The Journal of Horticultural Science and Biotechnology

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/thsb20

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To cite this article: Morteza Goldani, Fatemeh Yaghoubi & Ali Asadi (19 Jun 2024): Light extinction coefficient and radiation use efficiency of two greenhouse basil (*ocimum basilicum* L.) cultivars under deficit irrigation, The Journal of Horticultural Science and Biotechnology, DOI: 10.1080/14620316.2024.2366885

To link to this article: https://doi.org/10.1080/14620316.2024.2366885

THE JOURNAL OF HORTICULTURAL SCIENCE AND BIOTECHNOLOGY
https://doi.org/10.1080/14620316.2024.2366885

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Light extinction coefficient and radiation use efficiency of two greenhouse basil (*ocimum basilicum* L.) cultivars under deficit irrigation

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ABSTRACT

This two-year experiment with different planting seasons (April 2018 and August 2021) aimed to determine the effect of deficit irrigation (DI) levels (DI0: 100%, DI30: 70%, and DI60: 40% field capacity) on light interception, light extinction coefficient (*k*), dry biomass and radiation use efficiency (RUE) of two basil cultivars (Green and Purple). The greenhouse experiment was arranged in a split-plot design with three replications. The results showed that the *k* values ranged from 0.57 to 0.68 and 0.31 to 0.43 in April and August planting, respectively. The cumulative solar radiation interception, dry biomass, and RUE depended on DI levels, harvest numbers, and seasons. In two study years, dry biomass decreased and RUE increased with the reduction in irrigation water at all harvests and their total. Compared to DI0, basil dry biomass did not show a considerable decrease under DI30 in three harvests in April planting and in the first and second harvests in August planting. April planting had the higher cumulative solar radiation interception in the first and third harvest than the August planting. The basil dry biomass and RUE in the April planting were higher than those in the August planting at all three harvests and their total.

ARTICLE HISTORY
Received 15 November 2023
Accepted 5 June 2024

KEYWORDS
Biomass accumulation; leaf area index; light interception; planting date; solar radiation

Introduction

Basil (*Ocimum basilicum* L.), a member of the Laminaceae family, is an important herbaceous aromatic plant with a noteworthy contribution to enhancing landscape aesthetics, healthy living and cuisine nutrition (Barickman et al., 2021). Globally, a large proportion of high-quality basil is cultivated for its dry leaves, essential oil and flowers (Pushpangadan & George, 2012). Basil with antispasmodic, stomachic, carminative and expectorant properties has been claimed to be effective for suppressing muscle spasms and inflammation, reducing cholesterol and glucose levels in the blood, lowering blood pressure and fevers and strengthening the body's natural activity (Kathirvel & Ravi, 2012; Kopsell et al., 2005). The basil cultivars often have the same uses in food, perfumery and pharmaceutical industries. However, their biochemical constituents have great differences in terms of type and amount (Makri & Kintzios, 2008). The studies (Ferrarezi & Bailey, 2019; Prinsi et al., 2019) conducted on the amount of anthocyanin in Green and Purple cultivars have shown a significant difference between the amount of this metabolic compound in these cultivars. Purple basil indeed appears to exhibit a conservative resource use strategy typically observed in highly stress-tolerant species. In this cultivar, the presence of epidermal coumaroyl anthocyanins has protective advantages under high light, but it is associated with decreased flexibility to accommodate changing light fluxes as compared with Green cultivar (Tattini et al., 2014).

In Iran, as well as other Mediterranean countries, the cultivation of medicinal plants has long been common practice to improve sustainability and diversity in agricultural systems. *O. basilicum* is largely employed in the country for fresh consumption and rarely as the dry product and for the production of essential oils (Hamzezadeh et al., 2012). Despite having a long history in the sustainable development and management of water resources, Iran is currently facing major problems in the water sector (Saatsaz, 2020). Recent droughts and limited access to water on the one hand, and increasing population and rising demand for water and food on the other hand, have required proper use of available water resources (Goldani et al., 2021).

Adjusting the time and amount of irrigation in different stages of crop growth can be a solution to optimise irrigation water in drought periods (Zou et al., 2021). Deficit irrigation (DI) is one possible adaptation strategy to decrease the amount of applied water based on the water availability and irrigation quota (Ajaz et al., 2020). In semi-arid regions, the crop yield response to full irrigation is usually stable; but, the response to DI depending on the time and quantity of irrigation along with the amount of initial soil water content at the time of planting and the occurrence of rainfall can have substantial fluctuations (Kang et al., 2000).

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Radiation use efficiency (RUE), defined as the ratio between crop biomass accumulation and intercepted radiation, is the main driving variable that includes and integrates all the climatic and management restrictions for crop growth; Thus, RUE can be used to evaluate crop yield and dry matter accumulation under different cropping systems and environmental conditions (Garofalo & Rinaldi, 2015; Monteith, 1977). Although some studies (Monteith, 1994; Russell et al., 1989) have indicated that the intercepted photosynthetically active radiation (PAR), the light extinction coefficient (*k*) and RUE are crop-specific parameters, they can vary according to crop management and environmental factors (Rosenthal & Gerik, 1991). Water stress changes the relationship among these variables in a way that reduces the plant's ability to capture light (Williams & Boote, 1995). The impact of water stress on crops RUE is more obvious when the stress occurs during the vegetative stage, through effects on the interception of incident PAR; Indeed, water stress can decrease the intercepted PAR by the crop due to leaf wilting or rolling, which can anticipate leaf senescence or limit canopy development (Ngugi et al., 2013; Tesfaye et al., 2006).

In Iran, electricity supply is very expensive and affects investment decisions for greenhouse lighting. Therefore, although in many parts of the country light is a limiting factor in greenhouses during the winter, growers are reluctant to use supplemental lighting even for the shortest and darkest days of the year. The aim of the present study was to determine the effect of different DI levels on light interception, *k*, dry biomass, and RUE of Green and Purple basil cultivars in April and August planting under greenhouse conditions with natural light.

Materials and methods

Study site

The experiment was conducted for two years (i.e. 2018 and 2021) in a research greenhouse at the Faculty of Agriculture, Ferdowsi University of Mashhad, Iran (36°18′N, 59°38′E, and altitude 994 m). The greenhouse is made of an aluminium frame with an area of 1,100 m^2 consisting of 16 independent units (each unit has an area of 60 m^2; 10 m length, 6 m width, and 3 m height), covered with a glass sheet. The greenhouse is equipped with a smart meteorological system (LS16 equipment by AP Holland) and each of the greenhouse units can be independently and automatically controlled and programmed in terms of temperature, relative humidity, carbon dioxide, light and irrigation. During the test, the greenhouse temperature was maintained in the range of 25–30°C, and no supplemental lighting was used in the greenhouse. The experimental soil texture was silty clay loam in both study years. The soil physicochemical characteristics are presented in Table 1.

Experimental design and treatments

The greenhouse study was arranged in a split plot layout as a randomised complete block design with three replications, where irrigation regimes and basil cultivars were assigned to the main and subplots, respectively (Figure 1). Irrigation treatments included irrigation up to 100% (DI0), 70% (DI30) and 40% FC (DI60). Basil (*Ocimum basilicum* L.) cultivars were Green and Purple from Mashhad, Razavi Khorasan province, Iran. Each plot consisted of four rows with a length of 90 cm. Plant spacing was 15 cm between plants within rows and 25 cm between rows. To minimise irrigation edge effects, plots were separated by 0.5 m distance. Furthermore, 2-mm aluminium plates were placed between the plots down to a depth of 0.5 m to prevent water leakage to adjacent plots (Figure 1).

The irrigation treatments were determined based on the soil water deficit defined as the difference between the root zone soil water content at FC and before irrigation. One day prior to each irrigation, the soil water content at the DI0 treatment plots was measured from three points in each plot using time-domain reflectometry (TDR) probes in order to determine the soil water deficit. The irrigation water volume required (V_m, L) to replenish this deficit up to the FC was determined as follows:

$$V_m = (\theta_F - \theta_i) \times BD \times D \times A \qquad (1)$$

where θ_F and θ_i denote the gravimetric soil water content at FC and before irrigation, respectively (g g^{-1}), BD is the soil bulk density (g cm^{-3}), D represents the root development depth (cm), and A is the plot area (m^2).

For each irrigation, the input water volume to each plot was measured with a flow meter.

Crop management

Seeds of both basil cultivars were sown in commercial nursery trays under control temperatures of 25–30°C

Table 1. Physicochemical characteristics of the experimental soil.

Year	Texture	θ_F[a] (g g^{-1})	BD[b] (g cm^{-3})	PH	EC (dS m^{-1})	N (%)	P (mg kg^{-1})	K (mg kg^{-1})
2018	Silty clay loam	21.01	1.23	7.79	1.05	0.12	29.5	183.1
2021	Silty clay loam	22.12	1.44	7.65	0.91	0.10	32.1	179.9

[a] θ_F denotes soil water content at the field capacity.
[b] BD is bulk density.

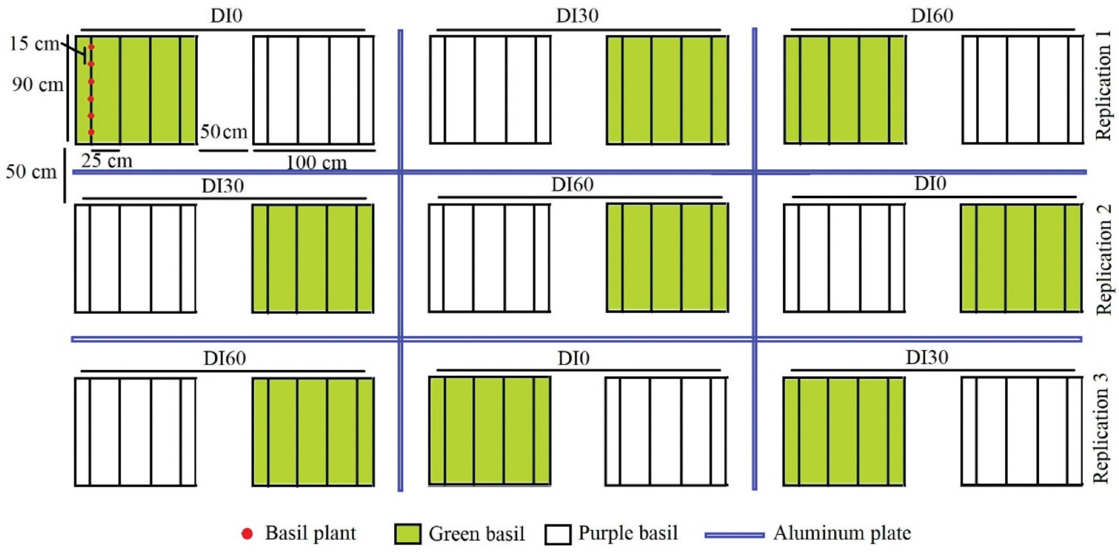

Figure 1. Experimental layout in 2018 and 2021. DI0, DI30, and DI60 are 100%, 70%, and 40% of the field capacity, respectively.

on 4 April 2018 and 8 August 2021. The seedlings were transplanted to the greenhouse soil on 1 May 2018 and 29 August 2021.

Before soil tillage, farmyard manure was added to soil at the rate of 30 tons per hectare in both study years. In addition, basil plants were fertilised with a water-soluble 12-12-36 NPK fertiliser at the rate of 2 g per litre of water about eight weeks after seedling stage in two experimental years. Diseases, weeds and pests were effectively controlled during the growing season.

At the beginning of the flowering stage, harvesting of the basil plants was done on 3 July, 2 August and 1 September 2018 and 28 November, 12 January and 26 February in 2021.

Measurements and calculations

Leaf area index (LAI)

LAI were measured (Leaf area meter LICOR-3100, USA) three times during each harvest using two plants in each plot.

Light interception

Light interception, defined as PAR penetration into the plant canopy (%), was calculated as follows:

Where PAR_{above} and PAR_{below} are the PAR average above- and below-the-canopy, respectively. Two measurements at above-the-canopy and three measurements at below the canopy per plot were recorded under clear sky conditions using an AccuPAR LP-80 (Decagon Devices, Inc., Pullman, WA, USA) at near-noon (11 am–1.00 pm), simultaneously with leaf area measurements. Above-the-canopy measurements were done once before and once after below-the-canopy measurements.

$$Light_{\text{interception}} = \frac{(PAR_{above} - PAR_{below})}{PAR_{above}} \times 100 \quad (2)$$

Extinction coefficient (k)

The relationship between light penetration and LAI was employed to determine the k of crop canopy using the following equation (Monsi & Saeki, 2005):

where I denotes transmitted PAR below the canopy, I_0 represents the PAR above the crop canopy and k is the extinction coefficient.

$$I = I_0 \times e^{-k \times LAI} \quad (3)$$

Cumulative solar radiation interception

Solar radiation interception was calculated by the solar radiation (MJ m^{-2}) at plant level multiplied by the light interception percentage in each measurement. Solar radiation at plant level was calculated by multiplying the outside solar radiation (recorded by the weather station) by a light transmission coefficient of the greenhouse cover (0.875). The coefficient was determined under overcast sky conditions by two identical AccuPAR LP-80, one inside and one outside the greenhouse, yielding a value of almost 0.87. Daily solar radiations were summed from planting to first harvest, first harvest to second harvest, second harvest to third harvest and planting to third harvest in each year.

Biomass dry weight

In each harvest, above ground biomass were recorded from 12 plants of each plot. The plants were harvested

10 cm above the ground. Next, the harvested plants were dried at 70°C for 48 h and thereafter weighed to obtain dry biomass.

Radiation use efficiency (RUE)

The RUE (g MJ^{-1}) in each harvest was calculated as above ground dry biomass (g m^{-2}) divided by the amount of solar radiation intercepted (MJ m^{-2}) by the canopy of each plot (Rinaldi & Garofalo, 2011).

Statistical analysis

Variances for all variables (cumulative solar radiation, dry biomass and RUE for three harvests and their total) were not homogeneous across years (Bartlett test, $p < 0.05$) probably because of difference in planting date across years. Therefore, the data were statistically analysed separately for each year by ANOVA (analysis of variance) and the mean comparisons were conducted based on the Fisher's LSD test ($p \leq 0.05$). The relationship between LAI and light interception was evaluated using regression analysis. The k values were estimated by the relationship between $\ln(I/I_0)$ and LAI.

Results

Leaf area index and light interception

The basil LAI was significantly affected by interaction of deficit irrigation and cultivar during three harvests in two experimental years (Tables 2 and 3). For both study years, in all DI levels, LAI of Green and Purple cultivars peaked at the third sampling of each harvest (Figure 2). Decreasing the amount of irrigation to 40% FC (DI60) significantly decreased LAI of Green and Purple basil compared to the full irrigation at all harvests. In two experimental years and three harvests, Green basil had higher LAI than the other cultivar in three DI treatments. It was found that, by increasing the harvest number, LAI of two cultivars showed a considerable decrease. In August 2021 planting, LAI of Green and Purple basil was higher than April 2018 planting.

The interaction of deficit irrigation and cultivar had a significant effect on the light interception of basil plants at 60 and 100 days after transplanting in 2018 and at 75, 135, 150 and 165 days after transplanting in 2021 (Tables 2 and 3). For each two years, the light interception percentage for both basil cultivars in all DI levels peaked at the third sampling of each harvest except under full irrigation in the third harvest in both study years (Figure 3).

Table 2. The ANOVA for basil leaf area index (LAI) and light interception during three harvests in 2018.

	1st harvest			2nd harvest			3rd harvest		
	20	40	60	70	80	90	100	110	120
Source of variation	Days after transplanting								
LAI									
I	*	*	*	*	*	*	n.s.	n.s.	*
C	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
I * C	*	*	*	*	*	*	*	*	*
C.V.	28.69	26.81	25.35	15.21	28.03	23.01	29.04	26.94	27.58
Light interception									
I	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*	n.s.	n.s.
C	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
I * C	n.s.	n.s.	*	n.s.	n.s.	n.s.	*	n.s.	n.s.
C.V.	24.82	22.84	29.25	27.49	30.02	28.94	15.39	21.72	22.28

I and C represent deficit irrigation treatment and cultivar, respectively.
*is significance at the 0.05 probability level. n.s. denotes non-significance.

Table 3. The ANOVA for basil leaf area index (LAI) and light interception during three harvests in 2021.

	1st harvest			2nd harvest			3rd harvest		
	25	50	75	90	105	120	135	150	165
Source of variation	Days after transplanting								
LAI									
I	n.s.	*	*	*	*	*	n.s.	*	*
C	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
I * C	*	*	*	*	*	*	*	*	*
C.V.	29.34	29.60	28.27	23.21	27.64	27.19	24.70	29.74	28.20
Light interception									
I	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*	*
C	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	**	n.s.
I * C	n.s.	n.s.	*	n.s.	n.s.	n.s.	*	*	**
C.V.	21.04	24.13	9.93	28.07	25.36	22.43	23.63	11.54	11.36

I and C represent deficit irrigation treatment and cultivar, respectively.
** and * are significance at the 0.01 and 0.05 probability levels, respectively. n.s. denotes non-significance.

For the crops planted in April and August, light interception decreased with decreasing irrigation water. In most cases, the light interception for Green basil was higher than that of Purple basil in two study years. In addition, it was found that, by increasing the harvest number, light interception showed a considerable decrease only for the basils planted in August. In the first harvest in August planting, light interception was higher than April planting.

Linear regression was performed to explain the relationship between LAI and light interception (Figures 4 and 5). Light interception increased with increase in LAI. The range of light interception per unit increase in LAI was from 1.80% to 70.48% and from 8.13% to 71.63% for April and August planted basils, respectively. For two cultivars in all three harvests in April planting except Purple basil in the second harvest, the light interception percentage increased with decreasing irrigation water to 40% of the FC, when LAIs increased by one unit. However, in August planting, light interception percentage increased with decreasing irrigation water to 60% of the FC, when LAIs increased by one unit. In two study years in all DI treatments except 40% FC treatment in all three harvests and 70% and 40% FC treatments in the third harvest, Purple basil had a higher light interception percentage than Green basil, when LAIs increased by one unit. In all treatments except Green basil in DI60 in the first harvest and Purple basil in

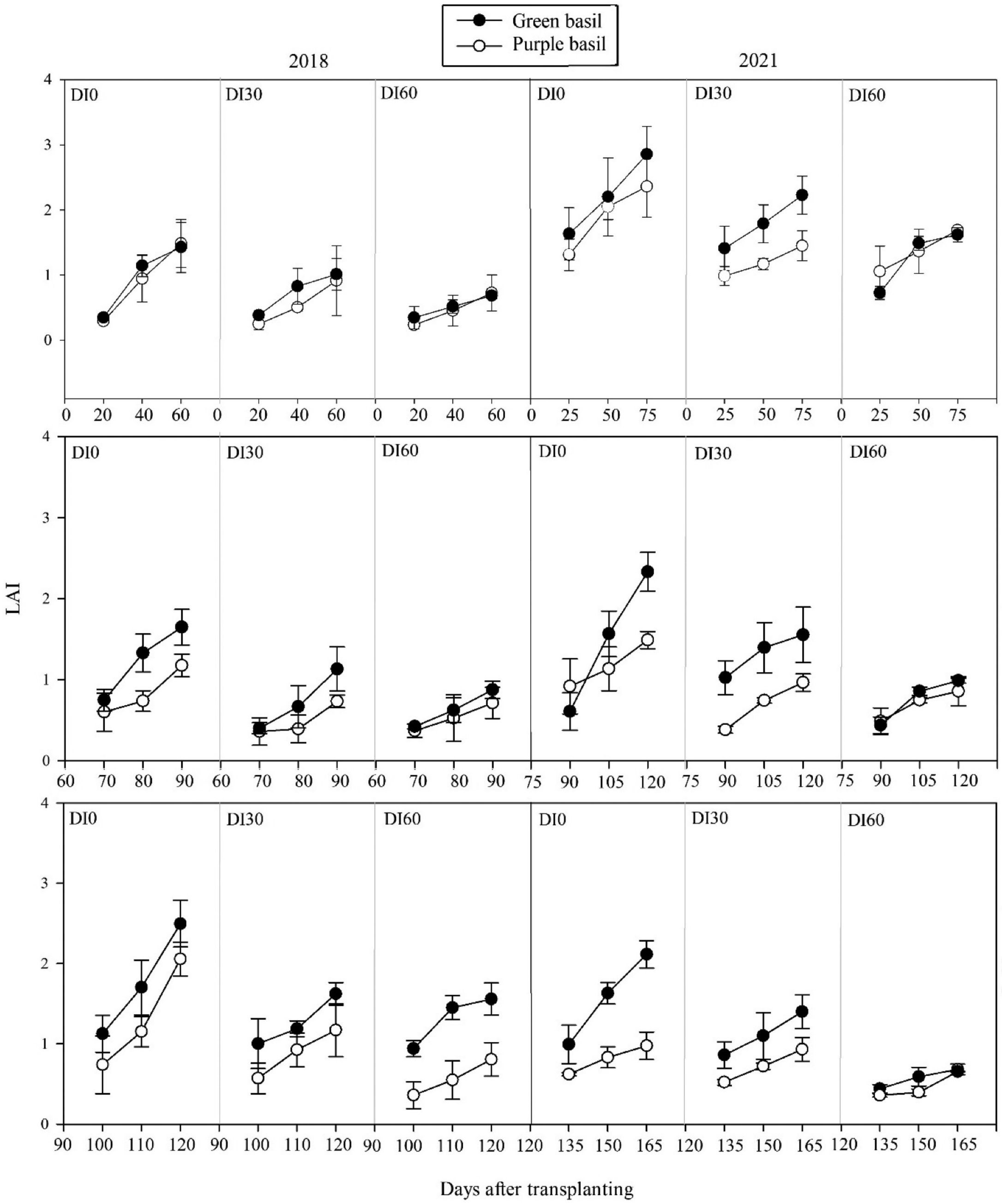

Figure 2. Leaf area index (LAI) of Green and Purple basil cultivars during three harvests under different deficit irrigation (DI) levels (DI0: 100%, DI30: 70% and DI60: 40% field capacity) in 2018 and 2021. Error bars represent standard deviation.

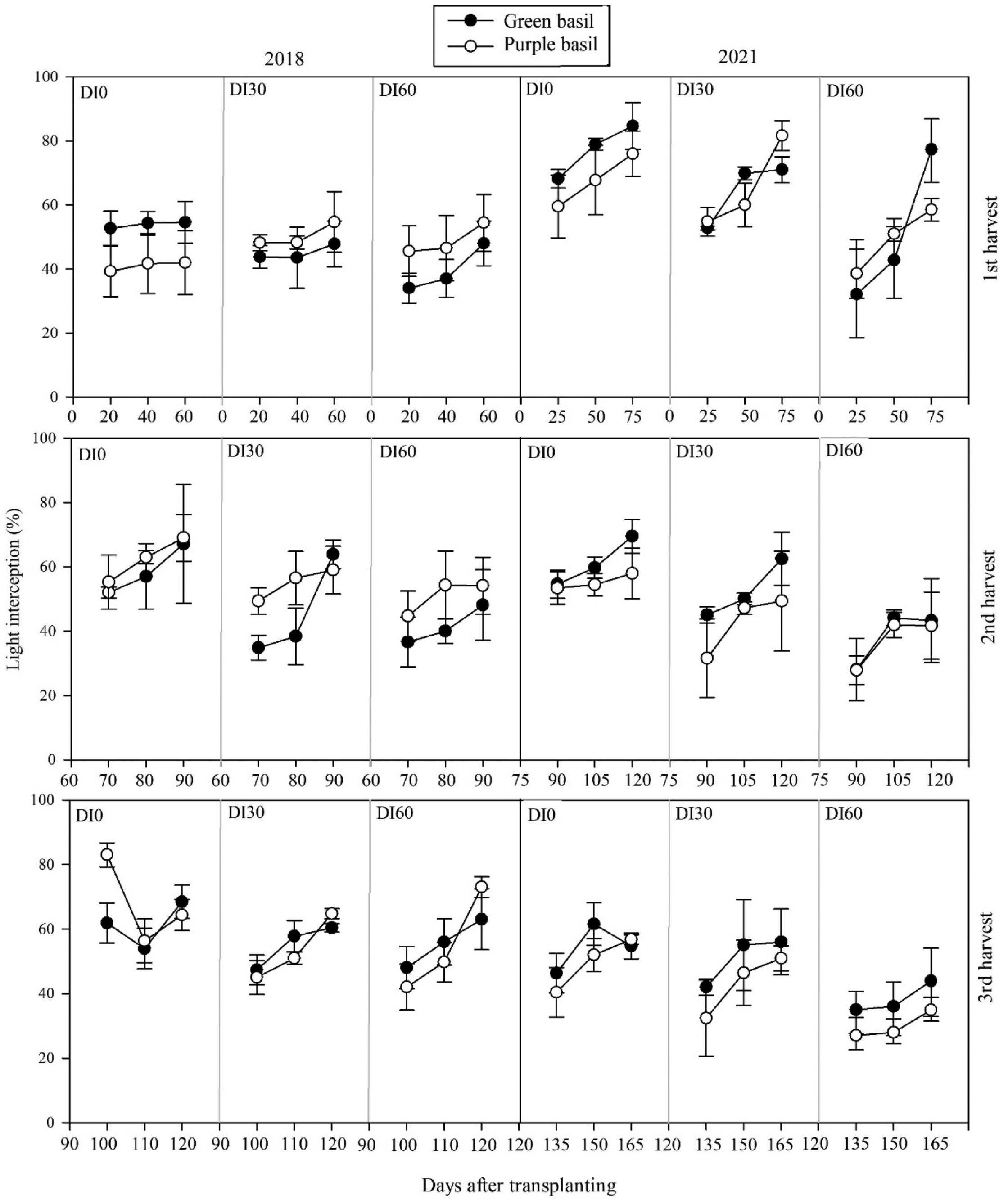

Figure 3. Light interception percentage of Green and Purple basil cultivars during three harvests under different deficit irrigation (DI) levels (DI0: 100%, DI30: 70%, and DI60: 40% field capacity) in 2018 and 2021. Error bars represent standard deviation.

DI30 in the second harvest, a higher increase in light interception percentage was observed in the August 2021 planting compared to the April 2018 planting, when LAIs increased by one unit.

Light extinction coefficient (k)

The *k* values ranged from 0.57–0.68 ($R^2 = 0.35–0.92$) and 0.31–0.43 ($R^2 = 0.39–0.845$) in April 2018 and August 2021 planting, respectively (Figure 6). The higher *k* was observed in DI0 treatment except for Green basil in April 2018 planting. In both years, in DI0 and DI30 treatments, the *k* value of Green basil was higher than Purple basil but, in DI60 treatment, Purple basil had a higher *k* value than Green basil. For the crops planted in April 2018, the estimated *k* values were higher than the crops planted in August 2021.

Cumulative solar radiation interception

Irrigation treatment had a significant effect on the cumulative solar radiation interception of basil plants at all harvests except the first harvest in 2018 (Table 4). However, no significant cultivar and interaction between irrigation and cultivar for cumulative solar radiation interception were observed at all harvests in two study years.

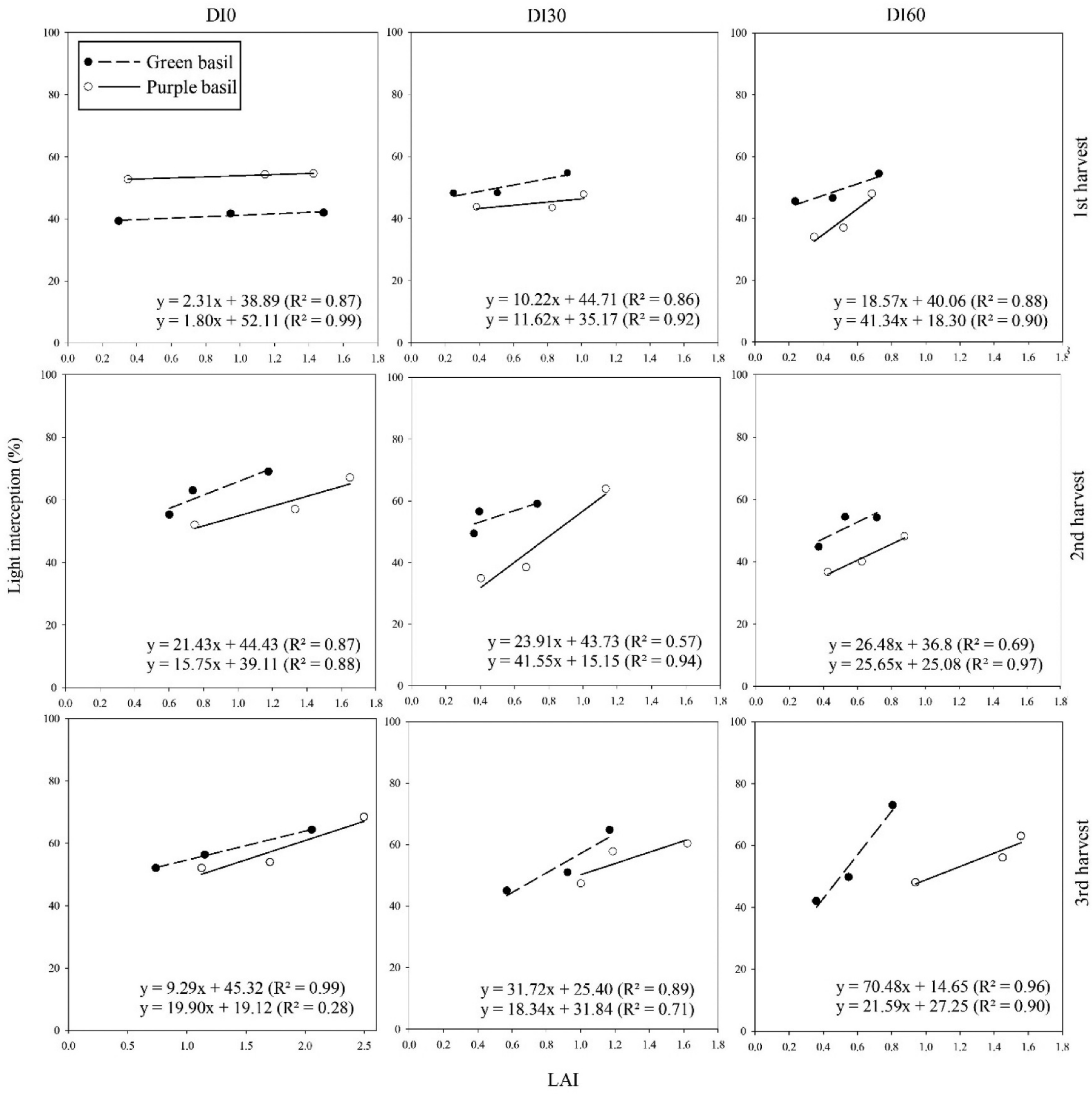

Figure 4. Relationship between light interception percentage and leaf area index (LAI) of Green and Purple basil cultivars in three harvests under different deficit irrigation (DI) levels (DI0: 100%, DI30: 70% and DI60: 40% field capacity) in 2018.

Cumulative solar radiation interception during total three harvests ranged from 1,056.78 to 1,256.14 MJ m^{-2} in 2018 and from 1,050.67 to 1,644.40 MJ m^{-2} in 2021. In all harvests and their total in two study years, the highest cumulative solar radiation interception was observed in basil plants under DI0 conditions. In general, solar radiation interception of both cultivars decreased by increasing DI levels. Among harvests, first harvest showed the highest cumulative solar radiation interception. For example, average across irrigation treatments, cumulative solar radiation interception in the first harvest was higher than the second and third harvests by 624.36 MJ m^{-2} and 673.86 MJ m^{-2} in the first experimental year and 223.16 MJ m^{-2} and 663.11 MJ m^{-2} in the second experimental year, respectively. In the first and third harvests, April 2018 planting had the higher cumulative solar radiation interception than the August 2021 planting, by 9.18% and 66.32%, respectively.

Dry biomass accumulation

Dry biomass accumulation was significantly affected only by irrigation at all harvests in two experimental years (Table 5). Dry biomass accumulation during the total three harvests ranged from 938.36 to 1,096.19 g m^{-2} in 2018 and from 681.15 to 887.30 g m^{-2} in 2021. The highest cumulative dry biomass at all harvests and their total in two experimental years were obtained in DI0 treatment. Dry biomass of basil plants decreased with decreasing irrigation water applied; however, often there was no significant difference between DI0 and DI30 treatments. In total harvests, basil dry biomass accumulation in the DI60 treatment decreased by 14.39% in 2018 and by 23.23% in 2021, respectively, relative to the DI0 treatment. The highest

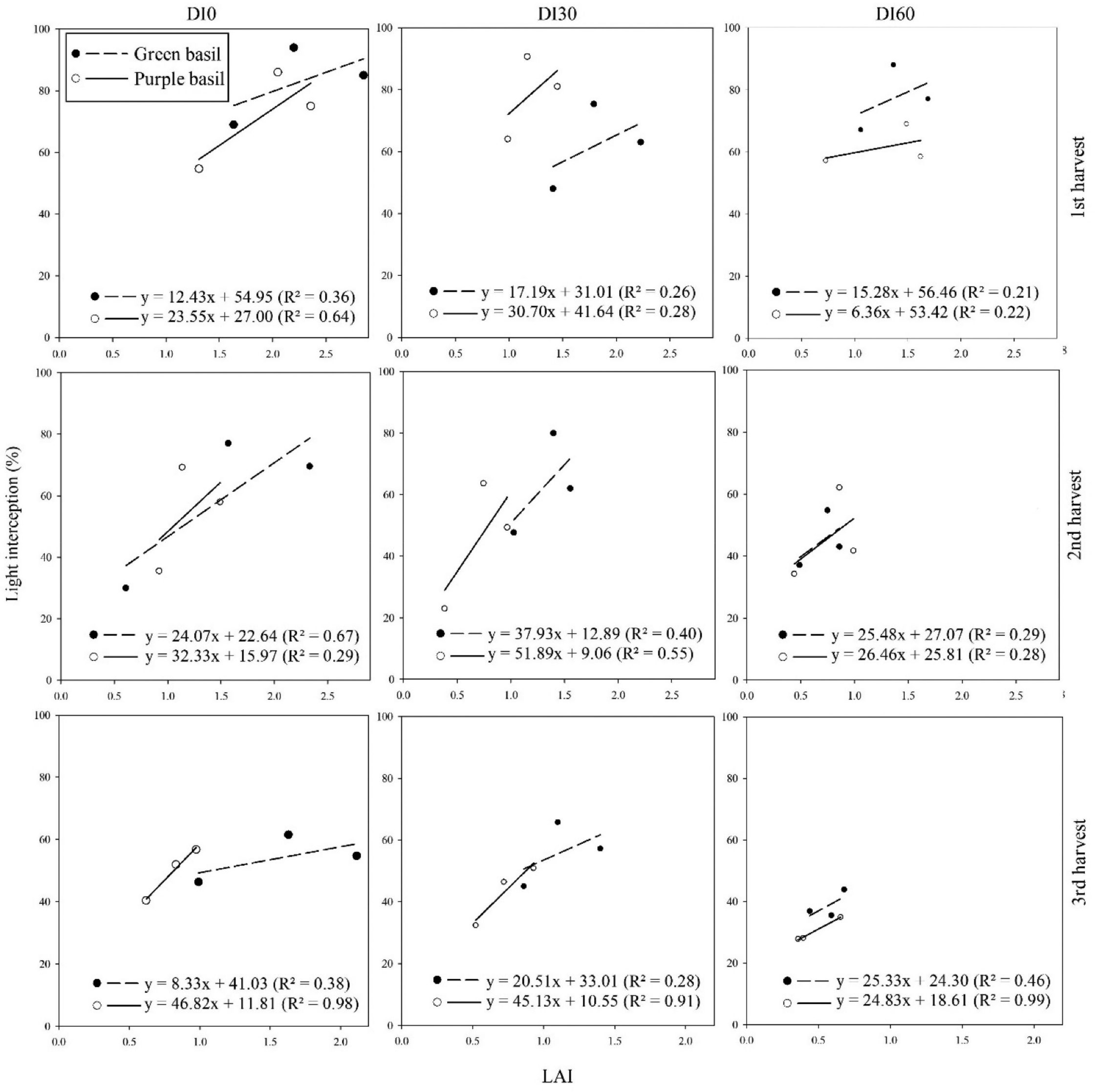

Figure 5. Relationship between light interception percentage and leaf area index (LAI) of Green and Purple basil cultivars in three harvests under different deficit irrigation (DI) levels (DI0: 100%, DI30: 70% and DI60: 40% field capacity) in 2021.

cumulative dry biomass was observed in the first harvest compared to other harvests. Average across treatments, the cumulative dry biomass in the first harvest (384.33 and 329.31 g m^{-2} in 2018 and 2021, respectively) was higher than that in the second and third harvests by 21.52% and 15.04% in 2018 and by 8.57% and 99% in 2021, respectively. The cumulative dry biomass in the first experimental year was higher than that in the second year at all three harvests and their total.

Radiation use efficiency

In two study years, only irrigation had significant effects on basil RUE in the second and third harvests in 2018 and in the first and third harvests in 2021 (Table 6). For the total three harvests, RUE ranged from 0.98–1.02 g MJ^{-1} in 2018 and 0.54–0.69 g MJ^{-1} in 2021. DI60 treatment showed the highest RUE in the second harvest in 2018 (2.10 g MJ^{-1}) and in the first and third harvests in 2021 (0.88 and 2.10 g MJ^{-1}, respectively). Among harvests, the highest RUE (average across treatments, 2.34 g MJ^{-1} in 2018 and 1.87 g MJ^{-1} in 2021) was obtained in the third harvest in both years. The basils planted in April 2018 had a higher RUE than the basil planted in August 2021 at all three harvests and their total. For example, average across irrigation treatments in the total three harvests, RUE in 2018 was higher than that in 2021 by 69.49%.

Discussion

LAI is a good measure for the plant light absorption and biomass accumulation, because the leaves are the most important organs of the plants that absorb light to produce dry matter under different conditions, including stress (Soleymani, 2017). Water-deficit stress decreases canopy cover by decreasing leaf size and number and enhancing leaf senescence

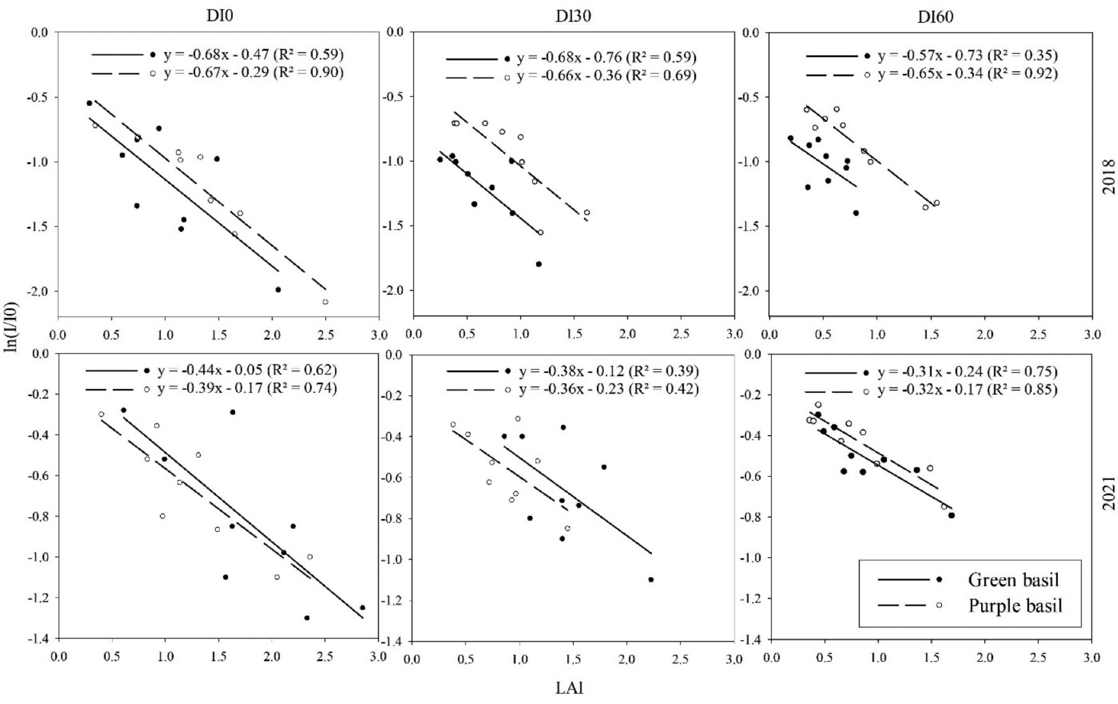

Figure 6. Regression analysis between $\ln(I/I_0)$ (where I and I_0 were PAR below and above the canopy, respectively) and leaf area index (LAI) to determine extinction coefficient (k) of Green and Purple basil cultivars in all three harvests under different deficit irrigation (DI) levels (DI0: 100%, DI30: 70% and DI60: 40% field capacity) in 2018 and 2021.

(Mahakosee et al., 2022). In this study, DI delayed basil canopy development and decreased LAI (Figure 2). Considering that there was a positive correlation between the light interception and LAI (Figures 3 and 4), by decreasing the irrigation water, light interception percentage decreased (Figure 3) due to the decrease in LAI. Nevertheless, the relationship between light interception and LAI was strong only in April (spring) sowing, having R^2 of 0.69–0.99 (Figure 4). In August planting, this relationship was variable, having R^2 of 0.21–0.99 (Figure 5), probably due to changes in incoming solar radiation and the arrangement and position of leaves in the canopy. Leaf angle, leaf position and leaf arrangement are the most important factors that affect solar radiation penetration into the bottom of the canopy (Mahakosee et al., 2022). Leaf angle can generally be estimated by the values of *k* that vary between 0.3 and 1.0 (de Oliveira

Table 4. Cumulative solar radiation interception (MJ m^{-2}) of basil plants in three harvests under different levels of deficit irrigation (DI) (DI0: 100%, DI30: 70% and DI60: 40% field capacity) and cultivar (Green (C1) and Purple (C2)) in 2018 and 2021.

	2018				2021			
Treatment	1st harvest	2nd harvest	3rd harvest	Total	1st harvest	2nd harvest	3rd harvest	Total
Irrigation								
DI0	866.94 a	226.76 a	162.43 a	1256.14 a	928.90 a	615.825 a	99.67 a	1,644.40 a
DI30	846.84 a	188.51 b	135.63 b	1170.99 ab	788.81 a	517.83 ab	95.68 a	1,402.33 ab
DI60	745.74 a	171.16 b	139.88 b	1056.78 b	534.91 b	449.48 b	67.95 b	1,050.67 b
Cultivar								
C1	833.64 a	200.77 a	147.64 a	1182.05 a	753.88 a	548.22 a	96.19 a	1,397.15 a
C2	806.04 a	190.19 a	144.33 a	1140.56 a	747.88 a	507.21 a	79.36 a	1,334.45 a
Irrigation × Cultivar								
DI0×C1	865.32 a	232.20 a	160.67 a	1258.19 a	991.6 a	643.87 a	103.91 a	1,739.39 a
DI0×C2	868.56 a	221.33 a	164.20 a	1254.09 a	866.19 a	587.78 a	95.44 a	1,549.41 a
DI30×C1	889.47 a	194.35 a	134.01 a	1217.83 a	772.78 a	540.46 a	107.88 a	1,421.12 a
DI30×C2	804.21 a	182.68 a	137.26 a	1124.15 a	804.84 a	495.21 a	83.49 a	1,383.54 a
DI60×C1	746.13 a	175.76 a	148.24 a	1070.13 a	497.24 a	460.32 a	76.76 a	1,030.95 a
DI60×C2	745.35 a	166.56 a	131.52 a	1043.43 a	572.59 a	438.65 a	59.15 a	1,070.39 a
Average	819.84	195.48	145.98	1161.29	750.88	527.72	87.77	1,365.80
ANOVA								
I	n.s.	*	*	*	*	**	*	**
C	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
I * C	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C.V.	27.22	18.65	9.8	17.8	27.1	9.6	6.24	16.69

Within a column for each year, values followed by different letters are significantly different at $p < 0.05$ by Fisher's LSD test.
I and C represent deficit irrigation treatment and cultivar, respectively.
** and * are significance at the 0.01 and 0.05 probability levels, respectively. n.s. denotes non-significance.

Table 5. Basil dry biomass (g m^{-2}) in three harvests under different levels of deficit irrigation (DI) (DI0: 100%, DI30: 70% and DI60: 40% field capacity) and cultivar (Green (C1) and Purple (C2)) in 2018 and 2021.

	2018				2021			
Treatment	1st harvest	2nd harvest	3rd harvest	Total	1st harvest	2nd harvest	3rd harvest	Total
Irrigation								
DI0	403.86 a	327.74 a	369.59 a	1,096.19 a	360.76 a	329.27 a	197.26 a	887.30 a
DI30	398.44 a	322.71 a	343.08 ab	1,069.24 a	342.56 a	313.60 a	145.57 b	771.73 ab
DI60	350.68 b	298.34 b	289.34 b	938.36 b	292.25 b	246.50 b	142.4 b	681.15 b
Cultivar								
C1	388.07 a	310.60 a	327.09 a	1,025.76 a	329.88 a	321.02 a	173.33 a	824.23 a
C2	380.58 a	321.93 a	341.07 a	1,043.58 a	313.84 a	271.89 a	150.16 a	735.89 a
Irrigation × Cultivar								
DI0×C1	401.36 a	316.61 a	350.57 a	1,068.54 a	376.40 a	857.07 a	218.13 a	951.60 a
DI0×C2	406.36 a	328.87 a	388.62 a	1,123.85 a	345.13 a	301.47 a	176.40 a	823.00 a
DI30×C1	407.88 a	322.20 a	341.78 a	1,071.86 a	328.93 a	348.80 a	138.47 a	816.20 a
DI30×C2	389.01 a	333.23 a	344.83 a	1,067.07 a	296.20 a	278.40 a	152.67 a	727.27 a
DI60×C1	354.98 a	293.00 a	288.93 a	936.91 a	284.30 a	257.20 a	173.33 a	704.90 a
DI60×C2	346.38 a	303.68 a	289.76 a	939.82 a	300.20 a	235.80 a	150.16 a	657.40 a
Average	384.33	316.26	334.08	1,034.67	329.31	296.45	161.74	780.06
ANOVA								
I	*	*	*	**	*	*	*	*
C	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
I * C	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C.V.	5.72	4.37	12.96	3.16	13.31	16.24	23.49	12.50

Within a column for each year, values followed by different letters are significantly different at $p < 0.05$ by Fisher's LSD test.
I and C represent deficit irrigation treatment and cultivar, respectively.
** and * are significance at the 0.01 and 0.05 probability levels, respectively. n.s. denotes non-significance.

Pereira et al., 2019; Zhang et al., 2014). In this study, the values of *k* ranged from 0.31 to 0.68 depending on water conditions, cultivar, harvest number, and season (Figure 6). Alizadeh et al. (2010) reported a *k* value of 0.47 for basil. The larger estimate of *k* was mostly obtained under full irrigation and, with decreasing irrigation water applied, the *k* value decreased (Figure 6). *k* is a function of environmental conditions and so it is considered a useful and important parameter in determining the plant response to different conditions such as stress (Chavez et al., 2022).

In all DI levels, the August planting only in the first harvest had the higher LAI than the Green and Purple basil planted in April (Figure 2). In all treatments, a higher increase in light interception percentage per unit increase in LAI was observed in August compared to April planting (Figures 3 and 4). As a result, higher LAI in the first harvest in 2021 resulted to higher light interception compared to 2018 planting (Figure 3). In addition, compared to August 2021 planting, the larger estimate of *k* in April 2018 planting (Figure 6) resulted in a reduction in light penetrating into the plant canopy. A horizontal leaf position can intercept more light than a vertical position leaf (Liu et al., 2021). However, only the upper parts of the canopy can intercept light, while the shading effect on the lower parts of the canopy

Table 6. Radiation use efficiency (RUE, g MJ^{-1}) for basil dry biomass in three harvests under different levels of deficit irrigation (DI) (DI0: 100%, DI30: 70% and DI60: 40% field capacity) and cultivar (Green (C1) and Purple (C2)) in 2018 and 2021.

	2018				2021			
Treatment	1st harvest	2nd harvest	3rd harvest	Total	1st harvest	2nd harvest	3rd harvest	Total
Irrigation								
DI0	0.68 a	1.45 b	2.31 ab	0.98 a	0.39 b	0.53 a	1.95 a	0.54 a
DI30	0.56 a	1.91 ab	2.61 a	1.02 a	0.40 b	0.60 a	1.54 b	0.55 a
DI60	0.56 a	2.10 a	2.10 b	1.00 a	0.88 a	0.55 a	2.10 a	0.69 a
Cultivar								
C1	0.65 a	1.69 a	2.35 a	0.98 a	0.58 a	0.59 a	1.83 a	0.63 a
C2	0.55 a	1.96 a	2.33 a	1.02 a	0.54 a	0.54 a	1.91 a	0.56 a
Irrigation × Cultivar								
DI0×C1	0.91 a	1.45 a	2.29 a	1.07 a	0.38 a	0.55 a	2.08 a	0.55 a
DI0×C2	0.45 a	1.45 a	2.33 a	0.90 a	0.41 a	0.51 a	1.83 a	0.54 a
DI30×C1	0.58 a	1.71 a	2.69 a	1.03 a	0.43 a	0.65 a	1.28 a	0.57 a
DI30×C2	0.54 a	2.11 a	2.55 a	1.00 a	0.37 a	0.56 a	1.81 a	0.53 a
DI60×C1	0.46 a	1.89 a	2.08 a	0.83 a	0.92 a	0.56 a	2.13 a	0.76 a
DI60×C2	0.66 a	2.32 a	2.12 a	1.17 a	0.84 a	0.54 a	2.08 a	0.62 a
Average	0.6	1.82	2.34	1.00	0.56	0.56	1.87	0.59
ANOVA								
I	n.s.	*	*	n.s.	*	n.s.	*	n.s.
C	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
I * C	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C.V.	28.1	15.67	14.48	25.68	29.2	10.95	17.54	28.47

Within a column for each year, values followed by different letters are significantly different at $p < 0.05$ by Fisher's LSD test.
I and C represent deficit irrigation treatment and cultivar, respectively.
*is significance at the 0.05 probability level. n.s. denotes non-significance.

results in a low light interception (Santanoo et al., 2020). The lower estimate of *k* in 2021 planting compared to 2018 planting, can be the result of a higher fraction of diffuse light on cloudy days that enters the greenhouse in the winter season compared to the summer season. Li et al. (2014) reported that diffuse light usually exhibits a lower *k* than direct light. Sunlight consists of a diffuse and a direct component. Diffuse light is scattered by larger molecules or particles in the atmosphere and arrives at the earth's surface from many directions, while direct light reaches the earth surface in a straight line from the sun without being scattered (Li, 2015). Several studies (e.g. Farquhar & Roderick, 2003; Gu et al., 2003; Alton, 2008; Mercado et al., 2009) have shown that plants can use diffuse light more efficiently than direct light, and this is mainly due to a deeper penetration and more uniform distribution of light within the canopy.

DI decreased basil dry biomass, due to the decreased rate of solar radiation interception (Tables 2 and 3). Similar results for the reduction of basil dry biomass by increasing water stress, as well as for the harvest periods, were obtained by José et al. (2016) and Goldani et al. (2021). Under water deficit stresses, plants close their stomata to reduce water loss, which leads to increased leaf temperature and reduced CO_2 assimilation (Galmés et al., 2007). These physiological changes under water stress are also reflected in plant morphology and leaf area reductions, which is the main factor for intercepting solar radiation and therefore biomass decreases (Patanè & Cosentino, 2013). Compared to DI0, basil dry biomass did not show a considerable decrease under DI30 at three harvests in 2018 planting and in the first and second harvests in 2021 planting (Table 5). Therefore, DI30 was more effective in a good marketable basil dry biomass with saving irrigation water compared to DI0. In this conditions, it seems logical to have at least three basil harvests in April planting and a maximum of two basil harvests in August planting. However, it should be noted that by changing the management conditions (such as plant density and nitrogen management) in August planting, it is possible to have more than two harvests.

In the present study, the lowest RUE was often observed in DI0 treatment (Table 6). This revealed that basil plants have been able to use some mechanisms, which can mitigate water-deficit stress on efficient use of absorbed light; further research in this respect is suggested. Karimzadeh Soureshjani et al. (2019) reported that, in two common bean genotypes, DI resulted in an increase of RUE under medium drought stress conditions and then it decreased under severe drought stress conditions. However, most studies have indicated that crops suffering from water stress have low RUE, as Zhou et al. (2021) indicated that, compared to the treatment of 100 mm irrigation at growth stage of jointing (GS34) and heading (GS48), the RUE of winter wheat decreased by 14.00% and 21.28% in the treatments of 50 mm irrigation at GS34 and GS48 and 100 mm irrigation at GS34, respectively.

At the DI levels, there were no differences in the amount of cumulative solar radiation interception, dry biomass, and RUE of Green and Purple basil cultivars in two study years (Tables 2–4). This indicated that these two cultivars had similar efficiency in response to DI.

The cumulative solar radiation interception during the second harvest and total three harvests in the 2021 planting was higher than that in the 2018 planting, whereas cumulative solar radiation interception during the first and third harvests in 2018 planting was higher than in the 2021 planting (Table 4). The amount of solar radiation absorbed by the crop canopy depends on incoming solar radiation, in addition to the characteristics of the canopy, including leaf orientation, leaf thickness, leaf shape, and leaf area (Mahakosee et al., 2022). The variation in incoming solar radiation and canopy's characteristics in different harvests and planting dates affected cumulative solar radiation interception. In general, the April 2018 planting had the higher dry biomass and RUE at all harvests than the basil planted in August 2021 (Tables 3 and 4). It can be related to higher solar position, the quantity of solar radiation, and the fraction of direct PAR in April 2018 compared to August 2021 planting.

In two study years, by increasing the harvest number, cumulative solar radiation interception and dry biomass of basil plants decreased; however, basil RUE increased (Tables 2–4). The basil plants during the first harvest were subjected to favourable conditions (in terms of incoming solar radiation); therefore, the plants in this harvest intercepted more light and provided higher photoassimilation than other harvests.

Conclusion

Throughout this study, Green and Purple basil cultivars were planted under three DI levels in April 2018 and August 2021. The basil LAI, light interception, *k* value, dry biomass and RUE depended on DI level, harvest number and planting date. However, the studied traits were not significantly affected by cultivars. Therefore, the basil cultivar was not a significant determining factor in the response of the basil plant to light.

The results also revealed that DI30 was more effective in both good marketable basil yield and saving irrigation water compared to full irrigation treatment in the greenhouse conditions. Considering the effect of the harvest number on the basil dry biomass, in the case of applying DI at 70% of the FC, it is recommended to have at least three basil harvests in April planting and a maximum of two harvests in August planting.

The high rate of light variation in August 2021 planting resulted in a less efficient use of radiation by the basil canopy. Consequently, the properties of plant and canopy such as rate of nitrogen fertilisation, plant LAI, and plant density should be managed in such a way that optimum use of light can be achieved by the canopy in August planting of greenhouse basil.

The results obtained in this study would be valuable for water management for greenhouse basil production in the April and August planting.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

No funds, grants or other support was received.

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Authors’ contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Morteza Goldani, Fatemeh Yaghoubi and Ali Asadi. The first draft of the manuscript was written by Fatemeh Yaghoubi and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Consent to participate

The authors voluntarily agree to participate in this research study.

Consent for publication

The authors confirm no conflict of interest and agree with submission of the manuscript to the Journal.

Data availability statement

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Ethics approval

This research meets all the ethical guidelines, including adherence to the legal requirements of Iran.

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