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Drip irrigation and fertilization improve yield, uptake of nitrogen, and water-nitrogen use efficiency in cucumbers grown in substrate bags

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Abstract: This study was conducted to identify ideal irrigation and fertigation levels for maximum yields and profitability of cucumber grown in a substrate-bag cultivation system. The experiment was laid out in randomized complete-block design, with combinations of four drip irrigation rates (75, 100, 125, or 150% of crop evapotranspiration (ETc)) and three fertilization (F) levels (60, 100, or 125% of one dose of Yamazaki nutrient solution formula). The 'irrigation level × fertilization level' interaction significantly affected cucumber yield and nitrogen accumulation. The treatment combination of 125% ETc and 100% F promoted yield relatively best. Plants were grown in the 125% ETc and 125% F treatment combination accumulated the most nitrogen. The greatest nitrogen use efficiency (NUE) was observed in the 100% ETc plus 60% F treatment combination. Water use efficiency (WUE) decreased with increasing irrigation rate, and considering just one fertilization level. Through the multivariate regression analysis and the spatial analysis methods to evaluate yield, WUE, and NUE, we conclude that the combination of 13.54–23.78 g/plant and 37.71–52.59 L/plant were the best strategy of fertigation and irrigation for the production of drip-irrigated cultivated cucumber grown in substrate bags in spring.

Keywords: *Cucumis sativus* L.; vegetable management; crop nutrition; soilless culture; controlled environment agriculture

An optimal supply of water and soil nutrients is basic to optimize agricultural yields (Chen et al. 2018, Dang et al. 2019). In China at present, there is a shortage of water resources, which has resulted in escalating irrigation costs, and fertilization is also costly. Consequently, it is of great interest to growers to adopt practices that improve water and fertilizer use efficiency (Bagr et al. 2016, Li et al. 2019).

Controlled environment agriculture (CEA) is the modification of the natural environment (including temperature, light, water, humidity, carbon dioxide, and plant nutrition) to achieve optimum plant growth. In China, CEA often called protected agriculture, which is developing rapidly and has increased the yield and income of farmers (Fang et al. 2016). Substrate-bag culture is one kind of soilless culture; the plants are grown in a plastic bag containing a solid substrate (Zhang and He 2006). The advantages to this cultivation method include the avoidance of continuous cropping, reduction of plant diseases and insect pests, increased yield, and easy recycling of agricultural waste. However, its appropriate use requires understanding

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the ideal levels of irrigation and fertilization. The 100% of crop evapotranspiration (ETc) is a relative saturated water supply for plant growth. So, many studies set 100% ETc as a maximal irrigation amount (Sinha et al. 2017). However, for Curcurbitaceae, especially cucumber, which needs a lot of water in its growth, it is unclear whether the yield and nitrogen use efficiency increases with improving ETc.

Cucumber is commercially important worldwide, and the demand for it continues to increase annually. Farmers who grow cucumbers often irrigate and fertilize them excessively (Du et al. 2017). Understanding the interactive effects of water and nutrient availability, and the cucumber's ability to efficiently use these resources, are crucial for improving the plants' water use efficiency (WUE) and nitrogen use efficiency (NUE). However, most of the studies relevant to water and fertilization use efficiency in cucumber have been done for cucumbers grown in soil conditions (Cao et al. 2016, Wang et al. 2017), which does not necessarily pertain to cucumbers grown in substrate-bag culture. The objective of this study, therefore, was to investigate the interactive effect of irrigation and fertilization strategy on cucumber yield, nitrogen uptake and use efficiency, and WUE in a substrate-bag culture system.

MATERIAL AND METHODS

Experimental site. The experiments were conducted in controlled environment greenhouse at the research farm of College of Horticulture, Northwest A&F University, located at Yangling, Shaanxi province, China during the spring seasons (March to June) of 2017. The date of planting is March 27, and ending of the experiment is July 3. The experimental greenhouse is at the latitude of 34°17'N and longitude of 108°04'E. The daily average temperature and relative humidity of air were 15.3–32.0°C and 29.9–95.0% during the cultivation.

Plant material and growth conditions. Seeds of *Cucumis sativus* L. cv Bonai 14-3 were germinated at 28°C in Petri plates lined with two layers of moistened filter paper, planted in 50-well plates filled with a mixture of waste organic matrix and vermiculite (1:8, v/v), and grown in a controlled environment greenhouse until the third true leaf was fully expanded. The seedlings were then transplanted into substrate bags, the line spacing is 0.75 m, the small line spacing is 0.50 m, and the plant spacing is 0.35 m, described below.

Each substrate bag had approximate dimensions of 1.30 × 0.20 × 0.16 m (length × width × height) and could contain 40 L of the substrate, and the substrate ratio is decomposed mushroom residue waste and vermiculite (1:8, v/v). The substrate contained: total nitrogen 9.75 mg/g, available nitrogen 318.4 mg/kg; at pH 6.68, with electrical conductivity (EC) of 2.25 mS/cm.

Experimental design and treatments. The experiment was laid out in a randomized complete-block design, with combinations of four irrigation treatments and three fertilization levels. The irrigation treatments were: 75, 100, 125, and 150% ETc, and the irrigation amount was based on the daily ETc. ETc was determined by weighing daily lost water amount of cucumber plants of three bags each treatment with an electronic scale (National Utility Model Patent in China, ZL 201620194394.3). The fertilizer supplied was Yamazaki cucumber special nutrition solution formula, and compositions of the formula were 826 mg/L $Ca(NO_3)_2·4\ H_2O$, 607 mg/L KNO_3, 115 mg/L $NH_4H_2PO_4$, 483 mg/L $MgSO_4·7\ H_2O$, 25 mg/L EDTA-NaFe, 2.86 mg/L H_3BO_3, 1.61 mg/L $MnSO_4·H_2O$, 0.22 mg/L $ZnSO_4·7\ H_2O$, 0.08 mg/L $CuSO_4·5\ H_2O$, 0.02 mg/L $(NH_4)_6Mo_70_{24}·4\ H_2O$. The EC and pH of the Yamazaki cucumber special nutrition solution were 1.2 mS/cm and 6.5, respectively. Drip irrigation was applied to each bag with a lateral pipe with a discharge of 4.0 L/h. There were a total of 12 treatment combinations, and three replicates of each treatment combination. There are 40 plants for each treatment per repetition, and the experiment has there repetition. Treatments began when the plants entered the flowering stage and harvests 52 times during the cultivation.

Measurements of crop parameters. Plant yield was measured from 20 randomly selected plants from each treatment combination for one replicate.

Nitrogen content of the tissues was measured at different growth stages. Ten representative plants from per treatment combination for each replicate were harvested at each stage: early fruiting stage, full bearing stage, telophase of fruiting stage. Leaf, shoot, root, and fruit tissues were separated and dried at 75°C in a forced air oven. Tissue samples were ground and passed through a 0.5 mm screen and were digested with H_2SO_4 in the presence of H_2O_2 and analyzed for total nitrogen (Bremner and Mulnavey 1982.).

Element accumulation amount (EAA) in different fruit development stage, element use efficiency

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(EUE) and WUE were calculated using the following equations (Mon et al. 2016):

$$\text{EAA (mg/plant DW)} = \text{En}_2 - \text{En}_1$$

$$\text{EUE (\%)} = (\text{Eu}_2 - \text{Eu}_1)/\text{F}$$

$$\text{WUE (kg/m}^3) = \text{Y}/(\text{I} - \Delta\text{W})$$

Where: En_2 (mg/plant DW (dry weight)) – element accumulation amount in latter development state; En_1 (mg/plant DW) – element accumulation amount in preceding development state; Eu_2 – nutrient (nitrogen) uptake amount with fertilization treatment; Eu_1 – nutrient (nitrogen) uptake amount without fertilization treatment; F – fertilization amount; Y – yield per plant (kg/plant). The parameter ΔW is the change amount of water stored in the initial and end stages of the experiment; I – irrigated water quantity (mm).

Statistical analysis. Data were analyzed by SPSS statistical software package (IBM Corporation, Armonk, USA). Two-way analysis of variance (ANOVA) was performed with the general linear model procedure to calculate the effects of irrigation water level and fertilizer levels on the investigated parameters. When the *F*-value was significant, a multiple means comparison was carried out using the least significant difference (*LSD*). The difference between treatments was deemed significant if the observed significance *P* value was less than 0.05.

RESULTS AND DISCUSSION

Effects of yield. Irrigation, fertilization rate, and their interaction significantly affected yield (Table 1). Plants receiving 125% ETc had yields of 2.61 kg/plant, an increase of 10.13% over plants receiving 150% ETc (with yields of 2.37 kg/plant). The high yield obtained at 100% F may indicate that this is the suitable fertilization rate for maximum yield, closely matching cucumber's requirements. The treatment combination of 125% ETc plus 100% F resulted in the greatest yield, relatively.

Water and nutrient availability are crucial for crop production (Chen et al. 2018). In general, the yield in this study increased with increasing irrigation and fertilization up to a point, after which yield decreased. Specifically, irrigation at 125% ETc with fertilization at 100% F maximized yield, which is consistent with previous studies (Li et al. 2017b). In this experiment, a moderate amount of water (37.71–52.59 L/plant: 94–119% ETc) and fertilizer (13.54–23.78 g/plant: 60–87% F) supply has a major impact on the crop yields.

Nitrogen accumulation. Considering irrigation only, leaves of plants grown in 100% ETc had more nitrogen than the other irrigation levels in both the early and telophase stages of fruit development. Total nitrogen accumulation in the leaves was not significantly different in 100% and 125% ETc ($P > 0.05$), but nitrogen accumulation in these two irrigation levels were significantly greater than it was in 150% ETc during the full bearing stage (Table 2).

In the early fruiting stage, total nitrogen accumulation in the leaf increased by 72.6% and 27.2% in the 125% F plus 100% ETc treatment combination and in the 100% F plus 100% ETc treatment combination, respectively, compared with the 60% F plus 100% ETc treatment combination. Total nitrogen accumulation in stems during the full bearing and telophase stage of fruiting was similar in 100% ETc and 125% ETc, but significantly greater than in 75% ETc. However, in the early fruit stage, total nitrogen accumulation in the stems was significantly greater in 100% ETc than in either 75% or 150% ETc. Stem nitrogen was greatest in 125% F, and if ranked by nitrogen concentration, it was followed by 100% F and 60% F.

Total nitrogen in the fruit was greatest at 100% F during the early and full bearing stages of fruit development. In contrast, during telophase, total nitrogen in fruit increased with increased fertilization from 60% to 125% F and was greatest at 125% F. The

Table 1. Yield of cucumber plants in different combinations of irrigation and fertilization (kg/plant fresh weight)

Fertigation schedule (FS)	Irrigation schedule (IS)				
	75% ETc	100% ETc	125% ETc	150% ETc	mean
60% F	2.03^{d}	2.17^{cd}	2.46^{abc}	2.32^{bcd}	2.25
100% F	2.46^{abc}	2.52^{ab}	2.75^{a}	2.46^{abc}	2.55
125% F	2.35^{bc}	2.55^{ab}	2.62^{ab}	2.33^{bcd}	2.46
Mean	2.28	2.41	2.61	2.37	2.42
$LSD_{0.05}$	FS =13.70; IS = 3.31; IS × FS = 4.13				

ETc – crop evapotranspiration; F – fertilization (one dose of Yamazaki nutrient solution formula)

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Table 2. Nitrogen accumulation by cucumber plants grown in different combinations of irrigation and fertilization at three stages of fruit development (mg/plant DW)

Organ	Fertigation (FS)	The early fruit stage irrigation schedule (IS)					Full bearing irrigation schedule					Telophase of fruiting irrigation schedule				
		75% ETc	100% ETc	125% ETc	150% ETc	mean	75%ETc	100% ETc	125% ETc	150% ETc	mean	75% ETc	100%ETc	125% ETc	150% ETc	mean
Leaf	60% F	268.75^{i}	629.67^{fg}	433.89^{h}	237.25^{i}	392.39	650.31^{j}	829.18^{g}	708.7^{h}	406.58^{k}	648.69	429.11^{c}	337.85^{d}	82.43^{h}	146.62^{g}	249.00
	100% F	700.48^{f}	800.62^{e}	853.36^{de}	616.36^{g}	742.71	898.38^{e}	1024.09^{d}	860.32^{f}	680.49^{i}	865.82	344.84^{d}	689.15^{a}	592.78^{b}	190.09^{f}	454.21
	125% F	1000.81^{b}	1086.74^{a}	912.43^{cd}	950.67^{bc}	987.66	1059.37^{c}	1248.67^{b}	1456.99^{a}	1271.19^{b}	1259.05	25.74^{i}	172.83^{fg}	25.31^{i}	267.78^{e}	122.91
	mean	656.68	839.01	733.23	601.43	707.59	869.35	1033.98	1008.67	786.09	924.52	266.56	399.94	233.50	201.50	275.38
	$LSD_{0.05}$	FS = 463.57; IS = 41.16; IS × FS = 11.30					FS = 495.72, IS = 53.43; IS × FS = 23.91					FS = 155.31; IS = 32.02; IS × FS = 48.55				
Steam	60% F	62.93^{f}	72.85^{de}	72.78^{de}	55.89^{g}	66.11	125.81^{f}	135.56^{e}	114.71^{g}	103.12^{h}	119.80	133.72^{k}	178.43^{i}	214.60^{g}	144.83^{j}	167.90
	100% F	73.80^{de}	80.41^{bc}	78.93^{cd}	72.69^{e}	76.46	135.99^{e}	166.27^{d}	208.24^{a}	127.86^{f}	159.59	192.92^{h}	270.67^{e}	284.34^{d}	224.13^{f}	243.01
	125% F	85.90^{b}	114.15^{a}	76.64^{cde}	82.22^{bc}	89.73	166.75^{d}	191.69^{b}	196.42^{b}	181.07^{c}	183.98	311.10^{c}	334.34^{b}	346.14^{a}	288.94^{d}	320.13
	mean	74.21	89.14	76.12	70.26	77.43	142.85	164.51	173.12	137.35	154.46	212.58	261.15	281.70	219.30	243.68
	$LSD_{0.05}$	FS = 7.87; IS = NS; IS × FS = NS					FS = 58.96; IS = 12.31; IS × FS = 5.74					FS = 325.49; IS = 46.51; IS × FS = 3.11				
Fruit	60% F	334.06^{f}	506.66^{d}	494.76^{d}	293.90^{g}	407.35	307.63^{i}	594.01^{g}	628.29^{f}	600.50^{g}	532.61	519.83^{h}	666.03^{f}	786.44^{c}	758.54^{d}	682.71
	100% F	556.39^{c}	626.60^{b}	649.00^{ab}	499.21^{d}	582.80	775.73^{d}	957.96^{b}	1066.01^{a}	745.34^{e}	886.26	596.23^{g}	822.39^{b}	861.05^{a}	707.87^{e}	746.88
	125% F	565.71^{c}	649.43^{a}	416.99^{e}	331.14^{f}	490.82	525.33^{h}	857.65^{c}	853.89^{c}	773.56^{d}	752.61	764.96^{cd}	863.02^{a}	876.33^{a}	704.01^{e}	802.08
	mean	485.39	594.23	520.25	374.75	493.65	536.23	803.21	849.39	706.47	723.82	627.00	783.81	841.27	723.48	743.89
	$LSD_{0.05}$	FS = 56.31; IS = 45.75; IS × FS = 11.08					FS = 233.15; IS = 105.22; IS × FS = 11.69					FS = 26.10; IS = 45.98; IS × FS = 9.45				
Root	60% F	24.58^{bcd}	22.54^{d}	28.29^{a}	28.22^{a}	25.91	42.12^{cd}	46.01^{ab}	45.55^{abc}	47.02^{a}	45.18	57.65^{bc}	57.94^{abc}	61.20^{a}	60.81^{ab}	59.40
	100% F	23.26^{cd}	26.73^{abc}	29.24^{a}	24.33^{cd}	25.89	41.35^{d}	42.67^{bcd}	48.72^{a}	45.75^{ab}	44.62	55.05^{cd}	53.49^{d}	59.41^{ab}	54.51^{cd}	55.62
	125% F	23.12^{cd}	28.15^{ab}	22.79^{d}	24.04^{cd}	24.53	41.53^{d}	48.13^{a}	45.20^{abc}	42.56^{bcd}	44.36	57.84^{abc}	57.47^{bc}	58.87^{ab}	52.11^{d}	56.57
	mean	23.65	25.81	26.77	25.53	25.44	41.67	45.60	46.49	45.11	44.72	56.85	56.30	59.83	55.81	57.20
	$LSD_{0.05}$	FS = NS; IS = NS; IS × FS = NS					FS = NS; IS = NS; IS × FS = NS					FS = NS; IS = NS; IS × FS = NS				
The whole plant cucumber	60% F	690.32^{i}	1231.72^{g}	1029.73^{h}	615.25^{j}	891.76	1125.86^{i}	1604.77^{g}	1497.25^{h}	1157.23^{i}	1346.28	1140.30^{gh}	1240.25^{e}	1144.67^{gh}	1110.80^{h}	1159.01
	100% F	1353.94^{f}	1534.36^{d}	1610.53^{c}	1212.59^{g}	1427.85	1851.46^{e}	2190.99^{d}	2183.29^{d}	1599.43^{g}	1956.29	1189.03^{f}	1835.70^{a}	1797.58^{b}	1176.60^{fg}	1499.73
	125% F	1675.54^{b}	1878.47^{a}	1428.85^{e}	1388.07^{f}	1592.73	1792.98^{f}	2346.14^{b}	2552.50^{a}	2268.39^{c}	2240.00	1159.63^{fg}	1427.66^{c}	1306.64^{d}	1312.84^{d}	1301.69
	mean	1239.93	1548.18	1356.37	1071.97	1304.11	1590.10	2047.30	2077.68	1675.02	1847.52	1162.99	1501.20	1416.30	1200.08	1320.14
	$LSD_{0.05}$	FS = 137.32; IS = 30.75; IS × FS = 6.15					FS = 213.21; IS = 48.28; IS × FS = 6.89					FS = 30.65; IS = 21.24; IS × FS = 8.93				

ETc – crop evapo-transpiration; F – fertilization (one dose of Yamazaki nutrient solution formula); DW – dry weight

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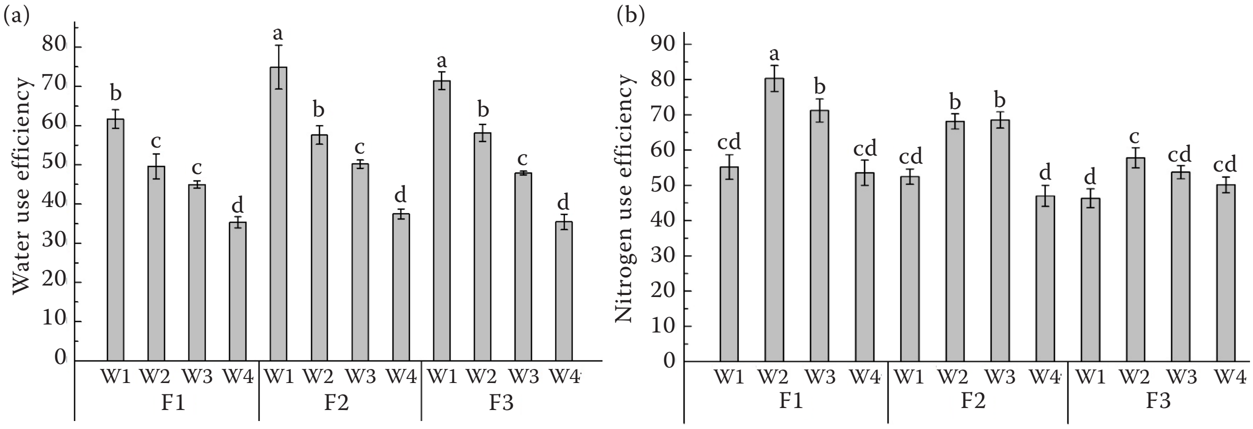

Figure 1. Effect of different irrigation and fertilization coupling treatments on cucumber (a) water use efficiency (kg/m^3) and (b) nitrogen use efficiency (%). W1–W4: 75, 100, 125 and 150% ETc (crop evapotranspiration); F1–F3: 60, 100 and 125% F (fertilization). F1 – 60%; F2 – 100%; F3 – 125% one dose of Yamazaki nutrient solution formula

maximum nitrogen (1066.01 mg/plant DW) was in the 125% ETc and 100% F treatment combination in the full bearing stage.

The total nitrogen in the root was not significantly affected by irrigation and fertilization treatments ($P > 0.05$). We also examined nitrogen in the whole plant (Table 2). Maximum values occurred in the 125% F treatments during the early and full bearing stages of fruit development. Differences between the irrigation and fertilizer combinations were highly significant ($P < 0.05$) during all growth stages. Whole-plant nitrogen concentration was greatest in the treatment combination 125% ETc plus 125% F.

These results suggested that the accumulation of nitrogen was mostly in leaf and fruit throughout the fruiting period. The accumulation of nitrogen in leaf as a function of time was a downward parabola, with the downward trend associated with late fruiting. In contrast, the accumulation of nitrogen in stems continued to rise over this period. It may be that in the late, telophase period of fruit development, the plant was still capable of continued growth, but the transfer of nitrogen from old leaves to new leaves and fruit was completed.

WUE and NUE. WUE is an important water use indicators in the study of sustainable irrigated agriculture (Ucar et al. 2017). WUE was significantly affected by irrigation and fertilization ($P < 0.05$), but the 'irrigation level × fertilization level' interaction was not significant (Figure 1). Increasing irrigation level reduced WUE. Considering just fertilization levels, we observed that the WUE increased slightly in plants grown in 100% F compared to 60% F, but then decreased at 125% F. The 75% ETc plus 100% F treatment combination had the highest WUE (74.92 kg/m^3). When the fertilization levels were constant, the WUE was dramatically affected by the irrigation amount (Figure 1). Thus, improved WUE may be achieved by reducing the water supply. However, excessive reduction of irrigation reduced the crop yields (Li et al. 2017a).

Irrigation, fertilization, and the 'irrigation level × fertilization level' interaction affected NUE, ($P < 0.05$; Figure 2). NUE first increased and then decreased with increasing irrigation level, and considering just

Table 3. The regression relationship between irrigation-fertilizer amount and yield, water use efficiency (WUE) and nitrogen use efficiency (NUE)

Dependent variable	Regression equation	R^2	P
Yield	$Y1 = -6.73 + 0.64\ F + 0.30\ W - 1.16 \times 10^{-2}\ F^2 - 2.36 \times 10^{-3}\ W^2 - 2.43 \times 10^{-3}\ F \times W$	0.8833	0.0091
Water use efficiency	$Y2 = 44.83 + 5.21\ F - 0.99\ W - 8.79 \times 10^{-2}\ F^2 + 5.46 \times 10^{-3}\ W^2 - 2.53 \times 10^{-2}\ F \times W$	0.9854	0.0001
Nitrogen use efficiency	$Y3 = -80.62 + 1.11\ F + 6.19\ W - 6.58 \times 10^{-2}\ F^2 - 6.61 \times 10^{-2}\ W^2 + 1.21 \times 10^{-2}\ F \times W$	0.8715	0.0120

W – irrigation amount; F – fertilization amount; R^2 – coefficient of determination; P – statistically significant value

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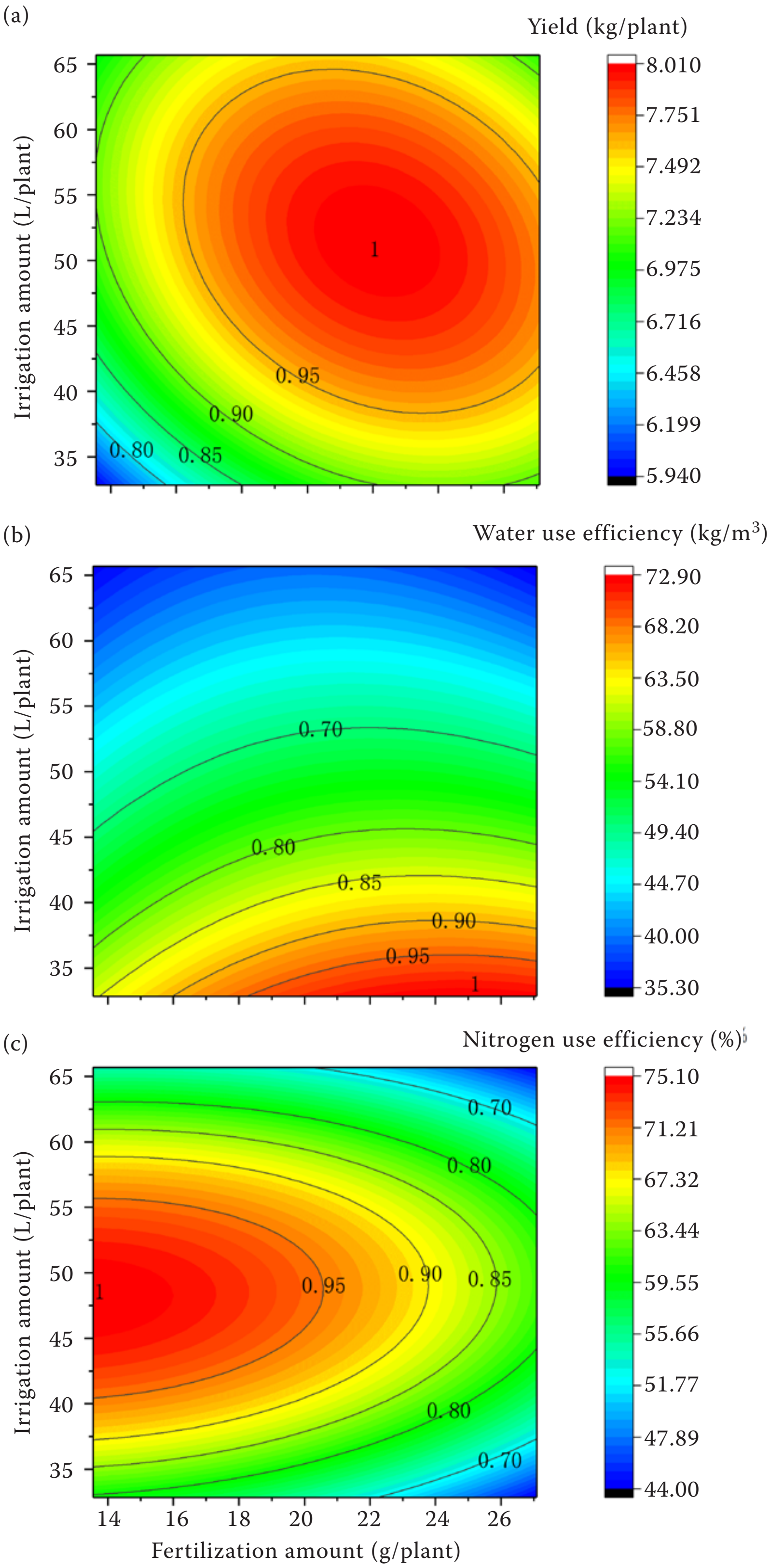

Figure 3. Relationship between irrigation-fertilization amount and (a) yield, (b) water use efficiency (WUE) and (c) nitrogen use efficiency (NUE). The different color represents the different yield (WUE, NUE) range and yield (WUE, NUE) value increase with tonal changing to warm color. The lines of 0.80, 0.85, et al. represent the different value of yield (WUE, NUE) with irrigation and fertilization management

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one fertilization level. The greatest NUE peaked at 100% ETc plus 60% F treatment combination. The NUE was influenced greatly by the level of nitrogen supply. Others have observed that the maximum NUE occurs in the lower range of nitrogen supply (Zotarelli et al. 2009). In this experiment, also, the highest NUE was observed at the lowest level of fertilization. We noted that, at the lowest fertilization rate (60% F), the greatest NUE was associated with the moderate irrigation rates (100% ETc was associated with the highest NUE). Relevant here also is the finding of Zotarelli et al. (2008).

Coupling effect of water-fertilization in cucumber. Taking the input amount of water and fertilizer as the independent variable and defining the yield, WUE, and NUE as the dependent variables, then, regression analysis was conducted (Table 3). Results showed that the effects of irrigation amount and fertilizer amount on each dependent variable were significant ($P < 0.05$), and the coefficient of determination in regression analysis was above 0.85.

Spatial analysis method and Origin software were used to form the plane projection chart of each equation (Figure 3). The spatial analysis method was used to evaluate the optimal value of yield, WUE, and NUE, respectively at 0.85, 0.7, 0.9, and to comprehensively evaluate them, forming the results of Figure 4. In this study, the appropriate fertilization and irrigation range for per cucumber production was about 13.54–23.78 g and 37.71–52.59 L.

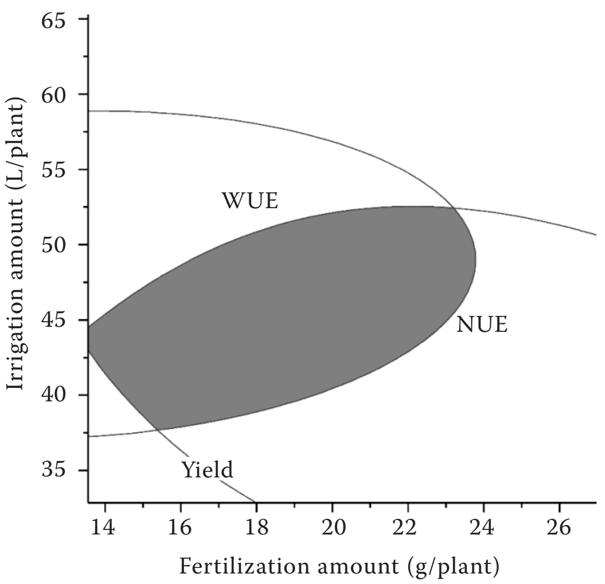

Figure 4. A comprehensive evaluation of yield, water use efficiency (WUE), and nitrogen use efficiency (NUE). The shadow area is the overlapping area of the optimal value of yield (0.85), WUE (0.7) and NUE (0.9)

Water and nutrient may interact with each other to produce a coupling effect (Pan et al. 2017, Ierna et al. 2018). This study used multiple regression and spatial analysis method to a comprehensive evaluation of the effect of irrigation and fertilization rate on yield, WUE, and NUE. When 0.85, 0.70 and 0.90 of optimal value were selected for yield, WUE, and NUE, respectively, the yield per cucumber plant could reach 6.81 kg/plant, WUE reached over 50.99 kg/m^3, N utilization rate reached 67.56%. So, when irrigation and fertilizer amount were within the appropriate range, cucumber plants' absorption and utilization of N and water could be promoted, and the yield increased. It is of great significance to reduce fertilizer and save water in cucumber production.

In conclusion, there was a significant 'irrigation level × fertilization level' interaction in cucumber yield and nitrogen accumulation. Comprehensive consideration of water and fertilizer amount, and high yield, the amount of 13.54–23.78 g/plant and 37.71–52.59 L/plant were the best strategies of fertigation (Yamazaki nutrient solution) and irrigation for the production of drip-irrigated cultivated cucumber grown in substrate bags in spring.

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