

营养液EC值及滴灌频率对日光温室耶糠基质栽培西瓜生长及品质的影响

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摘要:【目的】研究营养液EC值与滴灌频率对温室西瓜植株生长及果实产量、品质的影响,以期寻求营养液最优供给方式,为实现设施西瓜椰糠基质栽培过程中营养液的高效供给及标准化管理提供理论依据。【方法】试验以椰糠为栽培基质,设置了4个EC值水平($E_1: 0.15 \text{ mS} \cdot \text{cm}^{-1}$, $E_2: 0.25 \text{ mS} \cdot \text{cm}^{-1}$, $E_3: 0.35 \text{ mS} \cdot \text{cm}^{-1}$, $E_4: 0.45 \text{ mS} \cdot \text{cm}^{-1}$)和2个灌溉频率($R_1: 2 \text{ 次} \cdot \text{d}^{-1}$, $R_2: 4 \text{ 次} \cdot \text{d}^{-1}$),采用两因素完全随机设计方法,共8组处理。【结果】西瓜不同生育期植株、根系形态指标及生物量随着营养液EC值的升高先增加后降低,团棵期(15 d)和坐果期(30 d)均以 E_2 处理为优,膨果中期(45 d)茎粗和叶面积分别以 E_3 和 E_2 处理为优;成熟期(65 d)果实质量随EC值的增大持续下降,而可溶性固体物、可溶性糖含量及糖酸比等品质指标持续上升。低灌水频率(2次·d⁻¹)显著提高了西瓜苗期(15 d)植株的茎粗、叶面积和根系形态参数,促进了根冠比的提高,有利于强苗的培养。高灌水频率(4次·d⁻¹)显著提高了西瓜坐果期(30 d)茎粗、根总表面积、根体积和生物量,以及膨果中期(45 d)的茎粗;成熟期(65 d)单果质量以高灌溉频率为优,品质以低灌溉频率为优。此外,试验因素的交互作用对团棵期径粗、根系总长、根系表面积、根系鲜质量影响极显著($p < 0.01$),以 E_2R_1 组合最好;对坐果期株高和根系鲜质量影响显著($p < 0.05$),对茎叶生物量影响极显著,均以 E_2R_2 组合最好;成熟期果实品质以 E_4R_1 组合为优。【结论】团棵期EC值为0.25 mS·cm⁻¹、灌溉频率为2次·d⁻¹,伸蔓至坐果期EC值为0.25 mS·cm⁻¹、灌溉频率为4次·d⁻¹,果实膨大期EC值为0.15~0.25 mS·cm⁻¹、灌溉频率为4次·d⁻¹,成熟期EC值为0.45 mS·cm⁻¹、灌溉频率为2次·d⁻¹的营养液分段灌溉方式能兼顾西瓜植株发育和果实品质良好。

关键词:西瓜;电导率;滴灌频率;椰糠;基质

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Effects of nutrient solution electrical conductivity (EC) and drip irrigation frequency on growth and quality of watermelon grown in coco coir substrate in solar greenhouse

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Abstract:【Objective】The study aimed to explore a kind of optimal supply mode of nutrient solution and provide a guidance basis for high efficiency and standardized management of the nutrient supplement for watermelon plants grown in coconut-coir substrate through investigating the effects of nutrient solution electrical conductivity (EC) and drip irrigation frequency on plant growth and fruit weight and quality.【Methods】The experiments were designed with 4 EC levels (E_1 , E_2 , E_3 , and E_4 representing the EC of nutrient solution at 0.15, 0.25, 0.35 and 0.45 $\text{mS} \cdot \text{cm}^{-1}$, respectively) and 2 irrigation rate levels

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(R_1 and R_2 representing the irrigation rate of nutrient solution at $2 \text{ times} \cdot \text{d}^{-1}$ and $4 \text{ times} \cdot \text{d}^{-1}$, respectively), complete stochastic region design of two factors was applied with 8 groups of treatment. The regulation of EC values of each treatment level was realized by diluting the A and B mother liquor. Because of the difference of the plant growth and the weather, average daily irrigation volume for each plant was controlled within 0.8–1.5 L, which was divided into several equal parts according to the irrigation rates. And the nutrient solution was applied at the following times: R_1 at 8:30 and 14:30, R_2 at 8:30, 11:30, 14:30 and 17:30. **【Results】** The different EC values of nutrient solution and drip irrigation frequency significantly affected the growth of watermelon plants and the formation of fruit yield and quality in the greenhouse. With the increase of EC value of nutrient solution, the shoot growth performance (including plant height, stem diameter, leaf area), and root morphology (including total length, surface area, volume and diameter of root), and the plant biomass of the watermelon during vegetative growth period increased first and then decreased. The low irrigation frequency ($2 \text{ times} \cdot \text{d}^{-1}$) significantly increased the stem diameter, leaf area and root morphological parameters of watermelon plants at the rosette stage, promoting the improvement of root-shoot ratio, 26.52% higher than that of the high irrigation frequency ($4 \text{ times} \cdot \text{d}^{-1}$), which was conducive to the cultivation of strong seedlings. In addition, compared with the low irrigation frequency, the high irrigation frequency significantly increased the plant height of watermelon in vine elongating stage by 6.75%, and obviously increased the stem diameter, total root surface area and root volume and biomass of watermelon in fruit setting stage by 5.29%, 13.33%, 10.90%, 7.71%, 11.26%, and 7.19%, respectively. At the same time, the interaction of the nutrient solution EC value and drip irrigation frequency on watermelon plant height reached a significant level ($p < 0.05$), and the comprehensive effect of the E_2R_1 combination was the highest, which was 2.94 cm 24.53 cm and 154.86 cm at the rosette stage, vine elongating stage and fruit setting stage, respectively. Furthermore, at rosette stage and/or fruit setting stage, this interaction on stem diameter, total root length, root surface area, root-shoot ratio and biomass reached extremely significant level ($p < 0.01$), and the E_2R_1 was the optimum combination. In the formation stage of fruit yield and quality, with the increase of EC value, the fruit weight and organic acid of watermelon respectively decreased from 2.49 kg and 0.67% to 1.96 kg and 0.58%, while the soluble solids, soluble sugar and sugar/acid ratio respectively increased from 10.07%, 5.89% and 8.87 to 10.39%, 6.47% and 11.19%. Meanwhile, compared with the high irrigation frequency, the low irrigation frequency significantly reduced the fruit weight and organic acid by 6.41% and 11.94, and significantly increased the soluble solids, soluble sugar and sugar/acid ratio by 2.08%, 6.20% and 11.94%, respectively. Therefore, the low irrigation frequency was beneficial to improving the fruit quality, and the high irrigation frequency was beneficial to increasing the fruit yield. In addition, the interaction of experimental factors only had an extremely significant effect on the fruit weight ($p < 0.01$), and the treatment of E_1R_2 and E_2R_2 had the largest fruit weight, which were 2.52 kg and 2.65 kg, respectively. In the different combinations, the fruit quality of E_4R_1 treatment was optimum, including the lowest organic acid content, which was 0.55%, and the highest soluble solids, soluble sugar and sugar/acid ratio, which were 10.62%, 6.73% and 12.18%, respectively. **【Conclusion】** In the condition of greenhouse cultivation, the combinations of $0.25 \text{ mS} \cdot \text{cm}^{-1}$ EC and $2 \text{ times} \cdot \text{d}^{-1}$ irrigation rate during rosette stage, $0.25 \text{ mS} \cdot \text{cm}^{-1}$ EC and $4 \text{ times} \cdot \text{d}^{-1}$ irrigation rate during vine stage, $0.15-0.25 \text{ mS} \cdot \text{cm}^{-1}$ EC and $4 \text{ times} \cdot \text{d}^{-1}$ irrigation rate during fruit swelling stage, and $0.45 \text{ mS} \cdot \text{cm}^{-1}$ EC and $2 \text{ times} \cdot \text{d}^{-1}$ irrigation rate during maturation stage, would ensure the watermelon plants grown in coconut-coir substrate to grow well and produce quality fruits with high yield.

Key words: Watermelon; Electrical conductivity; Drip irrigation frequency; Coconut-coir; Substrates

我国是世界重要的西瓜种植国和消费国,面积、产量均位居全球第一。2019年我国西瓜播种面积为153.9万hm²,总产量为6 324.1万t,收获面积、产量分别占全球的46.3%和60.6%^[1-2]。由于设施西瓜栽培能够增加反季节供应量,满足人们不同季节对西瓜的消费需求,单位面积经济效益约是露地栽培的3倍^[3]。因此,近年来设施栽培已成为西瓜的重要栽培模式。但由于设施栽培土壤长期处于高集约化、高复种指数状态,西瓜多年重茬种植后土壤连作障碍严重,导致西瓜的产量和品质下降,严重制约着设施西瓜生产的可持续发展^[4]。

采用无土栽培方式可有效克服土壤次生盐渍化、土传病虫害等连作障碍问题,目前已成为有效克服设施西瓜地土壤连作障碍的主要栽培措施之一^[5]。椰糠作为瓜菜栽培基质具有良好的保水性和透气性,有利于植物吸收养分和水分,并且其天然环保、性质稳定、重复利用率高等优点,已在果蔬生产中得到了广泛应用。以往研究结果表明,椰糠基质栽培较传统泥炭基质栽培可在一定程度上提高西甜瓜的果实品质^[6],较岩棉基质栽培能够促进黄瓜植株生长,获得较高的果实品质^[7]。

营养液是无土基质栽培的核心,是植物获取营养的主要途径,营养液的合理供给不仅可以提高作物的产量和品质,而且还是降低生产成本的关键因素^[8]。EC值能在一定程度上反映营养液的养分离子浓度,为营养液管理提供数据支持^[9]。在茄果类蔬菜方面,研究提出兼顾番茄植株发育和果实品质良好的营养液EC值为0.4 mS·cm⁻¹,灌溉频率为5次·d⁻¹^[10];黄瓜椰糠栽培适宜的流出液EC值控制区间为2.2~2.6 mS·cm⁻¹,流出率控制在15%^[11-12]。压砂西瓜采用中低频补灌(2~3次补灌)处理,补灌量控制在16.46~21.46 m³·666.7 m⁻²,能促进其营养物质积累,提高水分利用效率,改善西瓜品质^[13]。叶菜方面,研究提出水培生菜的最佳营养液EC值为1.0~1.2 mS·cm⁻¹^[14];水培蕹菜的最佳营养液EC值为1.5 mS·cm⁻¹^[15]。在瓜类方面,综合甜瓜植株生长、坐果、裂果和产量、品质等因素,研究提出设施网纹甜瓜椰糠基质栽培适宜的营养液EC值为:苗期1.8~2.3 mS·cm⁻¹、伸蔓期2.7~3.0 mS·cm⁻¹、开花结果期3.3~3.7 mS·cm⁻¹^[16]。由此可见,EC值是设施农业无土栽培营养液管理的重要技术参数,然而目前针对设施西瓜椰糠基质栽培模式下营养液灌溉技术的研

究未见报道。为此,笔者在本文中通过设施西瓜椰糠基质栽培模式下,不同营养液EC值与灌溉频率对西瓜植株、根系生长和果实产量、品质的影响研究,以期为营养液高效利用及西瓜的优质高产提供科学依据。

1 材料和方法

1.1 试验材料

试验地点:试验在甘肃省农业科学院张掖节水试验站塑料大棚中进行,地处典型的绿洲荒漠交错带,地理位置为100°22'51"E,38°50'49"N,属温带大陆性荒漠气候区,海拔1555 m,年均气温6 °C,无霜期165 d,年均降水量128 mm、蒸发量约2341 mm,年日照时数约3300 h。

西瓜品种为中早熟品种美丽(武威安泰达种业有限责任公司),果实圆形,皮色浓绿,瓜瓢大红,质地脆沙、汁多纤维细,中心可溶性固体物含量12.0%左右,单果质量6~8 kg。椰糠条(100 cm×20 cm×15 cm)采用冉美椰糠(由青岛冉美商贸有限公司提供),母液营养液配方见表1^[15],试剂为无土栽培专用(由北京艾格拉农业科技有限公司提供)。

表1 营养液母液组分

Table 1 Component of standard nutrient solution

A液 Mother liquor A		B液 Mother liquor B	
化学试剂	质量 Mass/g	化学试剂	质量 Mass/g
Ca(NO ₃) ₂ ·4H ₂ O	944	KNO ₃	604.00
KNO ₃	79	KH ₂ PO ₄	170.00
NH ₄ NO ₃	40	MgSO ₄ ·7H ₂ O	339.00
Fe-EDTA(13.1%)	7	MnSO ₄ ·4H ₂ O	1.70
		ZnSO ₄ ·7H ₂ O	1.45
		Na ₂ B ₄ O ₇ ·10H ₂ O	2.45
		CuSO ₄ ·5H ₂ O	0.19
		Na ₂ MoO ₄ ·2H ₂ O	0.12

注:A、B液试剂称好后,每罐各加10 L水。

Note: Add 10 L water to each tank after the A and B liquid reagents are weighted.

1.2 试验处理

本试验为椰糠基质开放式栽培,采用营养液EC值与灌溉频率两因素完全随机设计。依据实际生产经验设4个EC值水平(E₁:0.15 mS·cm⁻¹,E₂:0.25 mS·cm⁻¹,E₃:0.35 mS·cm⁻¹,E₄:0.45 mS·cm⁻¹)和2个灌溉频率水平(R₁:2次·d⁻¹,R₂:4次·d⁻¹),共8个处理组(E₁R₁,E₁R₂,E₂R₁,E₂R₂,E₃R₁,E₃R₂,E₄R₁,E₄R₂),3次重复,随机区组排列。

A、B母液等体积混合按不同比例稀释,利用电导率仪(精度 $0.01\text{ mS}\cdot\text{cm}^{-1}$, DDS-307实验室电导率仪)调节各水平工作液至目标EC值范围 $\pm 0.05\text{ mS}\cdot\text{cm}^{-1}$ 内,然后用磷酸调节各营养液pH值在6.5~6.8之间。各水平营养液灌溉频率实施时间: R_1 为08:30和14:30, R_2 为08:30、11:30、14:30和17:30。各处理每日每株灌溉量一致,且按照灌溉频率进行平均分配,根据西瓜生长发育和天气变化控制在0.8~1.5 L。按照营养液EC值水平,首部安装了4个储液罐和4条独立的输水主管道,并通过主管水表和支管球阀控制灌溉量和滴灌频率。

西瓜于2021年3月6日育苗,4月10日定植(三叶一心),6月27日收获。移栽前2 d将所有营养液EC值调至约 $0.05\text{ mS}\cdot\text{cm}^{-1}$ 冲洗浸泡椰糠栽培条至流出液与供给液EC值基本一致,选择长势一致且无病虫害的健康苗定植,每条椰糠袋定植3株,株距35 cm,行距80 cm。缓苗5 d后开始试验处理,采用吊蔓栽培和单蔓整枝方式,人工授粉,每株在12~15节位只留1个正常发育果实。

1.3 测试指标与方法

1.3.1 植株形态指标 从定植后的第15天(团棵期)开始,每处理选择5株长势一致的植株挂牌标记,每间隔15 d采集一次植株形态指标,一直到第45天即膨果中期。用卷尺测定株高,游标卡尺测定距椰糠块上表面约5 cm处茎粗,用便携式叶面积仪(LI-3000C,美国)测定茎基部以上第5~7枚叶片的叶面积,取其平均值。

1.3.2 根部形态指标 分别在西瓜团棵期(定植后15 d)和开花坐果期(定植后30 d),每处理选择3株长势一致的植株采集其根系,用根系扫描仪(WinRHIZO,加拿大)测定其根系形态指标,包括总根长、表面积、根体积和直径。

1.3.3 植株生物量指标 分别在西瓜团棵期和开花坐果期,结合根系形态指标的测定取样,根、茎分离后,分别测定根系和茎叶鲜质量,计算根冠比。

1.3.4 单果质量和品质指标 西瓜成熟期(定植后65 d),每处理选择10个具有代表性的果实先测定单瓜质量,再将果实沿纵径切开后利用手持测糖仪(精度0.1%,日本爱拓PAL-1型)测定可溶性固形物含量,然后沿果实纵径方向取等量果肉样品于组织捣碎机中研磨成浆,采用蒽酮比色法^[17]测定可溶性糖含量,滴定法^[17]测定有机酸含量,并计算糖酸比。

1.4 数据处理

采用Excel 2010和SPSS 19.0统计软件进行试验数据分析。

2 结果与分析

2.1 营养液EC值与灌溉频率对植株形态的影响

株高、径粗和叶面积能反映植物的健康情况,是生殖生长的基础。由表2可知,西瓜定植后的15 d即团棵期,营养液EC值对西瓜株高、径粗、叶面积的影响均达到极显著水平($p<0.01$),其中株高和径粗均以 E_1 和 E_2 水平的最高,叶面积则以 E_2 和 E_3 水平的最高;滴灌频率对径粗和叶面积影响达到极显著水平, R_1 水平显著高于 R_2 水平;两因素的交互作用对株高和径粗影响显著,其中株高以 E_1R_2 和 E_2R_2 处理的最高,径粗以 E_1R_2 和 E_2R_1 处理的最高,叶面积则以 E_2R_1 、 E_3R_1 处理的最高。西瓜定植后的30 d即坐果期,营养液EC值对株高、径粗、叶面积的影响均达到极显著水平($p<0.01$),其中株高以 E_2 水平最高,径粗和叶面积均以 E_1 和 E_2 水平最高,滴灌频率对株高影响显著,以 R_2 水平显著高于 R_1 水平,而对径粗和叶面积影响不显著,两因素的交互作用仅对株高影响显著,其中株高以 E_2R_2 和 E_3R_2 处理的最高,径粗以 E_1R_2 和 E_2R_1 处理的最高,叶面积则以 E_1R_2 、 E_2R_2 处理的最高。西瓜定植后的45 d即膨果中期,营养液EC值对径粗和叶面积的影响均达到极显著水平($p<0.01$),其中株高和叶面积以 E_2 水平较高,而径粗以 E_3 水平最高;滴灌频率仅对径粗影响显著, R_2 水平显著高于 R_1 水平;两因素的交互作用仅对株高影响显著,其中株高以 E_1R_2 和 E_2R_1 处理的最高,径粗以 E_3R_2 处理的最高,叶面积则以 E_2R_1 处理的最高。

2.2 营养液EC值与灌溉频率对根系形态的影响

西瓜根系的发育主要在营养生长期,从表3可以看出,西瓜团棵期,营养液EC值和滴灌频率对根系形态指标的影响均达到极显著水平($p<0.01$),根系形态指标均随着EC值的升高呈先增加后降低的变化趋势,整体在 E_2 水平时最高,且 R_1 水平显著高于 R_2 水平,两因素的交互作用对总根长和表面积影响达到极显著水平,其中总根长以 E_2R_1 处理最高,而表面积、根体积和根直径均以 E_2R_1 和 E_3R_1 处理最高。西瓜开花坐果期,营养液EC值和滴灌频率对根系形态指标的影响也达到显著水平,与团棵期相似,根系形态指标均随着EC值的升高呈先增加后降低

表2 营养液EC值和滴灌频率对不同时期植株形态的影响

Table 2 Effect of different EC and irrigation rates of nutrient solution on plant morphology during different periods

处理 Treatment	株高 Plant height/cm			径粗 Stem diameter/mm			叶面积 Leaf area/cm ²		
	团棵期 Rosette stage 15 d	坐果期 Fruit setting stage 30 d	膨果中期 Fruit swell- ing 45 d	团棵期 Rosette stage 15 d	坐果期 Fruit setting stage 30 d	膨果中期 Fruit swell- ing 45 d	团棵期 Rosette stage 15 d	坐果期 Fruit setting stage 30 d	膨果中期 Fruit swell- ing 45 d
EC值 EC values									
E ₁	3.05 a	22.33 c	145.54 a	7.22 a	7.47 a	10.25 c	68.25 b	134.45 a	159.98 b
E ₂	3.06 a	25.64 a	150.18 a	7.21 a	7.46 a	10.77 b	73.70 a	135.70 a	178.55 a
E ₃	2.65 b	25.13 ab	146.88 a	6.99 b	7.28 b	11.00 a	74.13 a	124.44 b	158.67 b
E ₄	2.73 b	23.67 bc	145.52 a	6.83 b	7.19 b	10.64 b	70.45 b	117.37 b	132.90 c
显著性 Significance	**	**	ns	**	**	**	**	**	**
滴灌频率 Irrigation rates									
R ₁	2.80 a	23.40 b	148.29 a	7.20 a	7.36 a	10.39 b	74.35 a	125.83 a	160.38 a
R ₂	2.94 a	24.98 a	145.78 a	6.93 b	7.33 a	10.94 a	68.91 b	130.14 a	154.66 a
显著性 Significance	ns	*	ns	**	ns	**	**	ns	ns
EC值×滴灌频率 EC values × Irrigation rates									
E ₁ R ₁	2.91 ab	20.33 c	136.46 d	7.17 bc	7.36 ab	9.86 f	70.93 c	132.17 abc	162.16 c
E ₁ R ₂	3.19 a	24.33 ab	154.62 a	7.28 ab	7.58 a	10.65 cde	65.56 e	136.72 a	157.78 c
E ₂ R ₁	2.94 ab	24.53 ab	154.86 a	7.53 a	7.56 a	10.47 de	75.03 ab	134.19 ab	179.79 a
E ₂ R ₂	3.17 a	26.73 a	145.51 bc	6.90 cde	7.34 ab	11.06 ab	72.38 bc	137.21 a	177.31 ab
E ₃ R ₁	2.60 bc	23.87 ab	152.34 ab	7.13 bcd	7.32 ab	10.81 bcd	77.57 a	121.81 bcd	165.27 bc
E ₃ R ₂	2.70 bc	26.40 a	141.42 cd	6.86 de	7.23 b	11.19 a	70.69 cd	127.06 abcd	152.07 c
E ₄ R ₁	2.53 c	24.87 ab	149.49 ab	6.96 cde	7.20 b	10.40 e	73.88 abc	115.16 d	134.29 d
E ₄ R ₂	2.93 ab	22.47 bc	141.56 cd	6.69 e	7.17 b	10.87 abc	67.02 de	119.58 cd	131.50 d
显著性 Significance	*	*	*	**	ns	ns	ns	ns	ns

注:同列不同字母表示0.05水平下差异显著($p<0.05$),*和**分别表示在0.05和0.01水平下的差异显著。ns.不显著。下同。

Note: Different letters in the same column indicate significant difference at 0.05 level ($p<0.05$), * and ** indicate significant difference at 0.05 and 0.01 levels respectively. ns. Not significant. The same below.

的变化趋势,总根长和表面积在E₂水平时最高,根体积和根直径在E₂和E₃水平时最高,R₂水平的总根长、表面积和根体积显著高于R₁水平,而根直径则相反。两因素的交互作用仅对根直径影响达到显著水平,其中总根长、表面积和根体积均以E₂R₂处理最高,而根直径则以E₁R₁处理最高。

2.3 营养液EC值与灌溉频率对西瓜地上、地下部生物量的影响

从表4营养液EC值与灌溉频率对西瓜营养生长期地上、地下部的生物量影响来看,团棵期EC值对西瓜地上、地下部生物量及根冠比的影响均达到极显著水平,其中地上部茎叶生物量以E₂水平最高,地下部根系生物量以E₂和E₃水平最高,根冠比则以E₁处理最高。滴灌频率及两因素的交互作用对根系生物量及根冠比影响极显著,R₁水平显著高于R₂水平,在不同组合处理中,E₂R₁和E₂R₂处理的茎叶生物量最高,E₁R₁、E₂R₁和E₃R₁处理的根系生物量

最高,E₁R₁处理的西瓜根冠比显著高于其他处理。在西瓜开花坐果期,EC值、滴灌频率及两因素交互作用对茎叶、根系生物量的影响均达到显著水平,其中茎叶和根系生物量均以E₂水平和R₂水平最高,E₁R₂、E₂R₁和E₂R₂处理显著高于其他处理。

2.4 营养液EC值与灌溉频率对西瓜单果质量和品质的影响

EC值、滴灌频率及两因素交互作用对西瓜单果质量的影响均达到极显著水平(表5),其中西瓜单果质量随EC值的升高而降低,E₁和E₂水平显著高于E₃和E₄水平,且R₂水平显著高于R₁水平,E₁R₂和E₂R₂处理显著高于其他处理。EC值和滴灌频率对西瓜品质指标的影响均达到极显著水平,其中西瓜果实可溶性固形物含量、可溶性总糖含量及糖酸比均随着EC值的升高而增加,且R₁水平显著高于R₂水平,而果实有机酸含量则表现出相反趋势。从不同处理组合对西瓜品质的影响来看,以E₄R₁处理的果实可

表3 营养液EC值和滴灌频率对不同时期根系形态的影响

Table 3 Effect of different EC and irrigation rates of nutrient solution on root morphology during different periods

处理 Treatment	团棵期 Rosette stage				坐果期 Fruit setting stage			
	总根长 Total root length/cm	根表面积 Root surface area/cm ²	根体积 Root volume/cm ³	根直径 Root diameter/mm	总根长 Total root length/cm	根表面积 Root surface area/cm ²	根体积 Root volume/cm ³	根直径 Root diameter/mm
EC值 EC values								
E ₁	1 166.75 c	341.32 b	8.57 b	0.93 b	1 449.79 b	560.86 b	18.10 b	1.31 b
E ₂	1 242.94 a	366.78 a	9.34 a	1.05 ab	1 604.63 a	609.94 a	20.46 a	1.38 a
E ₃	1 199.89 b	365.68 a	8.70 b	1.15 a	1 408.94 bc	584.37 ab	19.67 a	1.39 a
E ₄	1 169.72 bc	338.33 b	7.21 c	0.88 b	1 376.91 c	561.40 b	17.74 b	1.28 b
显著性 Significance	**	**	**	**	**	*	**	**
滴灌频率 Irrigation rates								
R ₁	1 243.51 a	374.76 a	9.36 a	1.09 a	1 368.84 b	549.22 b	18.29 b	1.37 a
R ₂	1 146.14 b	331.29 b	7.55 b	0.92 b	1 551.29 a	609.07 a	19.70 a	1.31 b
显著性 Significance	**	**	**	**	**	**	**	**
EC值×滴灌频率 EC values × Irrigation rates								
E ₁ R ₁	1 205.81 b	356.76 b	9.68 a	1.01 cd	1 366.25 c	553.11 cde	17.96 cd	1.33 cd
E ₁ R ₂	1 127.68 c	325.87 d	7.47 c	0.85 ef	1 533.32 b	568.61 bcde	18.23 cd	1.30 d
E ₂ R ₁	1 348.24 a	398.55 a	10.13 a	1.14 ab	1 542.71 b	581.55 abcd	19.17 bc	1.42 a
E ₂ R ₂	1 137.65 c	335.01 cd	8.55 b	0.96 de	1 666.54 a	638.33 a	21.74 a	1.34 bcd
E ₃ R ₁	1 203.19 b	395.24 a	9.58 a	1.22 a	1 294.39 cd	544.20 de	18.63 cd	1.40 ab
E ₃ R ₂	1 196.59 b	336.12 cd	7.81 bc	1.08 bc	1 523.48 b	624.54 ab	20.71 ab	1.37 abc
E ₄ R ₁	1 216.78 b	348.49 bc	8.04 bc	0.98 cd	1 271.99 d	518.02 e	17.39 d	1.34 cd
E ₄ R ₂	1 122.65 c	328.17 d	6.38 d	0.77 f	1 481.83 b	604.78 abc	18.09 cd	1.23 e
显著性 Significance	**	**	ns	ns	ns	ns	ns	*

表4 营养液EC值和滴灌频率对不同时期生物量的影响

Table 4 Effect of different EC and irrigation rates of nutrient solution on biomass during different periods (g·plant⁻¹)

处理 Treatment	团棵期 Rosette stage			坐果期 Fruit setting stage		
	茎叶 Stems and leaves	根 Root	根冠比 Root shootratio	茎叶 Stems and leaves	根 Root	根冠比 Root shootratio
EC值 EC values						
E ₁	21.13 c	3.47 c	0.165 a	188.10 b	16.81 b	0.089 a
E ₂	27.61 a	3.78 ab	0.137 b	224.34 a	19.52 a	0.087 a
E ₃	26.28 ab	3.97 a	0.148 b	183.73 bc	16.30 b	0.089 a
E ₄	24.03 b	3.57 bc	0.147 b	175.52 c	14.25 c	0.082 a
显著性 Significance	**	**	**	**	**	ns
滴灌频率 Irrigation rates						
R ₁	24.95 a	4.12 a	0.167 a	182.64b	16.14 b	0.088 a
R ₂	24.58 a	3.26 b	0.132 b	203.20 a	17.30 a	0.085 a
显著性 Significance	ns	**	**	**	*	ns
EC值×滴灌频率 EC values × Irrigation rates						
E ₁ R ₁	21.44 c	4.15 ab	0.194 a	165.18 c	15.00 bc	0.089 a
E ₁ R ₂	20.82 c	2.78 d	0.133 cd	211.02 a	18.63 a	0.088 a
E ₂ R ₁	27.23 ab	4.37 a	0.162 b	221.23 a	19.24 a	0.087 a
E ₂ R ₂	27.99 a	3.17 c	0.114 d	227.44 a	19.81 a	0.087 a
E ₃ R ₁	26.43 ab	4.14 ab	0.157 bc	180.67 bc	16.26 b	0.090 a
E ₃ R ₂	26.13 ab	3.79 b	0.146 bc	186.80 b	16.34 b	0.088 a
E ₄ R ₁	24.68 abc	3.83 b	0.155 bc	163.50 c	14.07 c	0.086 a
E ₄ R ₂	23.37 bc	3.31 c	0.142 bc	187.55 b	14.44 bc	0.077 a
显著性 Significance	ns	**	**	**	*	ns

表5 营养液EC值和滴灌频率对西瓜单果质量与品质的影响

Table 5 Effect of different EC and irrigation rates of nutrient solution on fruit weight and quality

处理 Treatment	单果质量 Fruit mass/kg	w(可溶性固形物) Soluble solids content/%	w(可溶性糖) Soluble sugar/%	w(有机酸) Organic acid content/%	糖酸比 Sugar/acid ratio
EC值 EC values					
E1	2.49 a	10.07 b	5.89 b	0.67 a	8.87 c
E2	2.40 a	10.13 b	6.08 b	0.64 ab	9.59 bc
E3	2.20 b	10.14 b	6.19 ab	0.61 bc	10.22 ab
E4	1.96 c	10.39 a	6.47 a	0.58 c	11.19 a
显著性 Significance	**	*	**	**	**
滴灌频率 Irrigation rates					
R1	2.19 b	10.28 a	6.34 a	0.59 b	10.88 a
R2	2.34 a	10.07 b	5.97 b	0.67 a	9.06 b
显著性 Significance	**	**	**	**	**
EC值×滴灌频率 EC values × Irrigation rates					
E1R1	2.34 b	10.09 b	6.12 ab	0.63 bc	9.76bcd
E1R2	2.65 a	10.03 b	5.67 b	0.72 a	7.97 d
E2R1	2.28 bc	10.17 b	6.22 ab	0.59 c	10.63 ab
E2R2	2.52 a	10.10 b	5.94 b	0.70 ab	8.55 cd
E3R1	2.12 cd	10.24 b	6.29 ab	0.58 c	10.93 ab
E3R2	2.29 b	10.00 b	6.08 ab	0.64 bc	9.51 bcd
E4R1	2.02 de	10.62 a	6.73 a	0.55 c	12.18 a
E4R2	1.90 e	10.16 b	6.21 ab	0.61 c	10.20 bc
显著性 Significance	**	ns	ns	ns	ns

溶性固形物、可溶性总糖含量及糖酸比最高。

3 讨 论

无土栽培学中,电导率(electrical conductivity, EC)是营养液管理中最重要的参数之一,EC值的大小反映营养液中盐类化合物的含量高低,也直接决定养分供应量的多少^[18]。本研究结果表明,营养液EC值对西瓜营养生长和果实产量、品质形成的影响不尽相同。在西瓜营养生长阶段,除苗期株高、径粗随营养液EC值的升高表现出降低的趋势外,其他植株、根系生长指标均随着营养液EC值的升高表现出先增加后降低的变化趋势,且整体表现为在EC值 $0.25\text{ mS}\cdot\text{cm}^{-1}$ 时最高。前人在生菜^[14]、蕹菜^[15]、黄瓜^[19]和网纹甜瓜^[20]上的研究也表明,营养液EC值过高或过低均不利于植株的生长发育。其原因可能有以下三方面:首先,根系是最易受到逆境胁迫的器官,根际可溶性盐含量过高会造成离子胁迫和渗透胁迫,阻碍根系吸收运输水分及养分^[21-23],过低则满足不了植物生长需要。在较高的营养液环境下,番茄的根系活力^[24]、西瓜根系形态指标^[25]均会受到显著抑制。其次,高浓度营养液可以改变植株内源激

素的动态平衡,通过影响细胞壁的可塑性和细胞微管排列方向,从而调控细胞生长^[26]。高晓旭等^[27]的研究表明在栽培基质电导率EC值为 $8.08\text{ dS}\cdot\text{cm}^{-1}$ 营养液处理下黄瓜和番茄幼苗下胚轴皮层薄壁细胞较对照分别缩短49%和48%。另外,营养液浓度过高会导致植株光合能力减弱。高博文等^[21]的研究发现随着盐浓度的增加,所有品种的西瓜幼苗净光合速率呈持续降低的趋势。林多等^[20]的研究表明,过高或过低浓度的营养液对网纹甜瓜叶片净光合速率的影响主要是由与叶肉细胞光合活性下降有关的非气孔限制因素造成的。在西瓜果实生长发育阶段,西瓜单果质量随营养液EC值增加表现出降低的趋势,而可溶性固形物含量、总糖含量及糖酸比等品质指标则相反。王中原等^[28]的研究也表明,网纹甜瓜在EC值 $2.0\text{ mS}\cdot\text{cm}^{-1}$ 时平均单果质量最大,但可溶性固形物和总糖含量最低,EC值 $3.0\text{ mS}\cdot\text{cm}^{-1}$ 时,单果质量较小,但果实总糖含量最高。同样的研究结果也表现在番茄上^[29-32]。营养液EC值升高导致单果质量降低的主要原因可能是盐胁迫下,植株生长减缓、碳同化量减少,渗透调节能耗和维持生长能耗增加,生物量分配格局发生改变^[33]。而果实可溶性糖含量增

加的主要原因可能是盐胁迫后,光合运转糖—蔗糖在果实内的快速分解,提高了蔗糖向果实内的运输,从而增加了果实的可溶性糖含量^[34]。果实可溶性糖是植株适应高盐环境的产物之一,其含量的增加有利于保持植株的吸水能力^[35]。

灌溉频率是科学合理灌溉的重要内容之一,灌溉频率能够影响作物地下及地上的生长环境,尤其对作物地下生长环境的影响更为明显,作物在不同的生长发育期,由于根系吸水能力以及在介质中的分布不同,对灌溉频率也有不同的响应。水分敏感指数表明,西瓜苗期和果实成熟期的水分敏感程度较低,开花坐果期和果实膨大期的水分敏感程度较高^[36]。本研究结果表明,西瓜团棵期,2次·d⁻¹的灌溉频率有利于壮苗;伸蔓期至膨果期,4次·d⁻¹的灌溉频率有利于促进植株营养生长和提高单果质量,而2次·d⁻¹的灌溉频率则显著提高了果实品质。这主要是由于西瓜苗期外界气温较低、地上部分生长缓慢,蒸发蒸腾量较少,另外,苗期根系生长迅速,适度亏水能够刺激根系生长,有利于开花坐果期复水后植株的加速生长^[37]。从团棵期至膨果期,外界气温持续上升,地上部茎叶和果实开始旺盛生长,蒸发蒸腾量增加,逐步健全的根系群需吸收大量水分和养分供给地上部生长发育。研究表明,灌水量相同条件下,增加灌水频率,可以增加土壤蓄水、减少渗漏和蒸发^[38],既保证了根际的水分充分供应,又降低了养分浓度,扩大了根接触面,促进了根系对水分和养分的吸收利用^[10]。果实成熟期,由于植株的营养生长和生殖生长都进入末期,植株的需水量较果实膨大期有所降低。研究表明,在果实成熟期采用中低水量有利于获得理想的植株叶片光和色素含量^[37],低频率灌溉有利于改善果实的品质和口感^[39-42]。

合理营养液灌溉管理是无土栽培作物高产优质的基础,不同营养液EC值与灌溉频率的处理通过对基质条EC值、含水量以及含氧量等根际生长环境因素的影响,进而影响植株的生长发育以及果实产量和品质^[10,43]。本研究结果表明,营养液EC值与滴灌频率的交互作用对西瓜地上、地下部生物量的影响均达到显著水平,表明营养液EC值与灌溉频率是相互作用的,EC值通过影响根系活性从而调控作物对水分的吸收运输^[23],而灌溉频率则可以通过调控基质中的含水量和EC值水平,从而调节植株的生长发育^[44]。作物全生育期单一的营养液管理模

式难以同时保证产量最高和品质最佳,如本研究中,E₁R₂组合处理的单果质量最高,而E₄R₁组合处理的果实含糖量及糖酸比最高,这与Magán等^[45]的研究结果一致。因此,为改善品质、提高产量,基质栽培应根据作物不同生育时期生长情况合理调整营养液灌溉方式,进行分段管理,以满足实际生产需求。

4 结 论

兼顾西瓜植株发育和果实品质的营养液分段管理方式为:团棵期营养液以EC值0.25 mS·cm⁻¹,灌溉频率2次·d⁻¹为宜;伸蔓期营养液以EC值0.25 mS·cm⁻¹,灌溉频率4次·d⁻¹为宜;果实膨大期营养液以EC值0.15~0.25 mS·cm⁻¹,灌溉频率4次·d⁻¹为宜;成熟期营养液以EC值0.45 mS·cm⁻¹,灌溉频率2次·d⁻¹为宜。

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