Crop water stress index for off-season greenhouse green peppers in Liaoning, China

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Abstract: The crop water stress index (CWSI) is a complex instrument to effectively monitor the degree of water stress of crops and provides guidance for timely irrigation. In an experiment utilizing the CWSI with off-season green peppers planted in barrels in a greenhouse in Liaoning Province, Northeast China, this study monitors the sub-indexes--such as canopy temperature, environmental factors and yield--determines the changing law of each constituent, achieves an empirical model as well as a baseline formula for the canopy temperature of the peppers with a sufficient water supply, and verifies the rationality of the formula with corresponding experimental data. The results obtained by using the CWSI show that the optimal time to determine the water deficit for off-season green peppers is at noon, by measuring the diurnal variation in the peppers with different water supplies. There is a nonlinear relationship between the yield and the average CWSI at the prime fruit-bearing period; moreover, the optimal time to supply water for off-season green peppers comes when the average water stress index ranges between 0.2 and 0.4 during the prime fruiting stage, thereby ensuring a high yield.

Keywords: crop water stress index, off-season green peppers in greenhouse, high yield, canopy temperature, irrigation, water deficit

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1 Introduction

As of 2011, there are 600 000 hectares of greenhouses in China, for which the water requirement of the crops grown within is mainly satisfied by means of irrigation. A large amount of water can be saved if the irrigation is appropriately scheduled and precisely arranged according to the respective water shortage conditions of the crops. Water conservation, the improvement of water use efficiency and the elimination of irrigation blindness can be achieved when proper indexes are chosen to guide and control the actual irrigation, the water status of the crops being reflected by their physiological changes, thereby ensuring that the irrigation is the most suitable and the most opportune[1].

Canopy temperature is determined by a combination of the internal heat of the crops as well as the water vapor and the soil-plant-atmosphere system. This measure shows the energy exchange between crops and atmosphere, being related to the energy absorption and the release of the crops[2]. Canopy temperature is also a good indicator of the water condition of the crops; whereas, other indicators such as crop-stem-flow change, leaf water potential, and stomatal conductance require more time and have a higher rate of deviation during measuring and sampling[3-5]. The crop water stress index (CWSI), which has been widely researched and applied[1,3,7], is an effective index to monitor crops with the help of the surface temperature of the crop canopy to determine whether a crop is undergoing water stress. The CWSI and the temperature difference between canopy and air (Tc-Ta) are effective ways to evaluate the water condition of crops with the help of the

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canopy temperature[6-9].

A crop water production function can be achieved on the basis of the CWSI with a relative error rate maintained at around 10%, thus overcoming the difficulty in obtaining accurate information on evapotranspiration of crops[10], thereby providing a new concept for the establishment of water production functions and the optimization of irrigation systems. However, current CWSI research is mainly focused on field crops[11-14].

The irrigation control system variables of greenhouse vegetables include the content, tension, and potential of soil moisture, as well as the evaporation, depth of wetting layer of irrigation and irrigation frequency of the soil[15-18]. Concurrently, a study of indexes associated with the physiological activities of crops to judge their respective water deficits has been implemented. However, the present production management of off-season greenhouse vegetables in China still focuses on experience management and lacks indexes which are effective, easily monitored and associated with the physiological information on crops to evaluate the degree of water deficit.

This research investigates the changes in the CWSI of off-season green peppers cultivated in a greenhouse in Northeast China on the basis of an experiment on the plant canopy temperature, the correlation between the CWSI and environmental factors, as well as the CWSI range when the peppers are deficient in water to form a foundation for the establishment of water production functions and proper irrigation systems for off-season greenhouse green peppers.

2 Experimental design and methods

2.1 Experimental conditions

The experiment was conducted during fall 2011 and winter 2012 in the greenhouse at the College of Water Conservancy, Shenyang Agricultural University (Shenyang, Liaoning Province, China), located at 41°46′ latitude north and 123°27′ longitude east at an altitude of 44.7 m. The green pepper variety "35-619" was the experimental target. Mid-September was selected as the period to determine the experimental numerical value. The irrigation mode was gravity drip. A brown loamy soil having an average bulk density of 1.52 g/cm^3 was used as the planting soil; the water retention capacity in the field, 39%. During irrigation, a drip irrigation belt covered by plastic film was set on a barrel, on which irrigation pipes having a diameter of 16 mm and a thickness of 0.6 mm were placed at an interval of 30 cm, at a flow rate of 2.4 L/h. The physical and chemical properties of the soil in the experimental site are listed in Table 1.

Table 1 Physical and chemical properties of soil in the experimental site

Total N/g·kg^{-1}	Total P/g·kg^{-1}	Total K/g·kg^{-1}	Alkalihydrolyzable N/g·kg^{-1}	Available P/g·kg^{-1}	Available K/g·kg^{-1}	Organic matter/g·kg^{-1}	pH value
1.19	1.07	20	58.86	48.29	145.5	10.73	7.9

2.2 Experiment layout

The experiment was conducted with green peppers planted in barrels having a height of 60 cm and a diameter of 50 cm with 50 cm of clay inside. The barrels had double bottoms separated by an interval of 10 cm, the upper level having seven holes for ventilation and dripping water, the lower level having one hole for drainage and also measuring the amount of water dripping through. The barrels were filled with gauze, pebbles, and compacted soil from bottom to top, fitted with a Time-Domain Reflectometer (TDR, manufactured in Germany by TRIME-PICO), gauging pipes to monitor the change in the humidity of the soil, facilitated by the hot-air drying method. The configuration is illustrated in Figure 1, which depicts a total of 39 steel buckets, with each three implementing one experimental treatment, respectively.

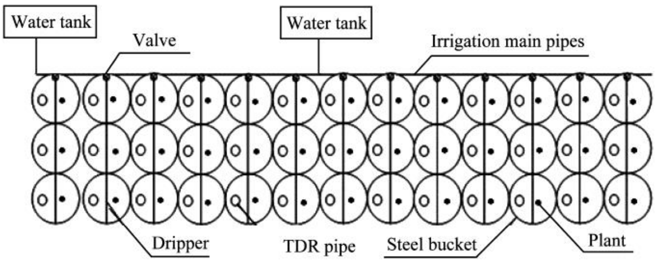

Figure 1 Drip irrigation configuration of the experimental site of experiment arrangements

2.3 Treatments

The growth of green peppers proceeds through four stages: (1) seedling, (2) blooming and fruiting, (3) prime fruiting and (4) late fruiting. During the experiment, 13 treatments were conducted, each being repeated three times, the first of which, designated "CK," was implemented without water deficit for the sake of comparison. The other treatments were designed to induce various degrees of water deficit in the successive growth stages, as listed in Table 2. In the experiment, the soil humidity content was considered to be a variable for irrigation. Because it was difficult to precisely determine the minimum requirement for irrigation, a range was set for each treatment. When the humidity content of the soil slipped below the range, water was added until it reached the maximum for irrigation, being equal to the water-saturation capacity of the field. With the range of minimum requirements as an indicator to control soil humidity, the water treatments at different stages are listed in Table 2. Each value in the table represents the percentage of water-holding capacity in the field.

Table 2 Treatments in water stress experiment on greenhouse peppers

Treatment Number	Water stress at seedling stage/%	Water stress at blooming and fruiting stage/%	Water stress at prime fruiting stage/%	Water stress at late fruiting stage/%
CK (no water deficit)	85-90	85-90	85-90	85-90
1	45-50	75-80	80-85	75-80
2	55-60	75-80	80-85	75-80
3	65-70	75-80	80-85	75-80
4	70-75	45-50	80-85	75-80
5	70-75	55-60	80-85	75-80
6	70-75	65-70	80-85	75-80
7	70-75	75-80	45-50	75-80
8	70-75	75-80	55-60	75-80
9	70-75	75-80	65-70	75-80
10	70-75	75-80	80-85	45-50
11	70-75	75-80	80-85	55-60
12	70-75	75-80	80-85	65-70

2.4 Procedures and observations

(1) The soil humidity was measured with the TDR about once every three days, being monitored continuously at specified times immediately before each irrigation and one day or one and a half days afterward at depths of 10 cm, 20 cm and 30 cm, respectively.

(2) During the first two months of the experiment, the leaf area index was obtained by multiplying the maximum length and width of each blade by a conversion coefficient of 0.6509[19]. Subsequently, our research team purchased a Handheld Leaf Area Meter (YK24/BCA-YMO2, manufactured in Beijing, China) from which we could easily read the value of the leaf area index, the interval between measurements being seven days.

(3) The canopy temperature was measured with a portable infrared thermometer (UT301A, manufactured in Shanghai, China) at an angle of 45 degrees between the instrument and the surface of the canopy. One observed value was obtained when eight groups of data were averaged, resulting from two iterations of circulatory observations arranged in northerly, southerly, easterly and westerly directions, respectively, within the experimental area. Each measurement was conducted once per hour from 9:00 to 16:00 on sunny days.

(4) The greenhouse air temperature was measured with a Catathermometer (130S, manufactured in Shanghai, China) once per hour from 9:00 to 15:00 daily throughout all growth stages of the crop.

(5) The air humidity was measured with a mechanical ventilated psychrometer (DHM2, manufactured in Shanghai, China) once per hour from 9:00 to 16:00 at a height of 1.5 m above ground, each measurement being repeated twice.

3 Empirical CWSI model

To date, the crop water stress index has both empirical and theoretical models. The theoretical model needs more variables that are difficult to measure, such as aerodynamic resistance, soil heat flux density, and others, which increase the complexity of the application; nevertheless, the model has a strong theoretical background[20]. Therefore, our team plans to introduce the theoretical model in future research. However, because the empirical model requires fewer, easily measured variables and the results obtained are close to those from a theoretical model for greenhouse crops[21], the empirical model was adopted for this research.

3.1 Definition of model

The empirical CWSI model[22] is defined by the following formulas:

$$CWSI=\frac{(T_c-T_a)-(T_c-T_a)_{ll}}{(T_c-T_a)_{ul}-(T_c-T_a)_{ll}} \tag{1}$$

$$(T_c - T_a)_{ll} = a + b \times VPD \qquad (2)$$

$$(T_c - T_a)_{ul} = a + b \times VPD \qquad (3)$$

where, T_c refers to the canopy temperature of crops; T_a , air temperature; $(T_c - T_a)_{ll}$, the minimum temperature difference between canopy and air when the water supply is sufficient; and $(T_c - T_a)_{ul}$, the maximum temperature difference between canopy and air when there is an acute shortage of water. Both canopy and air temperatures are expressed in ℃; a and b are the linear regression coefficients; VPD, the atmospheric vapor pressure deficit; and VPG, the difference between VPD with temperatures T_a and T_a+a, both of which are expressed in kPa units. Equation (2) is the baseline formula for the temperature difference between canopy and air.

Ideally, the CWSI ranges between 0 and 1, being 0 when the crops have a sufficient water supply and 1 when there is an acute shortage of water.

3.2 Determination of atmospheric vapor pressure deficit

The humidity in the air was measured with a mechanical ventilated psychrometer (DHM2, manufactured in Shanghai, China). The atmospheric vapor pressure deficit with different water treatments was obtained with an agro-meteorology computing method devised by Jiang Huifei[23]. This deficit is determined by the following formulas:

$$VPD = e_s - e_d \qquad (4)$$

$$e_d = e_s \times RH / 100 \qquad (5)$$

$$e_s = 0.611 \exp\left(\frac{17.27T}{T + 273.3}\right) \qquad (6)$$

where, e_s is the saturated vapor pressure and e_d, the actual vapor pressure, both of which are expressed in kPa units; RH, the actual relative humidity measured as a percentage; T, the actual measured air temperature.

4 Results and discussion

4.1 Calibration and validation of baseline equation for canopy-air temperature difference

Experimental data were collected for greenhouse-cultivated green peppers during the prime fruiting stage, including canopy temperature and the following environmental factors: air temperature, relative humidity, and atmospheric vapor pressure deficit. Two groups of typical data concerning diurnal variation collected on sunny days are listed in Table 3.

Table 3 Actual measurements of canopy temperature and environmental factors in December 2012

Date/Month-date	Time	Canopy temperature T_c/℃	Air temperature T_a/℃	Relative humidity RH/%	Atmospheric vapor pressure deficit VPD/kPa	Canopy-air temperature difference T_{ca}/℃
12-06	9:00	4	6	65	0.3099	-2
12-06	10:00	10	14	48	0.7371	-4
12-06	11:00	15	23	40	1.4009	-8
12-06	12:00	18	29	34	2.1139	-11
12-06	13:00	11	27	36	1.8474	-16
12-06	14:00	13	28	28	2.1897	-15
12-06	15:00	6	11	36	0.7628	-5
12-07	9:00	5	8	58	0.4194	-3
12-07	10:00	9	14	49	0.7229	-5
12-07	11:00	17	26	44	1.5338	-9
12-07	12:00	19	29	35	2.0819	-10
12-07	13:00	13	28	38	1.8855	-15
12-07	14:00	14	30	30	2.3605	-16
12-07	15:00	6	12	36	0.8085	-6

The baseline formula for the water shortage index was devised on the basis of a regression analysis of actual measured data on green peppers having a sufficient supply of water, reflecting the relationship between the VPD and the canopy-air temperature difference. The formula is as follows:

$$T_{ca} = -6.4217VPD - 0.1334 \qquad (7)$$

This equation indicates that there is a good linear relationship between the canopy-air temperature difference and the vapor pressure deficit, i.e., an R^2 of 0.8534, as plotted in Figure 2.

As indicated in Table 4, there is little deviation between the actual measured canopy temperatures and those calculated by formula (7), the maximum relative deviation being 17.46%. Moreover, formula (7) was obtained to predict the canopy temperature in accordance with the *VPD*. Furthermore, the canopy temperature can be determined by formula (2) and the CWSI by formula (1).

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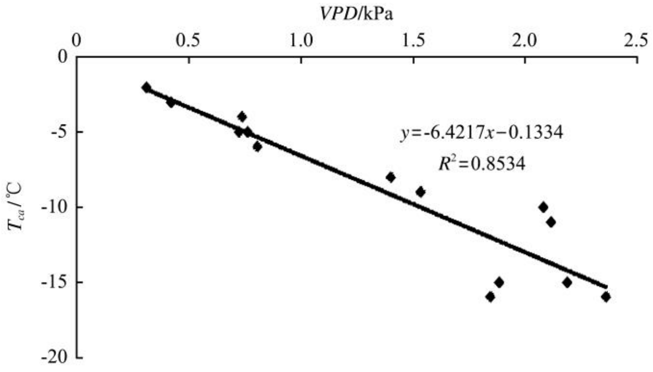


Figure 2 Relationship between VPD and canopy-air temperature difference

Table 4 Comparison of temperatures: actual measured canopy and theoretically calculated

Date/ Month-date	Time	Actual measured canopy temperature T_c/℃	Actual measured air temperature T_a/℃	Actual measured vapor pressure deficit of atmosphere *VPD*/kPa	Calculated canopy temperature T_c/℃	Absolute deviation of canopy temperature /℃	Rela- tive devia- tion /%
1-1-2012	9:00	6	8	0.2396	6.3277	0.3277	5.4620
01-01	10:00	12	18	0.6572	13.6462	1.6462	13.7187
01-01	11:00	16	26	1.5886	15.6651	0.3349	2.0929
01-01	12:00	19	32	2.4645	16.0405	2.9595	15.5765
01-01	13:00	12	24	1.5765	13.7428	1.7428	14.5237
01-01	14:00	13	23	1.4476	13.5709	0.5709	4.3913
01-01	15:00	7	14	0.8789	8.2229	1.2229	17.4693
01-02	9:00	8	10	0.3260	7.7733	0.2267	2.8340
01-02	10:00	10	17	0.8231	11.5809	1.5809	15.8089
01-02	11:00	15	27	1.5010	17.2273	2.2273	14.8489
01-02	12:00	17	30	2.0570	16.6571	0.3429	2.0172
01-02	13:00	12	20	1.1506	12.4781	0.4781	3.9838
01-02	14:00	14	22	1.4158	12.7749	1.2251	8.7507
01-02	15:00	6	10	0.6520	5.6800	0.3200	5.3340

4.2 Analysis of correlation between CWSI and LAI

The physical basis for crop yield is photosynthesis. The leaf area index (LAI) is an important parameter for characterizing photosynthesis and can reflect the influence of the CWSI of greenhouse-cultivated peppers on photosynthetic physiology[14]. In this research, a correlation analysis of CWSI and LAI averages was calculated with different water treatments. As plotted in Figure 3, there is a significant negative correlation between the CWSI and LAI averages during the breeding season for green peppers, i.e. R^2=0.9582.

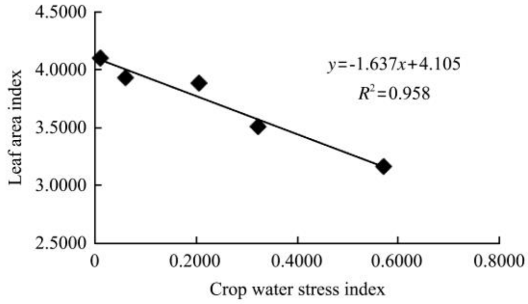


Figure 3 Correlation analysis of CWSI and LAI averages with different water treatments

4.3 Daily changes in CWSI

The CWSI is a comprehensive function of various environmental factors when there is a water deficit. As Figure 4 reveals, there is a significant daily change in the CWSI of peppers with different water treatments. Before 9:00 am the average CWSI is zero because of a lower temperature and VPD as well as high moisture. The CWSI average rises with an increase in temperature and solar radiation, reaching the maximum between 12:00 noon and 13:00 pm. Concurrently, the difference in the

CWSI with different water treatments increases continuously. Therefore, the optimum time to measure the water deficit of green peppers with CWSI is between 12:00 noon and 13:00 pm on sunny days. From treatment 1 to treatment 5, the degree of crop water deficit increases as demonstrated by the CWSI curves during the prime fruiting stage. The differences between treatments are listed in Table 5.

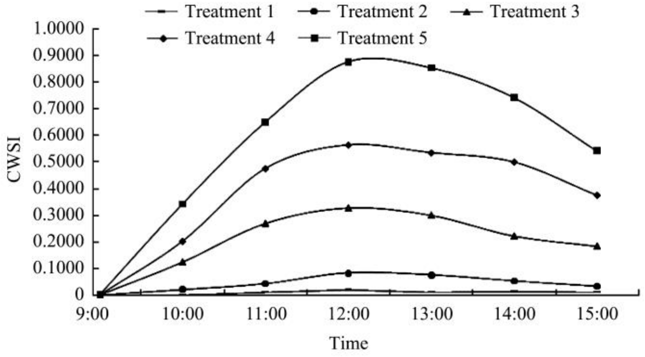


Figure 4 Daily changes in CWSI with different water treatments

Table 5 Differences between treatments during prime fruiting stage of green peppers

Item	No.				
	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
Range of minimum soil moisture /%	85-90	80-85	70-75	60-65	50-55

Note: The values in the table represent the percentage of water-holding capacity in the field.

Figure 5 was plotted according to the data from treatment 5, when the pepper was in the different growth stages of blooming and fruiting, prime fruiting, and late fruiting. The CWSI was most sensitive during the prime fruiting stage, which indicates that this index can proficiently reveal the crop water deficit during that important time when water is required.

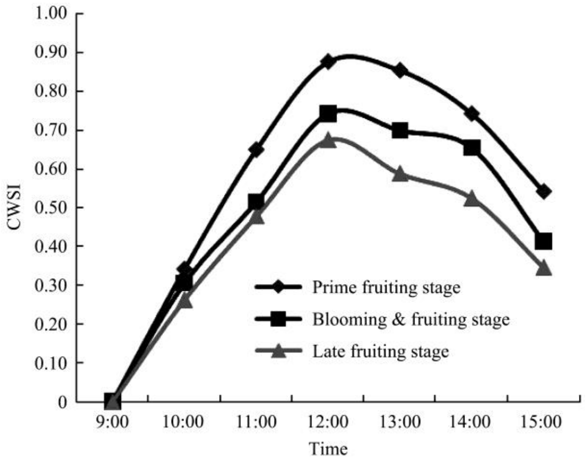


Figure 5 Daily changes in CWSI with identical water treatments but different growth stages

4.4 Fitting functions for daily change in CWSI

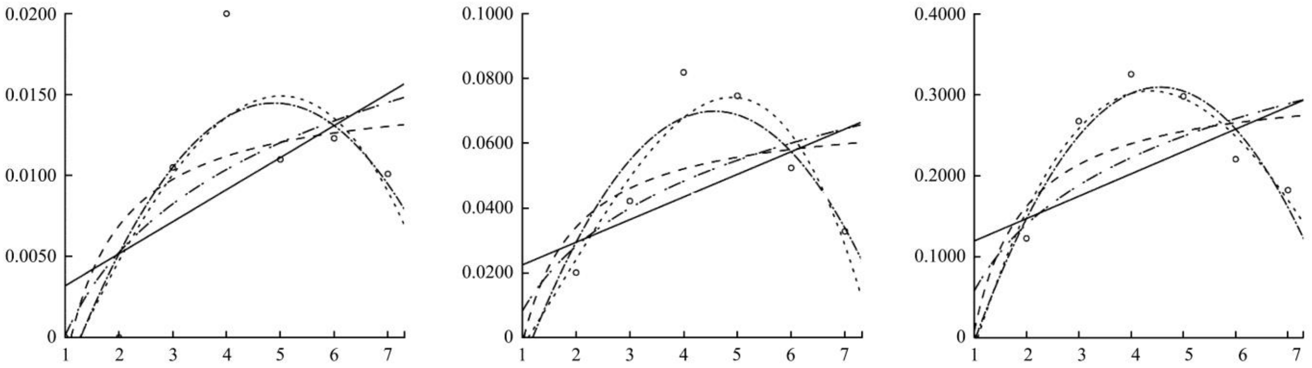
As indicated in Table 6, there is a relationship between the CWSI and the time of day. Various fitting functions for the daily change in the CWSI with different water treatments are established by the curve-fitting method as implemented in SPSS software (version 18.0, IBM, USA). The corresponding curves of the respective fitting functions are illustrated in Figure 6. From this figure, one can see that the cubic functions have the best fitting with a better relative coefficient. The cubic fitting functions of daily change in the CWSI with different treatments are listed in Table 6.

Table 6 Cubic fitting functions of daily changes in CWSI with different treatments

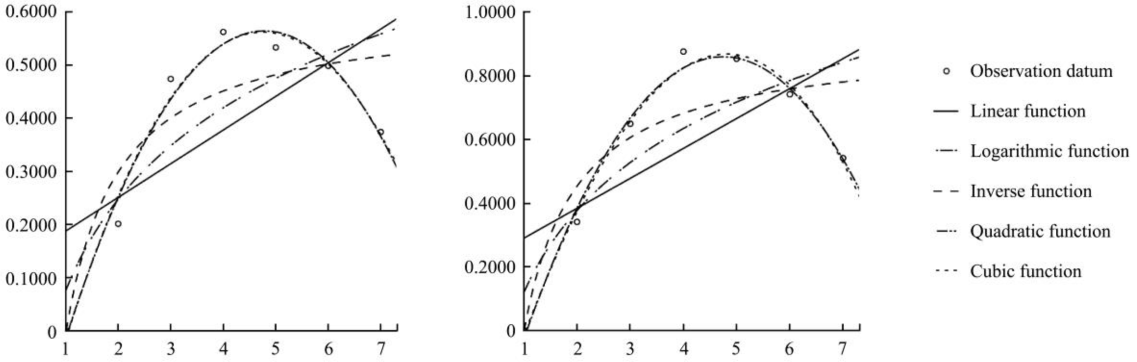
Treatments	Regression function	R^2
Treatment 1	$y=-0.0095+0.0079x-0.0002x^2-0.0001x^3$	0.7171
Treatment 2	$y=-0.0259+0.0195x+0.0045x^2-0.0009x^3$	0.9215
Treatment 3	$y=-0.2601+0.2877x-0.0428x^2-0.0015x^3$	0.9623
Treatment 4	$y=-0.3796+0.4074x-0.0463x^2-0.0005x^3$	0.9781
Treatment 5	$y=-0.4981+0.5270x-0.0421x^2-0.0017x^3$	0.9913

4.5 Relationship between yield and CWSI with different water treatments

The nonlinear relationship between the CWSI (T_{ca} of green peppers in prime fruiting stage) and the yield is plotted in Figure 7, drawn according to the data in Table 7. From this figure one can see that the yield increases with an increase in the CWSI, achieving the maximum when the CWSI reaches a certain point but subsequently decreases if the CWSI continues to increase. When the average CWSI ranges between 0.2 and 0.4, the maximum yield emerges, indicating that the optimal standard for irrigation is an average CWSI ranging between 0.2 and 0.4. That's to say, if off-season greenhouse peppers are irrigated when the average CWSI lies within the aforementioned range, the water use efficiency will be at its maximum.



a. Fitting functions for treatment 1 b. Fitting functions for treatment 2 c. Fitting functions for treatment 3



d. Fitting functions for treatment 4 e. Fitting functions for treatment 5

Figure 6 Fitting functions of daily changes of CWSI under different treatments

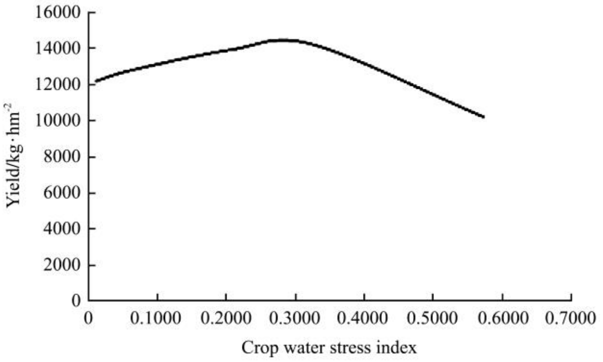


Figure 7 Relationship between average CWSI and yield of peppers

Table 7 CWSI and yield from different treatments during prime fruiting stage of peppers

items	No.				
	Treatment1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
CWSI	0.0107	0.0603	0.2059	0.3231	0.5723
Yield /$\mathrm{kg \cdot hm^{-2}}$	12212.79	12809.21	13962.85	14280.09	10211.34

5 Conclusions

The aim of this research has been to study the changes in the CWSI for greenhouse-cultivated green peppers and the corresponding influencing factors, with soil moisture as an indicator, for controlling irrigation. This research has also further explored the appropriate indicators for controlling irrigation for green peppers. The conclusions are made as follows:

(1) The trend in the daily changes in the CWSI for peppers grown with different water supply treatments is the same. There is a gradual change in the CWSI with a sufficient water supply and a significant change in the water shortage condition. This change reaches its maximum between 12:00 noon and 13:00 pm.

(2) Models for the functional relationship between the CWSI and treatment times with different water supplies have been established by the curve-fitting method utilizing SPSS. Among all the curves, the cubic functions have the best fitting.

(3) A nonlinear relationship exists between the yield and the CWSI of off-season green peppers with different water supplies; moreover, the optimal time for irrigation occurs when the average CWSI ranges between 0.2 and 0.4 during the prime fruiting stage, thereby ensuring a high yield.

Furthermore, this research has shown that the T_{ca} and the CWSI can not only reflect the condition of the crop water deficit but also function as an index to measure the water deficit conditions of greenhouse peppers and guide the water management thereof.

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