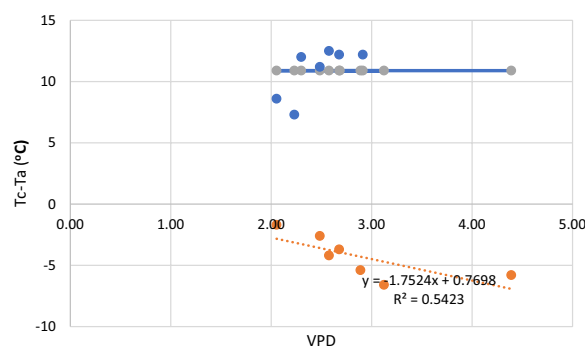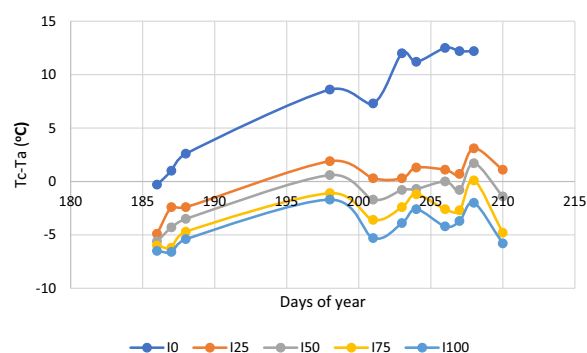

Fig. 3 CWSI base graph

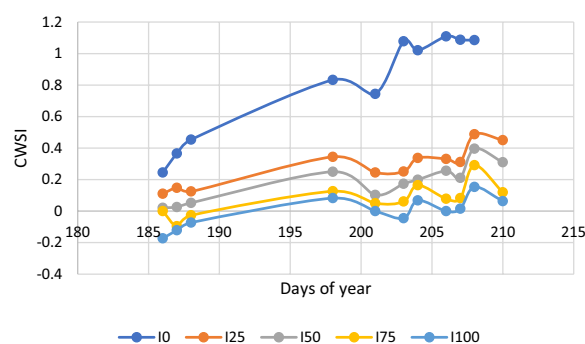**Fig. 2** Tc-Ta graph for irrigation treatments

Fig. 4 Treatment-based change in CWSI

decrease in relative water consumption. If the ky value is greater than 1, the plant is sensitive to water stress and if the ky value is less than 1, the plant is tolerant to water stress [21]. Since the yield-response factor is a parameter that is frequently used in water-yield studies, it is important for sustainable agriculture to determine the value of the decrease in yield in response to water deficits on a seasonal basis and to plan irrigation programs accordingly [47].

The ky value of the black cumin plant was identified as 1.33 (Fig. 1). Such a value indicated that black cumin was sensitive to water stress. It can be stated that with the appropriate irrigation programs, there will be significant yield increases in black seed plants.

Crop water stress index (CWSI)
Canopy temperature measurements were started on July 6 and the last measurement was made on July 29. The Tc−Ta graph of irrigation treatments is presented in Fig. 2.

The Tc−Ta value increased with increasing water stress levels (Fig. 2). The Tc−Ta values became negative with increasing irrigation water levels. The highest Tc−Ta values were seen in the I_0 treatments with the greatest water stress and the lowest from the I_{100} treatments without

any water stresses. While the plant canopy temperature was above the air temperature in unirrigated conditions, canopy temperature approached the air temperature with the applied irrigation water and fell below the air temperature in treatments with water deficits below 50%. Although it changed based on air humidity under full irrigation conditions, black cumin kept the canopy temperature − 1.7 to − 6.6 °C below the air temperature. Under non-irrigated conditions, plant canopy temperature increased by 6.2 to 15.9 °C as compared to full irrigation conditions.

The graph, which is the basis for the calculation of CWSI value, was obtained using the empirical equation specified in [23] using Tc−Ta and vapor pressure deficit (VPD) values and is shown in Fig. 3.

The upper limit (UL) value was obtained from the I_0 treatment with the greatest water stress and the lower limit (LL) value was obtained from the I_{100} treatment without water stress. The LL equation was determined as Tc−Ta =− 1.7524×VPD+0.7698 (R^2=0.54) and UL as 10.9 °C.

Treatment-based change in CWSI prepared based on the principles specified in [23] is presented in Fig. 4.

It was seen that different irrigation treatments affected CWSI values (Fig. 4). Transpiration decreased with

Irik *et al. Environmental Sciences Europe*   (2024) 36:93

Page 9 of 14

increasing water stress, Tc−Ta values turned into positive and CWSI value increased above 1. On the other hand, Tc−Ta value was negative and CWSI value was low in plants that were sufficiently irrigated and potentially transpired. Seasonal CWSI values for I_0, I_{25}, I_{50}, I_{75} and I_{100} treatments were found to be 0.80, 0.35, 0.24, 0.12 and 0.08, respectively.
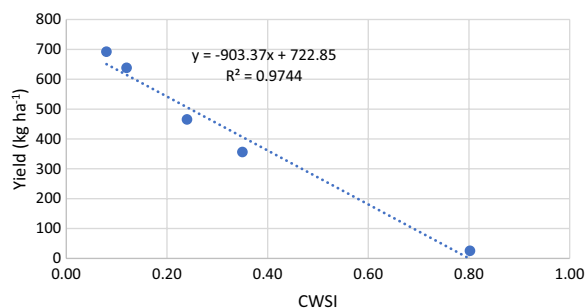
CWSI—yield relationships

The relationship between seasonal CWSI values and black cumin seed yield is presented in Fig. 5. There were significant correlations ($R^2 = 0.97$) between CWSI and yield. For yield estimation, the equation of Yield = − 903.37 × CWSI + 722.85 was obtained. Yields decreased with increasing CWSI and vice versa. Kirnak et al. [11] reported significant relationships between pumpkin seed yield and CWSI. Bozkurt Colak et al. [12] reported similar relationships for quinoa, [48] for mung bean and [49] for maize. It was indicated that CWSI could reliably be used for yield estimations.

Spectral reflectance values

Treatment-based change in spectral reflectance ratios is presented in Fig. 6.

In terms of spectral reflection ratios, there are significant differences between water-stressed and unstressed treatments. Water-stressed treatments had high reflection ratios at the visible wavelength (400–700 nm), whereas unstressed treatments had low reflection ratios. Such a case revealed that healthy plants absorbed more at the visible wavelength for photosynthesis, thus yielding lower reflection ratios. While there were high reflection ratios at the NIR wavelength (700–1400 nm) in treatments without water stress, the reflection ratios at this wavelength decreased in treatments under water stress. Stressed plants had higher reflection ratios in blue and red regions. Such a case could be attributed to a decrease in leaf water and the resultant decrease in photosynthetic pigment concentration. In addition, as the harvest approached, the difference in reflection ratios became

quite close to each other. Spectral reflections are largely affected by photosynthetic pigments [9]. Also, spectral reflectance is less affected by chlorophyll absorption properties beyond 730 nm in NIR and only changes if leaf morphology or water content changes in response to stress. If the stress is well developed and beyond the shortwave infrared, the effect of water absorption is better perceived near 970 nm [50–52].

Relationships between vegetation indices and yield

Spectral reflectance ratios were used to assess the relationships between vegetation indices and yields (Fig. 7). In the present experiments, 10 vegetation indices were examined. Since there is no study on vegetation indices of black cumin, comparisons were made with the other plants.

There were significant linear relationships between yield and vegetation indices (excluding GNDVI). The yield had the greatest correlation with EVI ($R^2 = 0.97$) and the lowest with WI ($R^2 = 0.42$). There was no significant relationship between GNDVI and yield. Irik and Kirnak [9] reported significant correlations of pumpkin seed yields with SR, NDVI, SAVI, EVI, GNDVI and OSAVI. In a study on tomatoes, it was reported that yield estimations could be made quickly and non-destructively with spectral data [53]. Coelho et al. [54] reported a significant relationship between NDVI and oat grain yield ($R^2 = 0.91$). Gopinath et al. [55] reported that vegetation indices can be used successfully in estimating rice yield. Saravia et al. [56] reported in their study on beans that the EVI was successful in yield prediction ($R^2 = 0.94$). Colovic et al. [51] emphasized the selection of appropriate indices to monitor the physiological response of plants to water stress.

Relationships between vegetation indices and morphological parameters
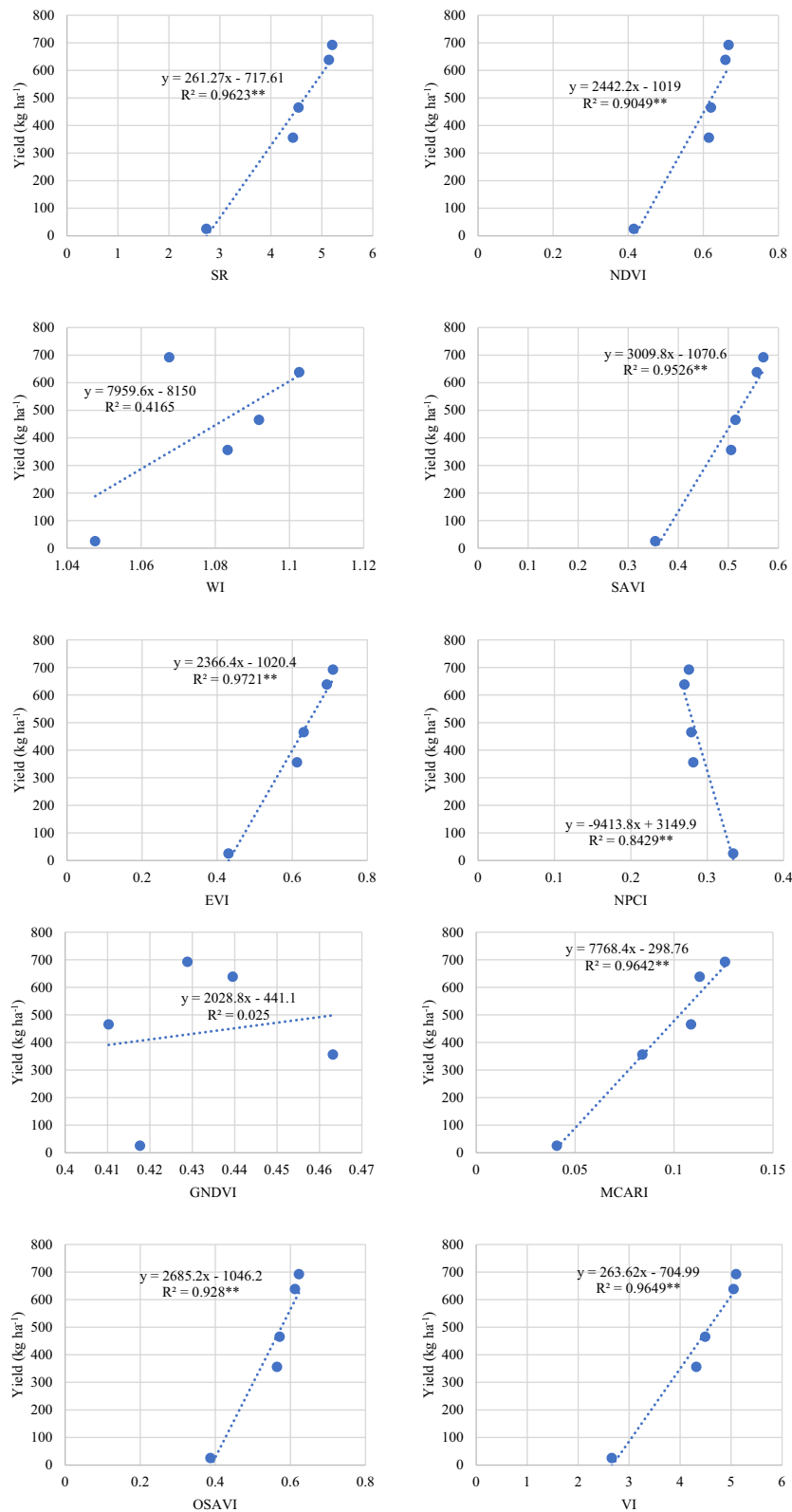
Relationships between vegetation indices and morphological parameters (plant height, number of seeds per capsule and 1000-seed weight) are provided in Table 8.

There were highly significant correlations between vegetation indices and morphological parameters (Table 8). Plant height had significant linear relationships with all vegetation indices. The highest correlation was obtained with MCARI ($R^2 = 0.99$) and the lowest with NDVI ($R^2 = 0.89$). Marino and Alvino [57] reported the relationships of wheat plant height with NDVI as between $R^2 = 0.52$–0.83 and with OSAVI as between $R^2 = 0.52$–0.82. Ryu et al. [58] reported the relationship of paddy plant height with NDVI as $R^2 = 0.93$.

The number of seeds per capsule had highly significant correlations with all vegetation indices. The highest correlations were encountered with SAVI, EVI and VI index

Fig. 5 CWSI—Yield relationships

Irik *et al. Environmental Sciences Europe*   (2024) 36:93

Page 10 of 14
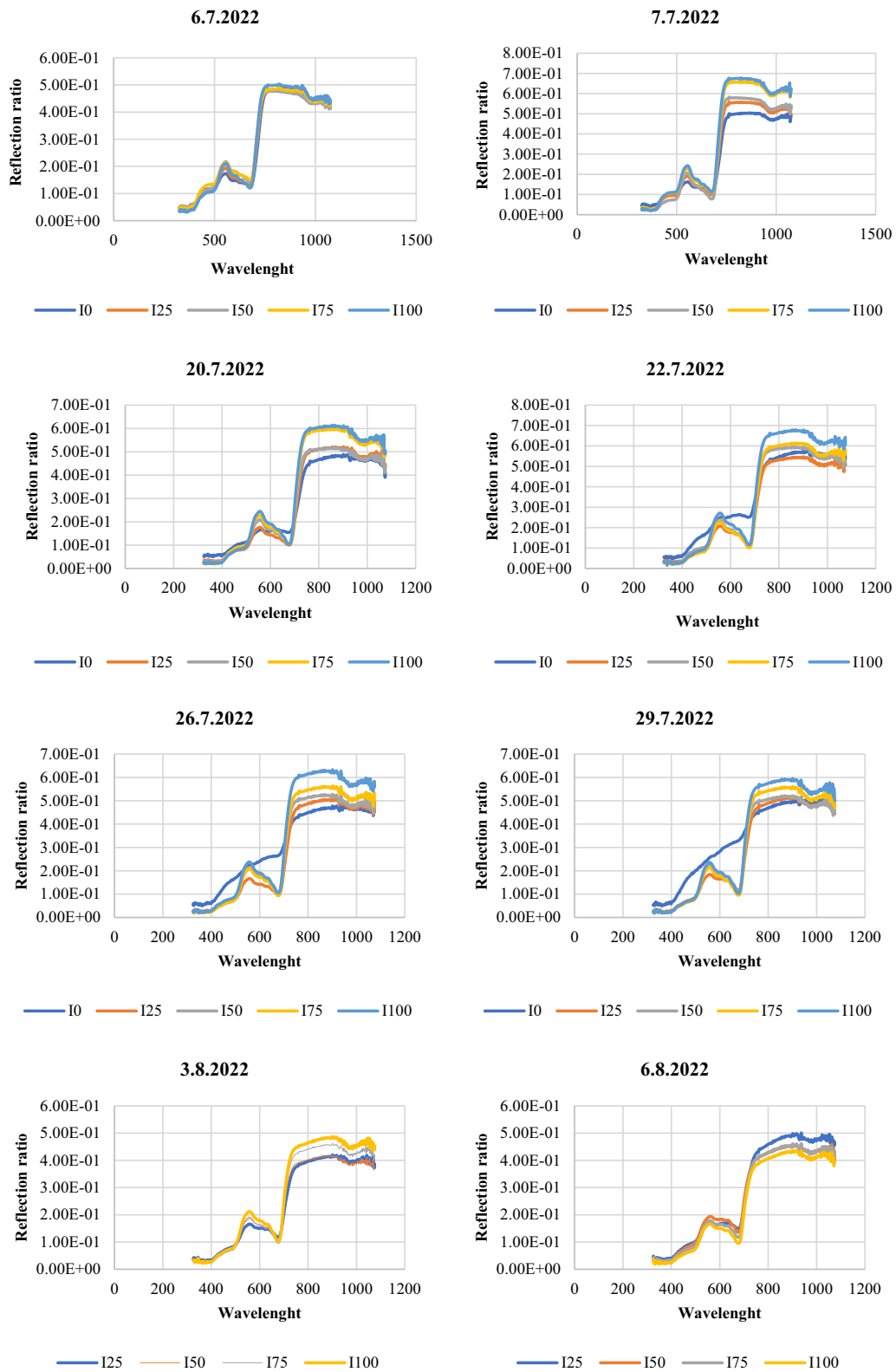
Fig. 6 Treatment-based spectral reflection ratios

Fig. 7 Relationships between vegetation indices and yields. **Significant at p < 0.01

Table 8 Relationships between vegetation indices and morphological parameters

VI	Plant height (cm)**	Number of seeds per capsule**	1000-seed weight**
SR	0.91	0.96	0.88
NDVI	0.87	0.96	0.92
SAVI	0.91	0.97	0.83
EVI	0.93	0.97	0.85
NPCI	0.79	0.93	0.97
MCARI	0.99	0.98	0.76
OSAVI	0.89	0.92	0.97
VI	0.92	0.97	0.88

** Significant at $p < 0.01$

($R^2 = 0.97$). It can be said that the number of seeds per capsule, an important yield parameter, could accurately be estimated with the use of spectral vegetation indices.

The 1000-seed weight also had significant correlations with vegetation indices $p < 0.01$. The lowest correlation was obtained with SAVI ($R^2 = 0.83$) and the highest with NPCI ($R^2 = 0.97$). Kaur et al. [59] reported significant correlations of wheat 1000-grain weight with NDVI and LCI indices.

Conclusions

In this study, changes in black cumin plants because of different irrigation water applications were tried to be revealed by using a spectroradiometer. Present findings revealed that irrigation played an important role in black cumin farming in arid and semi-arid regions.

The amount of irrigation water applied to black cumin plants varied between 20 and 276 mm and plant water consumption (ET) values varied between 182 and 425 mm. The lowest seed yield was obtained from I_0 treatments (25 kg/ha) and the highest from I_{100} treatments (692 kg/ha). The productivity increase achieved by irrigation was 27.7 times.

CWSI lower limit equation to be used in irrigation scheduling was identified Tc–Ta $= -$ 1.7524 × VPD + 0.7698 ($R^2 = 0.54$) and the upper limit 10.9 ºC. For black cumin plants, irrigation is recommended when the CWSI value is between 0.08 and 0.12. There was a significant relationship between CWSI and seed yield ($R^2 = 0.97$). It was concluded that CWSI could reliably be used in irrigation scheduling and yield estimation.

Increasing stress levels were encountered with increasing water deficits and plant response differed accordingly. As a result of the examinations made between 10 different vegetation indices and productivity, it was found that there were significant relationships between all indices except WI and GNDVI indices. The vegetation indices obtained by determining the changes in the visible and NIR regions, had significant correlations with morphological parameters such as yield, plant height, number of seeds per capsule and 1000-seed weight. It was concluded based on present findings that vegetation indices could reliably be used in irrigation programming and yield estimation of black cumin.

Author contributions
HAI: writing, data curation, investigation, methodology. EK: field work and analysis, PSP: field-work EB: field work, data curation, investigation, İSV: field-work, data curation, AU: investigation, methodology. HK: writing, data curation, investigation.

Declarations

References
1. IPCC (2007) Contribution of Working Groups I. II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Climate Change 2007: Synthesis Report. Geneva, Switzerland
2. Zhou S, Duursma RA, Medlyn BE, Kelly JWG, Prentice IC (2013) How should we model plant responses to dought? An analysis of stomatal and non-stomatal response to water stress. Agr Forest Meteorol 182–183:204–214. https://doi.org/10.1016/j.agrformet.2013.05.009
3. Zhang F, Zhou G (2019) Estimation of vegetation water content using hyperspectral vegetation indices: a comparison of crop water indicators in response to water stress treatments for summer maize. BMC Ecol 19:18. https://doi.org/10.1186/s12898-019-0233-0
4. Kumar N, Poddar A, Shankar V, Ojha CSP, Adeloye AJ (2020) Crop water stress index for scheduling irrigation of Indian mustard (*Brassica juncea*) based on water use efficiency considerations. J Agron Crop Sci 206(1):148–159
5. Pradawet C, Khongdee N, Pansak W, Spreer W, Hilger T, Cadisch G (2023) Thermal imaging for assessment of maize water stress and yield prediction under drought conditions. J Agron Crop Sci 209:56–70
6. Mwinuka PR, Mbilinyi BP, Mbungu WB, Mourice SK, Mahoo HF, Schmitter P (2021) The feasibility of hand- held thermal and UAV- based multispectral imaging for canopy water status assessment and yield prediction of irrigated African eggplant (*Solanumaethopicum* L). Agr Water Manage 245:106584. https://doi.org/10.1016/j.agwat.2020.106584
7. Zhang L, Zhou Z, Zhang G, Meng Y, Chen B, Wang Y (2012) Monitoring the leaf water content and specific leaf weight of cotton (*Gossypium hirsutum* L.) in saline soil using leaf spectral reflectance. Eur J Agron 41:103–117
8. Yi Q, Bao A, Wang Q, Zhao J (2013) Estimation of leaf water content in cotton by means of hyperspectral indices. Comput Electron Agr 90:144–151

Irik *et al. Environmental Sciences Europe*   (2024) 36:93

Page 13 of 14

9. Irik HA, Kirnak H (2022) Evaluation of spectral vegetation indices for drip irrigated pumpkin seed under semi-arid conditions. Arab J Geosci 15:861
10. Payero JO, Irmak S (2006) Variable upper and lower crop water stress index baselines for corn and soybean. Irrig Sci 1:31–32
11. Kirnak H, Irik HA, Unlukara A (2019) Potential use of crop water stress index (CWSI) in irrigation scheduling of drip-irrigated seed pumpkin plants with different irrigation levels. Sci Hortic-Amsterdam 256:108608. https://doi.org/10.1016/j.scienta.2019.108608
12. Bozkurt Colak Y, Yazar A, Alghory A, Tekin S (2021) Evaluation of crop water stress index and leaf water potential for differentially irrigated quinoa with surface and subsurface drip systems. Irrig Sci 39:81–100
13. Yetik AK, Candogan BN (2023) Chlorophyll response to water stress and the potential of using crop water stress index in sugar beet farming. Sugar Tech 25:57–68
14. Forouzanfar F, Bazzaz BSF, Hosseinzadeh H (2014) Black cumin (*Nigella sativa*) and its constituent (thymoquinone): a review on antimicrobial effects. Iran J Basic Med Sci 17:929–938
15. Baydar H (2013) The science and technology of medicinal and aromatic plants, 1st edn. Süleyman Demirel University, Isparta
16. Senyıgıt U, Arslan M (2018) Effects of irrigation programs formed by different approaches on the yield and water consumption of black cumin (*Nigella sativa* L.) under transition zone in the West Anatolia conditions. J Agr Sci 24:22–32
17. Tüzüner A, Korucu N, Börekçi M, Gedikoğlu I, Sönmez B, Eyyüboglu F, Agar A (1990) Soil and water analyses laboratuary handbook. General Directorate of Rural Affairs, Ankara
18. Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration-guidelines for computing crop water requirements. Irrigation and Drain, Paper No.56.FAO, Rome, Italy, p 300
19. James LG (1993) Principles of farm irrigation system design. Krieger publishing company, Florida
20. Howell TA, Tolk JA (1998) Water use efficiency of corn in the U.S. Southern High Plains. Agronomy Abstracts, 14–15, Madison, WI, USA
21. Doorenbos J, Kassam AH (1986) Yield response to water. FAO Irrigation and Drainage Paper No.33, Rome
22. Fucs M, Tanner CB (1966) Infrared thermometry of vegetation. Agron J 58:597–601
23. Idso SB, Jackson RD, Pinter RD, Reginato RJ, Hatfield JL (1981) Normalizing the stres-degree-day parameter for environmental variability. Agr Meteorol 24:45–55
24. Liu HQ, Huete AR (1995) A feedback based modification of the NDVI to minimize canopy background and atmospheric noise. IEEE T Geosci Remote 33:457–465
25. Penuelas J, Gamon JA, Fredeen AL, Merino J, Field CB (1994) Reflectance indices associated with physiological changes in nitrogen- and water-limited sunflower leaves. Remote Sens Environ 48:135–146
26. Gitelson AA, Kaufman YJ, Merzlyak MN (1996) Use of green channel in remote sensing of global vegetation from EOS-MODIS. Remote Sens Environ 58(3):289–298
27. Penuelas J, Pinol J, Ogaya R, Fiella I (1997) Estimation of plant water concentration by the reflectance water index WI (R900/R970). Int J Remote Sens 18:2869–2875
28. Daughtry CST, Walthall CL, Kim MS, Colstoun EB, McMurtrey JE (2000) Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance. Remote Sens Environ 74(2):229–239
29. Rondeaux G, Steven M, Baret F (1996) Optimization of soil-adjusted vegetation indices. Remote Sens Environ 55:95–107
30. Heute AR (1988) A soil-adjusted vegetation index (SAVI). Remote Sens Environ 25:53–70
31. Aparicio N, Viellegas D, Casadesus J, Royo AJL, C, (2000) Spectral vegetation indices as nondestructive tools for determining durum wheat yield. J Agron 92:83–91
32. SAS Institute Inc (1999) SAS/GRAPH software: reference, version 8. SAS Institute Inc, Cary
33. Ozer H, Coban F, Sahin U, Ors S (2020) Response of black cumin (*Nigella sativa* L.) to deficit irrigation in a semi-arid region: growth, yield, quality, and water productivity. Ind Crop Prod 144:112048
34. Ghamarnia H, Khosravy H, Sepehri S (2010) Yield and water use efficiency of (*Nigella sativa* L.) under different irrigation treatments in a semi-arid region in the West of Iran. J Med Plants Res 4:1612–1616. https://doi.org/10.5897/JMPR09.376
35. Ghamarnia H, Jalili Z (2013) Water stress effects on different Black cumin (*Nigella sativa* L.) components in a semi-arid region. Int J Agron Plant Prod 4(4):753–762
36. Safaei Z, Azizi M, Maryam Y, Aroiee H, Davarynejad G (2014) The effect of different irrigation intervals and anti-transpiration compounds on yield and yield components of black cumin (*Nigella sativa* L.). Int J Adv Biol Biomed Res 4(2):326–335
37. Karim M, Himel RM, Ferdush J, Zakaria M (2017) Effect of irrigation levels on yield performance of Black Cumin. Int J Environ Agric Biotech 2(2):960–966
38. Fu J, Huang B (2001) Involvement of antioxidants and lipid peroxidation in the adaptation of two cool season grasses to localized drought stress. Environ Exp Bot 45(2):105–114. https://doi.org/10.1016/S00988472(00)00084-8
39. Anjum F, Yaseen M, Rasul E, Wahid A, Anjum S (2003) Water stress in barley (*Hordeumvulgare* L.). I. Effect on chemical composition and chlorophyll contents. Pak J Agr Sci 40:45–49
40. Litvin AG, Van lersel MW, Malladi A (2016) Drought stress reduces stem elongation and alters gibberellin-related gene expression during vegetative growth of tomato. J Am Soc Hortic Sci 141:591–597. https://doi.org/10.21273/JASHS03913-16
41. Gerami F, Moghaddam PR, Ghorbani R, Hassani A (2016) Effects of irrigation intervals and organic manure on morphological traits, essential oil content and yield of oregano (*Origanum vulgare* L.). An Acad Bras Cienc 88(4):2375–2385
42. Moghadam HRT, Ghooshchi F, Zahedi H (2011) Effect of UV radiation and evaluated CO2 on morphological traits, yield and yield components of canola (*Brassica napus* L.) grown under water deficit stress. Not Bot Hortic Agrobot Cluj 39:213–219. https://doi.org/10.15835/nbha3915534
43. Nassiri H, Seghatoleslami M, Mousavi G, Ebrahimi A (2014) Effect of irrigation and planting date on yield and water use efficiency of Ajowan (*Carum copticum*). Annu Res Rev Biol 4(12):1968–1979
44. Wu T, Sun S, Wang C, Lu W, Sun B, Song X, Han X, Guo T, Man W, Cheng Y, Niu J (2015) Characterizing changes from a century of genetic improvement of soybean cultivars in Northeast China. Crop Sci 55:2056–2067. https://doi.org/10.2135/cropsci2015.01.0023
45. Frederick JR, Woolley JT, Hesketh JD, Peters DB (1991) Seed yield and agronomic traits of old and modern soybean cultivars under irrigation and soil water-deficit. Field Crops Res 27:71–82. https://doi.org/10.1016/0378-4290(91)90023-O
46. Gutierrez- Prieto LMV, Kirici S (2020) Effect of different irrigation levels on yield and quality of black cumin (*Nigella sativa* L.). C Univ J Fac Engine 39:10
47. Kirnak H, Gencoglan C, Degirmenci V (2003) Effect of deficit irrigation on yield and growth of second crop corn in Harran plain conditions. Res Agric Sci 34(2):117–123
48. Golgul I, Kirnak H, Irik HA (2022) Yield components and crop water stress index (CWSI) of mung bean grown under deficit irrigations. Gesunde Pflanz. https://doi.org/10.1007/s10343-022-00698-z
49. Han M, Zhang H, Dejonge KC, Comas LH, Gleason S (2018) Comparison of three crop water stress index models with sap flow measurements in maize. Agric Water Manage 203:366–375
50. Garriga M, Retamales JB, Romero-Bravo S, Caligari PDS, Lobos GA (2014) Chlorophyll, anthocyanin, and gas exchange changes assessed by spectroradiometry in *Fragaria chiloensis* under salt stress. J Integr Plant Biol 2014(56):505–515
51. Colovic M, Yu K, Todorovic M, Cantore V, Hamze M, Rossella A, Stellaci AM (2022) Hyperspectral vegetation indices to assess water and nitrogen status of sweet maize crop. Agron J 12:2181
52. Szekely A, Szaloki T, Jancso M, Pauk J, Lantos C (2023) Temporal changes of leaf spectral properties and rapid chlorophyll-A fluorescence under natural cold stress in rice seedlings. Plants 12(13):2415. https://doi.org/10.3390/plants12132415
53. Aldubai AA, Alsadon AA, Al-Gaadi KA, Tola E, Ibrahim AA (2022) Utilizing spectral vegetation indices for yield assessment of tomato genotypes grown in arid conditions. Saudi J Biol Sci 29:2506–2513
54. Coelho AP, Rosalen DL, Faria RT (2018) Vegetation indices in the prediction of biomass and grain yield of white oat under irrigation levels. Pesqui Agropecu Trop 48(2):109–117

55. Gopinath G, Surendran U, Vishak J, Sasidharan N, Muhamed Fasil CT (2024) Hyperspectral data and vehetative indices for paddy: a case study in Kerala. India Remote Sens Appl Soc Environ 33:101109

56. Saravia D, Valqui-Valqui L, Salazar W, Quille-Mamani J, Barboza E, Porras-Jorge R, Injante P, Arbizu CI (2023) Yield prediction of four bean (*Phaseolus vulgaris*) cultivars using vegetation indices based on multispectral images from UAV in an arid zone of Peru. Drones 7(5):325. https://doi.org/10.3390/drones7050325

57. Marino S, Alvino A (2019) Detection of spatial and temporal variability of wheat cultivars by high-resolution vegetation indices. J Agron 9(5):226. https://doi.org/10.3390/agronomy9050226

58. Ryu JH, Jeong H, Cho J (2020) Performances of vegetation indices on paddy rice at elevated air temperature, heat stress and herbicide damage. Remote Sens-Basel 12:2654

59. Kaur R, Singh B, Singh M (2015) Hyperspectral indices, correlation and regression models for estimating growth parameters of wheat genotypes. J Indian Soc Remote Sens. https://doi.org/10.1007/s12524-014-0425-1

Publisher's Note