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Interaction of Light Quality and EC of Nutrition Solution on Seedling Quality, Growth, and Physiology of Cucumber Seedlings

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ABSTRACT

Optimizing light and nutrient supply has a key role in seedling quality and yield of cucumber seedlings. The combined effects of light quality {blue (B), white [W; 41% B, 39% intermediate, and 20% red (R)], RB [red (80%) and blue (20%)], and red (R)} and EC value of the nutrient solution (1, 1.7, and 3 ds m-1) were evaluated on the growth and physiological responses of cucumber seedlings. The measurements were aimed at the growth rate, biomass distribution, water status, seedling quality, yield, and concentration of photosynthetic pigments, protein, proline, potassium, and phosphorous. The results showed that the effects of light quality on cucumber seedlings depended on the EC values of the nutrient solution. The RB treatment at EC 1.7 of the irrigation water had the highest value of seedling quality parameters and the maximum amount of osmolytes, elements, and pigments, showing adequate water performance. Moreover, in contrast to the conventional seedling production, yield and biomass production increased by 70% and 92%, respectively, in the transplanting phase. This probably resulted from a more efficient elemental uptake, higher biomass distribution, and low vegetative growth in the seedling production phase. These results can contribute to seedling production of vegetables as an efficient protocol for yield productivity. In sum, our findings showed that determining the ideal light spectrum for seedling growth should be considered together with the EC of the nutrient solution.

Introduction

In vegetable crops, seedling production and plant breeding are often spatially separated due to differences in management, such as spacing or nutrient requirements (Choi, 2020). However, seedling quality is closely related to subsequent plant growth and productivity. In this regard, producing high-quality seedlings is a prerequisite for higher crop yields (Moosavi-Nezhad et al., 2021). During periods of low light availability, seedling quality is generally low. This disadvantage is usually counteracted by the use of supplemental light. In cucumber, seedling spindle formation (long hypocotyl, low dry weight) results in reduced seedling quality due to low natural light intensity in a continuously cloudy environment in autumn, winter, or early spring (Wang et al., 2021). With the recent development of light-emitting diodes (LEDs), the possibility of optimizing seedling growth by adjusting light quality (spectral distribution) has recently gained attention (Moosavi-Nezhad et al., 2021). Seedling quality is also determined by the electrical conductivity of the nutrient solution (EC) (Li and Cheng, 2015). In this way, it remains unclear whether these two factors interact to affect seedling growth in general and specific traits in particular. Therefore, selecting the most appropriate combination of light quality and EC value of the nutrient solution would pave the way

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for higher quality seedlings and ultimately higher crop yields. Several measures have been developed to evaluate seedling quality, including shoot to root dry matter ratio (SSR), robustness quotient, Dickson quality index (DQI), and seedling index (Zhang et al., 2020). Recommendations based on total seedling biomass are less robust than those that consider biomass distribution in addition. Throughout the production and distribution chain (e.g. nurseries and orchards), the intensity of green color is another quality criterion, with pale green being considered a sign of low-quality seedlings grown under suboptimal conditions (Moosavi-Nezhad et al., 2021).

The objective of this study was to detect the mechanisms of action and relationships between important morphological and physio-biochemical indicators involved in the parameters of seedling quality, as they were the main factors that affected seedling production. Another objective was to evaluate the reciprocal effects of light quality and nutrient solution (EC) on seedling growth and yield. These were determined by several common indices, i.e. biomass distribution, leaf chlorophyll, protein content, secondary respiratory substrates and proline content (Chen et al., 2021). In addition, the effects of light and nutrient treatments were evaluated at the seedling stage. Cucumber was used as a model species because it is not only one of the most important vegetable crops in the world but is also highly sensitive to different light conditions (Hernández and Kubota, 2016).

Material and Methods

Plant materials and growth conditions

A commercial high-yielding cucumber cultivar (Seminis 189 Sina F1) was used in this research. Graded seeds were soaked in distilled water at room temperature (25 °C), 4 h prior to sowing. Following sieving (6 mm), 0.25 L pots (8 cm diameter, 8 cm height) were filled with a mixture of sterilized cocopeat and perlite (3:1, v/v; Meegaa substrates BV, Rotterdam, The Netherlands). The seeds were sown directly in the pots. One seed was planted per pot. The pots were placed in a glasshouse (Jiroft, 28o40′41′′ N). Day/night air temperatures were maintained at 25/20 °C, and relative humidity was adjusted to 70%. A density of 28 plants per m^2 was employed. Twelve treatments (four light regimes × three nutrient EC levels) were applied. The pots were placed on three ebb-and-flow tables in the greenhouse. Each table consisted of four separated and isolated spaces under different light regimes, including supplemental light with four LED modules (Parcham Company, Tehran, Iran; Input voltage: 220–240 V; 36 W; 0.09 A). To keep out unwanted light, opaque black-and-white plastic films were placed around each treatment group. To minimize the border effect, the plants that were adjacent to these films were not sampled. The LEDs emitted blue (B, peak at 460 nm), white [W; 41% B (400–500 nm), 39% intermediate (500–600 nm), and 20% red (R, 600–700 nm)], red and blue [RB; R (80%) and B (20%)], as well as red (R, peak at 660 nm) lights (Fig. 1). In all twelve light modules, photon flux density was set at 100 μmol m^{-2} s^{-1} for 16 h d^{-1} (09:00 to 01:00 h) at the seedling level. At the onset of the experiment, three EC values of the nutrient solution were realized, including half (low EC= 1 ds m^{-1}), full (medium EC= 1.7 ds m^{-1}) and double (highest EC= 3 ds m^{-1}) strength of Hoagland solution. Once a week, the plants were watered with distilled water to allow leaching.

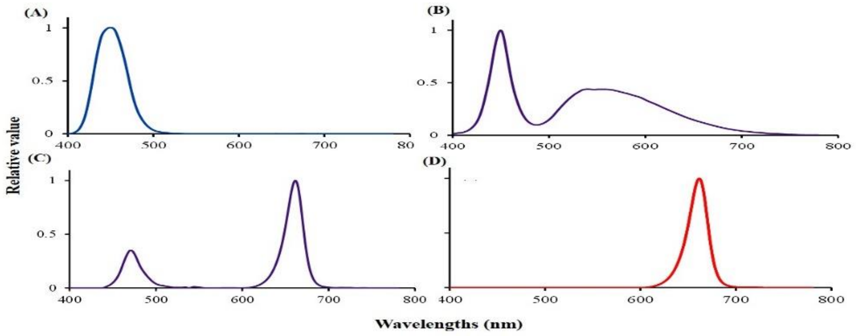

Fig. 1. Spectra of blue (400–500 nm; A), white [41% blue (400–500 nm), 39% intermediate (500–600 nm), and 20% red (600–700 nm); B], red and blue [RB; red (80%) and blue (20%); C], as well as red (600–700 nm; D) LED lights).

The experiment began on 1 October 2022, when natural light was typically weak in the autumn. The plants were allowed to grow for 30 days. All measurements were performed at the end of the growth period. Plant- and leaf-level measurements were conducted. For leaf-level measurements, the sampled leaves that had grown under natural light were fully expanded. In all cases, the time between sampling and the start of the evaluation did not exceed 15 minutes. When this was not possible, the samples were placed in vials, flash-frozen in liquid nitrogen and transferred to a freezer (-80 °C) for storage. Replicates were sampled from separate plants. In all cases, twelve treatments were assessed.

Seedling growth, morphology, and biomass partitioning

Thirty days following the onset of the experiment, seedling growth, morphology, and biomass allocation were measured. Evaluations included stem length (from the root-to-shoot junction to the apical end), internode length, hypocotyl length, petiole (stalk) length (from the base to the leaf joint), stem diameter (1 cm above the root-to-shoot junction), number of internodes, leaf number, cotyledon area (one-sided surface area) and leaf area index. For leaf area assessment, the leaves were scanned (HP Scanjet G4010, Irvine, CA, USA) and then processed via Digimizer software (version 4.1.1.0, MedCalc Soft-ware, Ostend, Belgium). Following the removal of the substrate from the roots by gentle washing, root length and volume were determined. The latter was measured by employing the volume-displacement technique (Asayesh et al., 2021). Plant roots were suspended in a cylinder filled with water. The root volume was then determined by measuring the volume of water carried by the plant roots. Cotyledon, leaf, hypocotyl, stem, and root (fresh and dry) volumes were also recorded (± 0.01 g; MXX-412; Denver Instruments, Bohemia, NY, USA). For measuring dry weight, the samples were placed in a forced-air drying oven for 72 h at 80 °C. By measuring dry mass, specific leaf area (SLA; leaf area/leaf mass) was calculated. All measurements were conducted on fifteen plants per treatment.

Seedling quality indices

Several seedling quality indicators were computed, including compactness (shoot dry weight/ hypocotyl length), SSR (shoot dry matter/ root dry matter), sturdiness quotient (stem length/ collar diameter), DQI [plant dry matter/ (SRR + sturdiness quotient)], and seedling index [(stem diameter/ stem length) × plant dry weight] (Silva et al., 2016; Zhang et al. 2020).

Leaf hydration status and leaf chlorophyll and carotenoid contents

Leaf water status was assessed by measuring relative water content (RWC – also referred to as relative turgidity). The leaves were collected 3 h following the onset of the photoperiod (Seif et al., 2021). Following excision, fresh weight was gravimetrically obtained (±0.0001 g; Mettler AE 200, Giessen, Germany). Immediately thereafter, the samples were allowed to float on distilled water inside a Petri dish, covered with a lid. After 24 h of incubation, the weight was recorded and regarded as the turgid (saturated) weight. Then, the dry weight (48 h at 80 °C) was determined. The RWC was calculated according to a relevant protocol (Taheri-Garavand et al., 2021). Leaf chlorophyll content is an important seedling quality criterion (Askari et al., 2022). Carotenoids are important non-enzymatic antioxidants (Yang et al., 2021). The leaf chlorophyll and carotenoid contents were assessed. Samples were processed immediately after collection. Following fine chopping, portions weighing 0.1 g were homogenized with the addition of 10 mL of 100% acetone. The extract was then centrifuged (14,000 g for 20 min) and the supernatant was collected. Since chlorophyll is sensitive to light, the extraction took place in a dark room (Maleki Asayesh et al., 2017). The obtained extract was subjected to a UV–visible spectrophotometer (Perkin-Elmer Lambda 25, USA) and the absorption values were read. Based on a method used by Lichtenthaler and Wellburn, total chlorophyll and carotenoid contents were calculated (Lichtenthaler and Wellburn, 1983).

Leaf soluble protein content and leaf proline content

Leaf soluble protein content was determined according to a relevant method (Chen et al., 2021). Leaf samples (0.1 g) were ground and extracted with distilled water and subsequently filtered. The filtrate (0.1 mL) was collected and mixed with 1 mL Coomassie Brilliant Blue G-250 solution for 2 minutes. The absorbance of the extract was measured at 595 nm with a UV–Vis spectrophotometer. Proline was actively involved in cell osmotic regulation by decreasing cell water potential, thereby protecting enzyme activity and macromolecule structures (Hassanvand et al., 2019). In this regard, the treatment effect on leaf proline content was assessed. Freshly cut leaf discs (0.5 g) were homogenized and added to 10 mL aqueous sulfosalicylic acid 3% (w/v). The extract was filtered through Whatman No. 2 filter paper and 2 mL of the filtrate was mixed with 2 mL of acid-ninhydrin and 2 mL of glacial acetic acid. The resultant solution was heated (100 °C for 1 h). The reaction mixture was extracted with 4 mL toluene and the chromophore containing toluene was aspirated from the liquid phase. After equilibration at 25 °C, the absorbance was measured at 520 nm with a UV–Visible spectrophotometer. The proline concentration was determined using a calibration curve and expressed as µmol g^{-1} fresh weight.

Leaf and root mineral analysis

Samples were washed with distilled water and then dried. They were ground into fine powder and assessed using a 30-mesh screen. A fine powder portion of 1 g was dry-ashed in a muffle furnace (515 °C for 6 h). Then, the ash was dissolved in 5 mL of 6 N HCl and diluted with double-distilled water (50 ml) (Chatzistathis et al., 2021). Phosphorous was measured via a colorimeter according to the vanadomolybdate method. Potassium was measured using a flame photometer. Mineral content was expressed per gram of dry weight. Three replicates were evaluated per treatment. For each replicate, four samples were collected using separate seedlings and were pooled. The assay was performed twice.

Yield

When the seedlings of each treatment group had fully grown, they were grown under environmentally controlled circumstances (40/50% RH at 27/20 ºC (day/night)) and compared to seedlings that had been irrigated with full-strength Hoagland solution and grown under natural light (Photosynthetic Active Radiation (PAR)= 750 s^{-1} m^{-2}). After 60 days, fruits were harvested for yield assessment. Finally, the shoots and roots of the plants were placed in an oven (70 ºC) for 48 h and weighed to determine the dry weight or biomass.

Statistical analysis

Data analysis was performed using the SAS software (version 9.4; SAS Institute Inc., Cary, NC, USA). This experiment was conducted in a factorial arrangement according to a completely randomized design (CRD) with two factors (i.e. four light regimes × three nutrient EC levels) and three replicates. The data were initially evaluated for a normality test of the residuals (Shapiro–Wilk test), a homogeneity test of variances (Levene's test) and a test of statistical relationships (Pearson's correlation coefficient). These were measured among mean values and variances of the treatment combinations per ANOVA. Subsequently, the analysis of variance was performed and then the mean values were compared using the Tukey's test ($P \leq 0.05$).

Results

Seedling growth, morphology, and biomass partitioning

The combined effects of light regime and EC value of the nutrient solution were recorded per the various aspects of seedling growth and morphology. The longest stem was found under R light in the presence of 3 ds m^{-1} EC of nutrient solution (Fig. 2; Table 1). These differences in stem length resulted from light quality and became more evident with an increase in EC value (Fig. 2; Table 1). Stem length was positively associated with the EC value (Fig. 2; Table 1). A higher level of EC-induced increase in stem length was driven by greater lengths and numbers of the nodes (Table 1). Namely, longer stems had more nodes and each node was longer than control conditions (Table 1).

The longest hypocotyl and petiole lengths occurred in response to blue light with 3 ds m^{-1} EC of the nutrient solution. At the same EC, small differences in hypocotyl length were generally noted among light quality treatments (Table 1). The hypocotyl length was positively associated with the EC value of the nutrient solution (Table 1). Petiole length varied between 2.56 and 7.12 cm among the different treatment groups (Table 1). The effect of light quality on petiole length varied depending on the EC level (Table 1). The petiole length was positively associated with the EC value of the nutrient solution (Table 1). Within each EC level (1, 1.7 and 3 ds m^{-l}), the largest leaf area and leaf count were noted under R light (Table 1 and Table 2). In response to 1 and 1.7 ds m^{-l}, the leaf area became smallest under W light (Table 2). The EC value of the nutrient solution strongly stimulated seedling leaf area (Table 2). The highest cotyledon area, stem diameter and root volume were achieved in response to the W light and 3 ds m^{-1} EC value (Table 2).

Fig. 2. Representative images of cucumber (cv. Seminis 189 Sina F1) seedlings cultivated under different light regimes and EC values of the nutrient solution for 30 days. The light treatment (from left to right) included red (R, 600–700 nm), blue (B, peak at 460 nm), white [W; 41% B (400–500 nm), 39% intermediate (500–600 nm), and 20% red (R, 600–700 nm)], as well as red and blue [RB; red (80%) and blue (20%)] (Fig. 1). The EC values were 1, 1.7 and 3 ds m^{-1} (corresponding to half, full and double strength of the Hoagland solution). The scale bar refers to a length of 40 mm.

Table 1. Effect of light regime and nutrient solution electrical conductivity (EC) on stem length, internode length, hypocotyl length, petiole length, and number of leaves in cucumber seedlings (cv. Seminis 189 Sina F1) when allowed to grow for 30 days. Mean values with at least one identical letter are not significantly different from each other.

Light	EC (ds m^{-1})	Stem length (cm)	Internode length (cm)	Hypocotyl length (cm)	Petiole length (cm)	Leaf number
Blue	**1**	15.9 ^{fg}	1.66 ^{fg}	4.84 ^{de}	3.37 ^{fg}	3.7 ^{d}
	1.7	31.1 ^{d}	3.41 ^{c}	7.04 ^{c}	6.42 ^{ab}	5.0 ^{c}
	3	49.8 ^{b}	5.23 ^{a}	8.87 ^{a}	7.12 ^{a}	6.0 ^{b}
White	**1**	12.6 ^{g}	1.04 ^{h}	4.26 ^{e}	2.56 ^{g}	4.0 ^{d}
	1.7	22.8 ^{e}	2.13 ^{e}	6.09 ^{cd}	4.59 ^{de}	5.0 ^{c}
	3	39.8 ^{c}	4.26 ^{b}	7.11 ^{bc}	6.03 ^{c}	6.0 ^{b}
Red+Blue	**1**	14.0 ^{fg}	1.25 ^{gh}	4.5 ^{de}	3.10 ^{fg}	4.0 ^{d}
	1.7	20.7 ^{e}	4.13 ^{b}	5.38 ^{de}	3.90 ^{ef}	5.0 ^{c}
	3	31.6 ^{d}	2.97 ^{d}	7.04 ^{c}	5.34 ^{cd}	5.8 ^{b}
Red	**1**	16.6 ^{f}	1.73 ^{ef}	4.95 ^{de}	3.89 ^{ef}	4.0 ^{d}
	1.7	28.7 ^{d}	2.95 ^{d}	7.00 ^{c}	5.44 ^{cd}	4.8 ^{c}
	3	54.0 ^{a}	5.14 ^{a}	8.65 ^{ab}	6.74 ^{ab}	7.1 ^{a}

Table 2. Effect of light regime and EC of the nutrient solution on leaf area, cotyledon area, stem diameter (1 cm above the root-to-shoot junction), specific leaf area (SLA) and leaf relative water content (RWC), root length and root volume in cucumber seedlings (cv. Seminis 189 Sina F1) when allowed to grow for 30 days. Mean values with at least one identical letter are not significantly different from each other.

Light	EC (ds m^{-1})	Leaf area (cm^2 $plant^{-1}$)	Cotyledon area (cm^2 $plant^{-1}$)	Stem diameter (mm)	SLA (cm^2 g^{-1})	RWC (%)	Root length (cm)	Root volume (cm^3)
Blue	**1**	82.1 ^{f}	7.5 ^{e}	3.7 ^{e}	187.3 ^{bc}	90.2 ^{de}	23.2 ^{ab}	6.4 ^{d}
	1.7	184.4 ^{e}	10.1 ^{abcde}	4.6 ^{abc}	196.6 ^{abc}	94 ^{abc}	22.7 ^{ab}	15.2 ^{a}
	3	330.1 ^{b}	10.7 ^{abcde}	4.6 ^{abc}	203.4 ^{abc}	82.2 ^{g}	17.3 ^{b}	14.4 ^{ab}
White	**1**	70.4 ^{f}	7.7 ^{de}	4.4 ^{cd}	164.3 ^{c}	96 ^{a}	25.2 ^{ab}	7.3 ^{d}
	1.7	176.3 ^{e}	10.1 ^{abcde}	4.2 ^{d}	180.9 ^{bc}	93 ^{bc}	25.6 ^{ab}	7.2 ^{d}
	3	320.4 ^{bc}	13.2 ^{a}	4.9 ^{a}	212.6 ^{abc}	85.9 ^{f}	15.3 ^{b}	14.5 ^{a}
Red+Blue	**1**	78.3 ^{f}	8.0 ^{de}	3.9 ^{e}	182.3 ^{bc}	90.1 ^{de}	27.7 ^{ab}	5.4 ^{d}
	1.7	176.6 ^{e}	11.4 ^{abc}	4.5 ^{bcd}	171.3 ^{bc}	95.3 ^{ab}	21.4 ^{b}	13.2 ^{abc}
	3	299.8 ^{c}	9.5 ^{bcde}	4.7 ^{abc}	199.6 ^{abc}	95.6 ^{ab}	19.0 ^{b}	9.7 ^{bcd}
Red	**1**	97.1 ^{f}	8.3 ^{cde}	3.8 ^{e}	207.1 ^{abc}	91.3 ^{cd}	27.9 ^{ab}	5.6 ^{d}
	1.7	222.5 ^{d}	12.6 ^{ab}	4.4 ^{cd}	214.0 ^{ab}	88.2 ^{ef}	34.9 ^{a}	9.5 ^{cd}
	3	416 ^{a}	11.3 ^{abcd}	4.8 ^{ab}	237.4 ^{a}	78.9 ^{h}	19.9 ^{b}	13.1 ^{abc}

Light quality and EC level affected leaf morphology, as indicated by SLA, a measure of thickness (Table 2). The effect of EC on SLA strongly depended on light quality (Table 2). For instance, a higher EC value led to thinner leaves in W light-exposed plants, and thicker leaves in R light-exposed ones (Table 2; Fig. 3). Leaf RWC ranged between 78.9% and 95.6% among treatments and the highest leaf RWC was noted at 1 ds m^{-1} under W light (Table 2). At 1.7 ds m^{-1} in the presence of R light, the root length was greater, compared to higher EC levels (Table 2). At 3 ds m^{-1}, the root volume was larger compared to 1 ds m^{-1} (Table 2).

At 1 ds m^{-1}, light quality had limited effects on stem, hypocotyl, leaf, and seedling DW (Table 3). At 1.7 and 3 ds m^{-1}, the effect of light assimilation in these traits strongly depended on light quality (Table 3). For instance, the largest root DW was recorded under RB and B light at 1.7 ds m^{-1}, whereas for seedling DW, the highest stem DW and leaf DW occurred under R light and 3 ds m^{-1}. Stem, hypocotyl, leaf and plant DW increased in response to higher EC levels (Table 3). Root DW was enhanced when the EC was increased from 1 to 1.7 ds m^{-1} (Table 3). The highest cotyledon DW was recorded at the lowest EC; 1 ds m-1 in W and RB light, whereas the highest hypocotyl DW was measured under the B light and 3 ds m-1 (Table 3). Plant mass was mostly allocated to the leaves, generally followed by the roots (Fig. 4). Supplementary light and EC strongly affected plant mass distribution (Fig. 4). The effect of EC on plant mass distribution depended on light quality (Fig. 4). The highest mass distribution (45%) was allocated to the roots in response to the B and RB light at 1.7 ds m^{-1}. However, the highest mass distribution occurred in the shoots (85%) in response to the RB at 3 ds m^{-1}, as well as the W and R at 1.7 ds m^{-1} (Fig. 4).

Several seedling quality indicators were considered. In the case of four quality indicators (i.e. seedling index, Dickson quality index (DQI), sturdiness quotient (SQ), and compactness), the lowest EC (1 ds m^{-1}) was always associated with the lowest value (Fig. 5A-D). Regarding three of the indicators (i.e. seedling index, DQI, and compactness), the optimum EC (either 1.7 or 3 ds m^{-1}) depended on light quality. Accordingly, the RB light and 1.7 ds m^{-1} caused the best results in this regard (Fig. 5A, B, D). The positive effect of increasing the EC level on sturdiness quotient depended on light quality. The B and R light at 3 ds m-1 caused the highest SQ (Fig. 5C). Minor differences were noted in dry matter (DM%) among the treatments, but the RB light at 1.7 ds m^{-1} produced higher DM% compared to the other treatments (Fig. 5E). With R light at 1 ds m^{-1}, as well as RB and R light at 3 ds m^{-1}, the highest SRR was recorded (Fig. 5F).

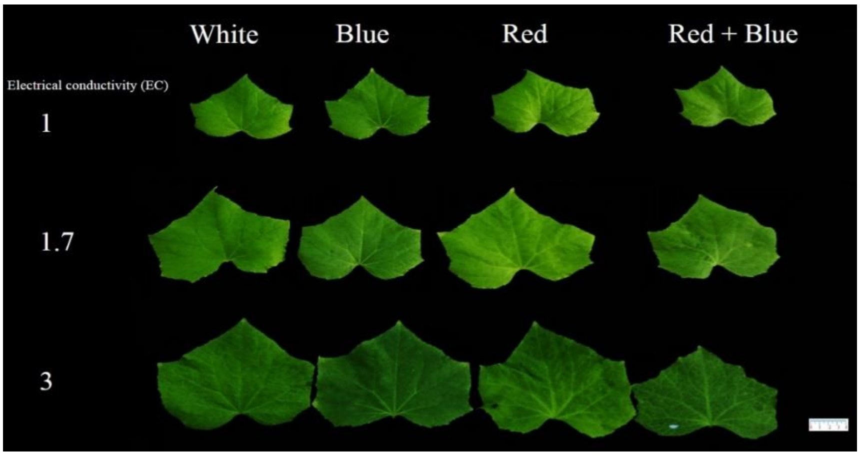

Fig. 3. Representative leaf images of cucumber seedlings (cv. Seminis 189 Sina F1) cultivated under different light regimes and EC of nutrient solution for 30 days. The scale bar refers to a length of 40 mm.

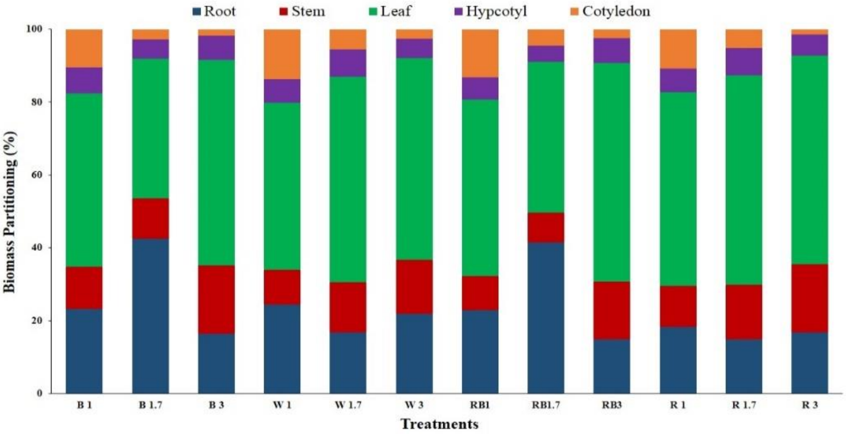

Fig. 4. Effect of light regime and nutrient solution electrical conductivity (EC; 1, 1.7 and 3 ds m^{-1}) on dry mass partitioning to root, stem, leaf, hypocotyl and cotyledon in cucumber seedlings (cv. Seminis 189 Sina F1) when allowed to grow for 30 days.

Table 3. Effect of light regime and nutrient solution electrical conductivity (EC) on root, hypocotyl, cotyledon, stem, leaf and plant (total) dry weight (DW) in cucumber seedlings (cv. Seminis 189 Sina F1) when allowed to grow for 30 days. Mean values with at least one identical letter are not significantly different from each other.

Light	EC (ds m^{-1})	DW root (g)	DW hypocotyl (g)	DW cotyledon (g)	DW stem (g)	DW leaf (g)	DW seedling (g)
Blue	**1**	0.23 ^{cd}	0.07 ^{e}	0.105 ^{ab}	0.11 ^{g}	0.48 ^{f}	1.01 ^{f}
	1.7	1.14 ^{a}	0.14 ^{cd}	0.077 ^{bc}	0.30 ^{e}	1.04 ^{e}	2.69 ^{cd}
	3	0.53 ^{b}	0.21 ^{a}	0.053 ^{c}	0.60 ^{b}	1.81 ^{b}	3.22 ^{b}
White	**1**	0.24 ^{cd}	0.06 ^{e}	0.136 ^{a}	0.09 ^{g}	0.45 ^{f}	1.00 ^{f}
	1.7	0.31 ^{cd}	0.14 ^{cd}	0.105 ^{ab}	0.26 ^{ef}	1.05 ^{e}	1.88 ^{e}
	3	0.68 ^{b}	0.17 ^{abc}	0.082 ^{bc}	0.49 ^{c}	1.84 ^{b}	3.33 ^{ab}
Red+Blue	**1**	0.24 ^{cd}	0.06 ^{e}	0.138 ^{a}	0.09 ^{g}	0.51 ^{f}	1.05 ^{f}
	1.7	1.21 ^{a}	0.12 ^{d}	0.131 ^{a}	0.23 ^{f}	1.19 ^{d}	2.90 ^{c}
	3	0.36 ^{c}	0.16 ^{bcd}	0.061 ^{bc}	0.36 ^{d}	1.44 ^{c}	2.45 ^{d}
Red	**1**	0.18 ^{d}	0.06 ^{e}	0.106 ^{ab}	0.11 ^{e}	0.52 ^{f}	0.99 ^{f}
	1.7	0.29 ^{cd}	0.15 ^{cd}	0.102 ^{ab}	0.3 ^{e}	1.14 ^{de}	1.99 ^{e}
	3	0.61 ^{b}	0.2 ^{ab}	0.051 ^{c}	0.66 ^{a}	2.04 ^{a}	3.58 ^{a}

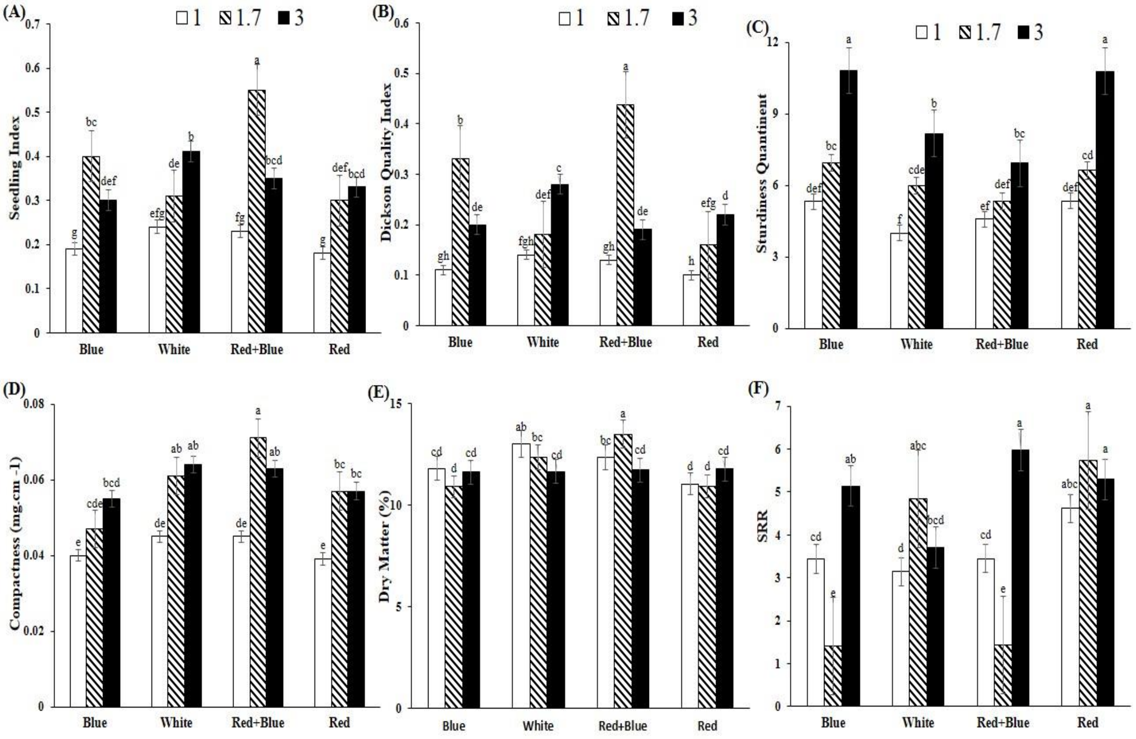

Fig. 5. Effect of light regime and EC of the nutrient solution (1, 1.7 and 3 ds m^{-1}) on seedling index (A), Dickson quality index (B), sturdiness quotient (C), compactness (D), dry matter content (E), and shoot to root dry matter ratio (SRR; F) in cucumber seedlings (cv. Seminis 189 Sina F1) when allowed to grow for 30 days. Mean values with at least one identical letter are not significantly different from each other.

Leaf chlorophyll and carotenoid contents

Seedlings cultivated under the RB light at the moderate EC level (1.7 ds m^{-1}) caused an increase in chlorophyll content in the seedlings (Fig. 5A). The degree of this effect depended on the light quality (Fig. 6A). Similar results were noted from this treatment regarding leaf carotenoid content (Fig. 6B).

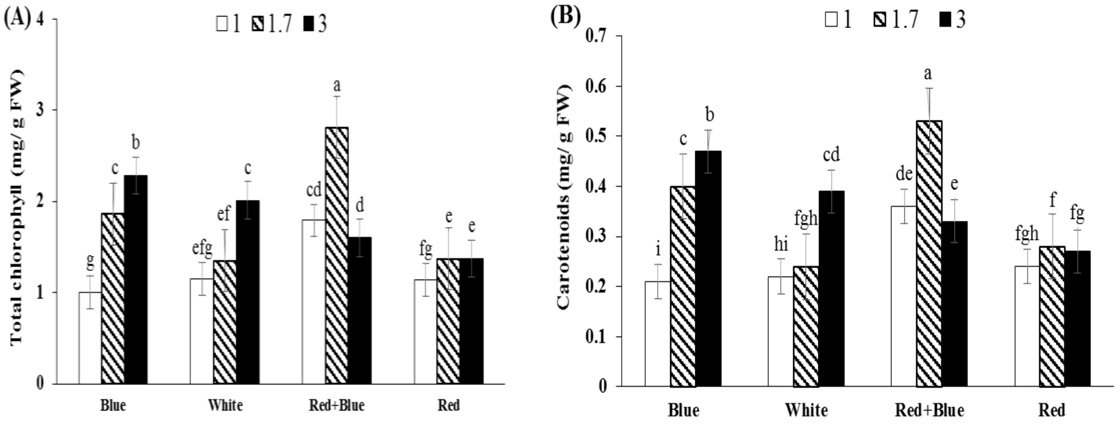

Fig. 6. Effect of light regime and EC of the nutrient solution (1, 1.7 and 3 ds m^{-1}) on leaf chlorophyll (A), and carotenoid (B) contents in cucumber seedlings (cv. Seminis 189 Sina F1) when allowed to grow for 30 days. Mean values with at least one identical letter are not significantly different from each other.

Leaf protein and proline content

Under the RB light, the moderate EC (1.7 ds m⁻¹) caused the highest leaf protein and proline content (Fig. 7). Under the R light, the lowest EC (1 ds m⁻¹) caused higher leaf protein content compared to the highest EC (3 ds m⁻¹) (Fig. 7A).

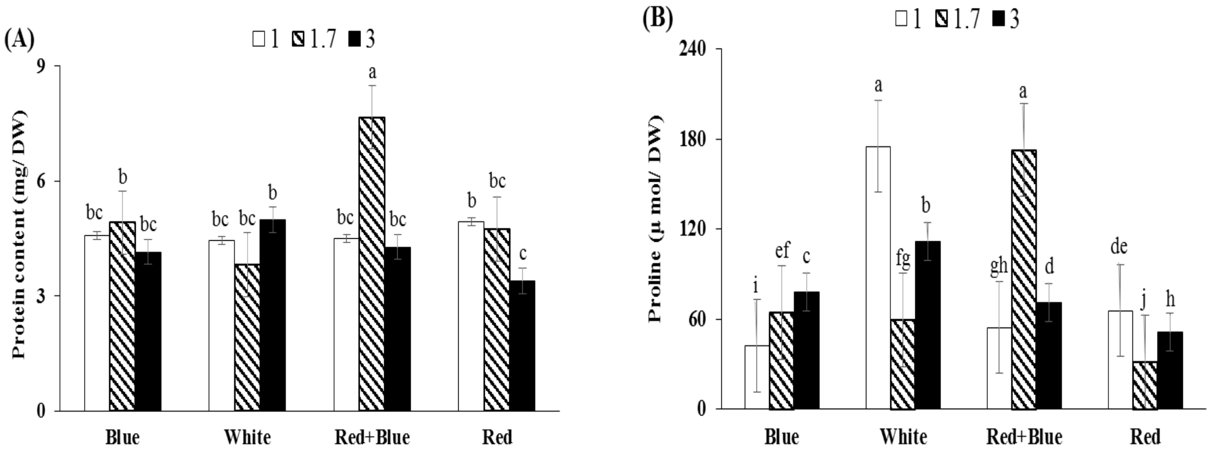

Fig. 7. Effect of light regime and EC of the nutrient solution (1, 1.7 and 3 ds m^{-1}) on leaf protein (A), and proline (B) contents in cucumber seedlings (cv. Seminis 189 Sina F1) when allowed to grow for 30 days. Mean values with at least one identical letter are not significantly different from each other.

Leaf and root mineral analysis

In all light regimes, the highest EC level (3 ds m⁻¹) had a negative effect on leaf and root K and P. The effect of the other two EC levels depended on the light quality significantly (Fig. 8). Seedlings organs (leaf and root) under the RB light with full-strength Hoagland's solution showed the maximum amounts of K and P (Fig. 8).

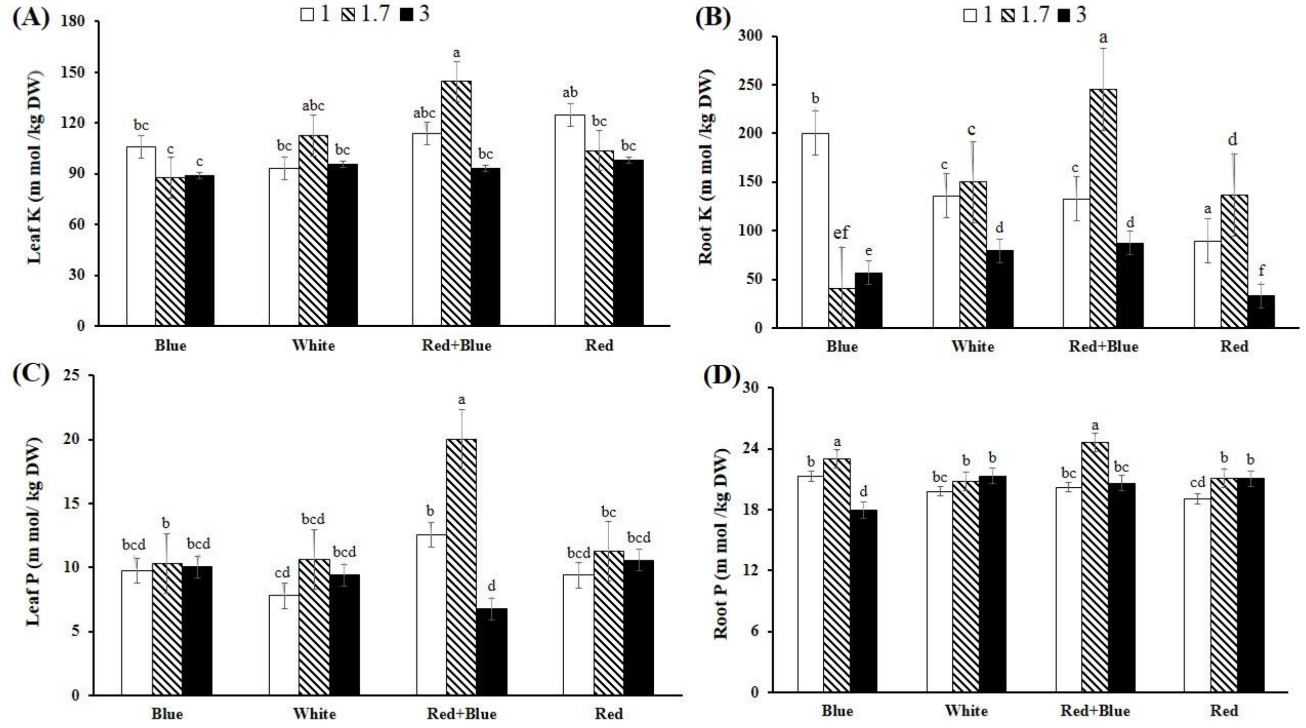

Fig. 8. Effect of light regime and EC of the nutrient solution (1, 1.7 and 3 ds m^{-1}) on leaf K (A), leaf P (C), root K (B) and root P (D) contents in cucumber seedlings (cv. Seminis 189 Sina F1) when allowed to grow for 30 days. Mean values with at least one identical letter are not significantly different from each other.

Crop yield properties

Seedlings from the first stage were transplanted for 60 days under natural sunlight in the greenhouse for evaluations of growth and crop yield during the cultivation period. The results of the second phase of the experiment clearly showed the significant effects of light and nutrients on seedling production, compared to the common method (Fig. 9A). As shown in Fig. 8, among the light treatments, seedlings that grew under a combination of red and blue light had the highest yield. The RB light along with EC 1.7 increased the yield by 69.6%, compared to the control. In this experiment, a significant difference was observed in the amount of biomass produced by plants in the treatment groups and the control (Fig. 9B). The lowest biomass production (9 g) was found in the sunlight treatment group. Higher quality seedlings led to greater biomass production in the greenhouse, so that in the RB light treatment, irrigated with full-strength Hoagland solution, the plant biomass increased by 91.5%, compared to the control (Fig. 9B).

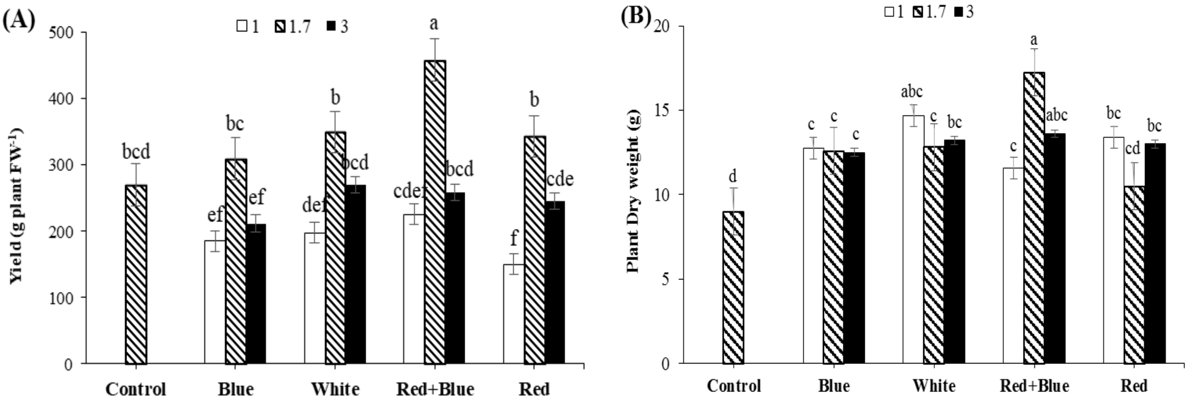

Fig. 9. Effect of light regime and EC of the nutrient solution (1, 1.7 and 3 ds m^{-1}) on crop yield (A), and dry weight (biomass) of plants (B) in cucumber seedlings (cv. Seminis 189 Sina F1) when allowed to grow for 60 days. Mean values with at least one identical letter are not significantly different from each other.

Relationship among properties

Regression analysis demonstrated that DQI highly correlated (via linear regression) with several morphological parameters, i.e. plant dry weight, root volume, and stem diameter (Fig. 10). Furthermore, the sturdiness quotient index correlated strongly (via a linear relationship) with the length and diameter of hypocotyls and stems (Fig. 11). Furthermore, there was a positive linear correlation between plant yield and seedling quality parameters (i.e. seedling index and DQI) (Fig. 12).

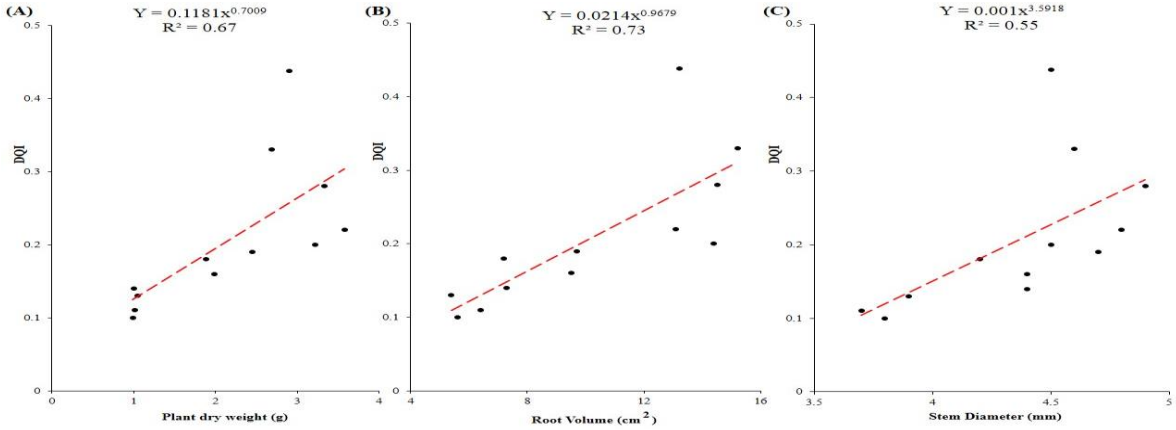

Fig. 10. Dickson's quality index (DQI) as a function of plant dry weight (A), root volume (B), and stem diameter (C) in cucumber seedlings (cv. Seminis 189 Sina F1) when allowed to grow under different light regimes and ECs of the nutrient solution for 30 days. The data in all treatment groups were pooled.

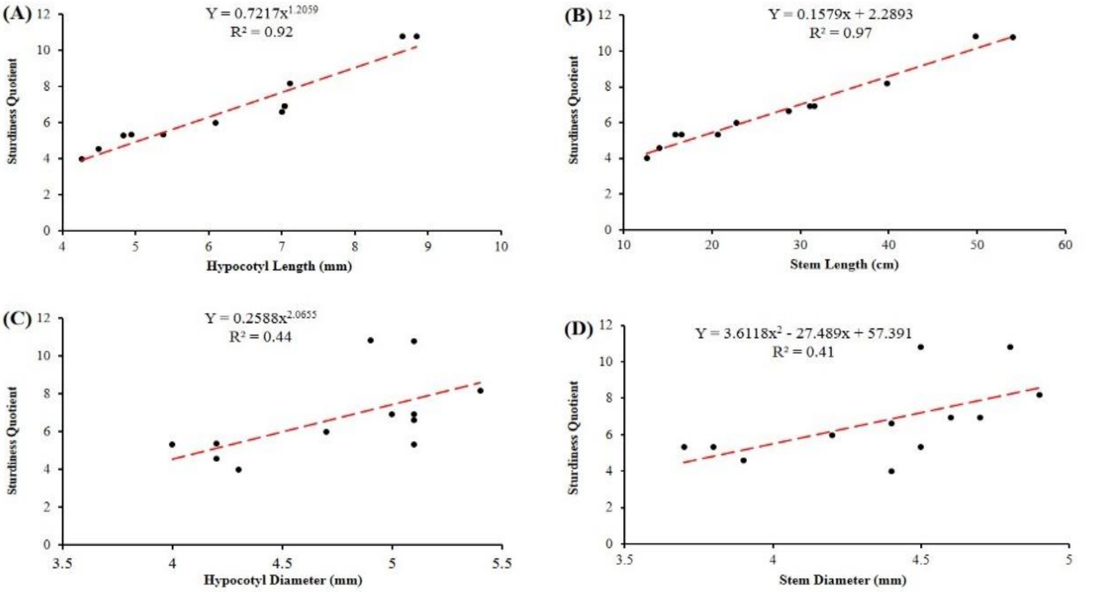

Fig. 11. Sturdiness quotient as a function of hypocotyl length (A), stem length (B), hypocotyl diameter (C), and stem diameter (D) in cucumber seedlings (cv. Seminis 189 Sina F1) when allowed to grow under different light regimes and ECs of the nutrient solution for 30 days. The data in all treatment groups were pooled.

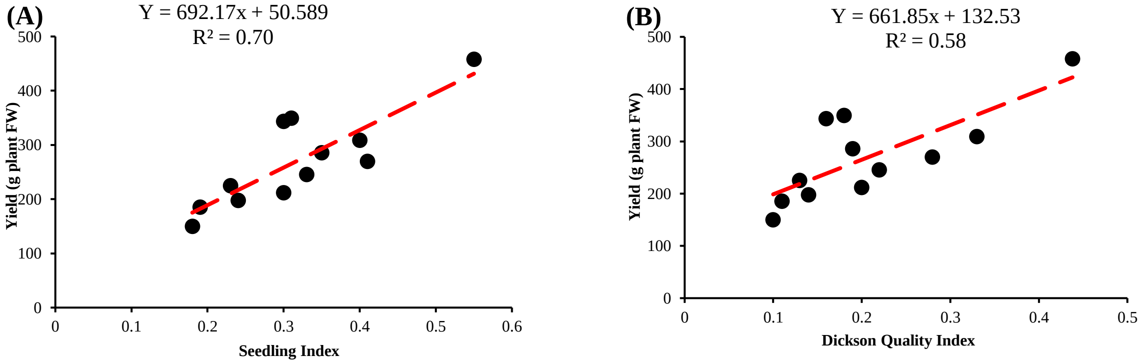

Fig. 12. Yield was a function of seedling index (A) and Dickson's quality index (B) in cucumber seedlings (cv. Seminis 189 Sina F1) in the first phase when allowed to grow in a greenhouse under natural light for 60 days. The data in all treatment groups were pooled.

Discussion

The results of the current research confirmed that the light spectrum altered plant growth and morphology by affecting active optical receptors such as phytochromes, as well as causing changes in plant hormonal balance, particularly auxin and cytokinin (Taiz et al., 2015). Light is the main source of energy for plants and also an important signal for plants to change as a function of wavelength (Rehman et al., 2020). Recently, advances in technology have led to the availability of LEDs, with different light spectra for growing crops, especially in protected areas (Qian et al., 2020). Cucumbers are highly in demand around the world and their cultivation can be expanded broadly into the off-season during the winter when light intensity is low (Ji et al., 2020). In cucumber, poor seedling quality usually results in poor-quality and low-quantity fruits during the growing season (Jeong et al., 2020). In this study, the improvement of cucumber seedling quality was explored by combining different light spectra and ECs of the nutrient solution. The results of this study showed a significant increase in several morphological parameters (i.e. stem length, internode length, leaf number, leaf area, and root length) in the presence of R light, which is consistent with the results of previous research (Shibuya et al., 2020). Also, the dry weight of seedlings was highest in response to the R light.

Plants may prefer the red spectrum to maximize their dry weight (Karimi et al., 2022). Additionally, Hernández and Kubota (2016) reported that blue light causes a notable reduction in plant height, leaf count, and length of hypocotyl in cucumber plants. This role of the B light is actualized by a suppression of the apical dominance by altering hormonal balance (Huché-Thélier et al., 2016). In cucumber, the cotyledon has a key role in gibberellins, carbohydrates, and protein biosynthesis (Asahina et al., 2007). The RB treatment under full-strength Hoagland solution (EC= 1.7) caused a significant increase in the cotyledon dry weight, whereas the cotyledon area was dramatically affected by the W light at 3 ds m-1 (Tables 2 and 3).

Moreover, the effects of light quality on seedling morphological responses depended on the EC value of the nutrient solution. For example, the highest dry weight of seedlings under the B or RB lights was measured at 1.7 ds m^{-l}, whereas this was evident under the R or W lights at 3 ds m^{-l} (Table 3). Although limited to a single EC level, previous studies have also highlighted the considerable influence of light quality on seedling growth (Hernández and Kubota, 2016). In contrast, the promoting effect of increasing the EC value on seedling growth was evident in all light quality regimes (Table 3). These results suggested that the nutrient concentration (which determines electrical conductivity) plays a crucial role in seedling production. The results indicated that the effective nutrient supply was possible under the highest EC level (3 ds m^{-l}), while lower EC levels caused limited plant growth. Leaf area is an important index of seedling quality (Moosavi-Nezhad et al., 2021). The highest EC level (3 ds m-l) was associated with an increase in stem length and leaf area (Tables 1 and 2) (Fig. 2). An increase in stem length usually leads to a more open canopy, thereby reducing self-shading and increasing light interception. An increase in biomass allocation to the leaves (Fig. 4) and thinner leaves, i.e. higher SLA (Table 2), contributed to an increase in leaf area under these conditions.

Six indicators of seedling quality were calculated (Fig. 5). Regarding four of these indicators (i.e. seedling index, DQI, robustness quotient, and compactness), the lowest EC (1 ds m^{-l}) was always associated with the lowest value (Fig. 5A-D). These results provided additional evidence that a low EC value (1 ds m-1) led to poor-quality seedlings. Dickson's quality index (DQI) is an important indicator of seedling vigor when transplanting in the field (Mello et al., 2016). Seedling vigor improved under the RB light (Fig. 5B). The higher the EC value of the nutrient solution, the higher the robustness quotient (Fig. 5C). The robustness quotient is an indicator of seedling soundness. A value higher than four (≥4) may promote seedling etiolating (Silva et al., 2016). Among the other light spectra, the RB showed a more favorable robustness quotient (Fig. 5C). Among the other three spectra, the EC values of 1.7 or 3 ds m^{-l} caused the highest value of robustness, depending on the light quality (Fig. 5A, D). These results indicated that other parameters in addition to the dry weight are important for seedling quality. Regarding almost all indicators of seedling quality, plants grown at 1.7 ds m^{-l} under the RB light performed better than the other treatments (Fig. 5). Previous research indicated that RB light improved several seedling quality indicators in cucumber (Silva et al., 2016). In addition, the RB light increases photosynthetic efficiency and growth, thereby increasing the biomass (Izzo et al., 2020). Under the RB and B lights, the biomass was mainly allocated to the roots, which is beneficial for a seedling to achieve higher performance after transplanting (Fig. 5). Regression analysis showed that DQI highly correlated with several morphological parameters, i.e. plant dry weight, root volume, and stem diameter (Fig. 10). The DQI can be used for early screening of seedling quality. Thus, an active rooting system contributed to higher plant dry weight and greater seedling quality. In addition, the robustness quotient was closely related to the length and diameter of the hypocotyl and stem (Fig. 11). In cucumber, a greater hypocotyl and a longer stem reduced seedling robustness.

In leaves, the relative water content (RWC) is an indicator of plant water status (Taheri-Garavand et al., 2021). In addition to RB, the highest EC level (3 ds m^{-l}) was associated with the lowest RWC within each light regime (Table 2), which may be attributed to a reduction in membrane stability (Behzadi Rad et al., 2021). Therefore, a higher EC affected more the hydration status of the seedlings, but this did not appear to have a negative effect on growth. A well-developed root system is important for subsequent establishment, growth, and yield (Moosavi-Nezhad et al., 2021). Although the roots tended to be shorter at the highest EC level (3 ds m-l), the root volume was generally greater under these conditions (Table 2). Therefore, the highest level of EC was not only optimal for shoot biomass and quality characteristics, but also appeared to be beneficial for the roots to spread in the soil.

Leaf green intensity and leaf uniformity are commonly used throughout the production and distribution chain (e.g. in vegetable nurseries and by farmers) as an index of seedling vigor

(Moosavi-Nezhad et al., 2021). Chlorophyll is a hydrophobic molecule with a crucial role in photosynthetic capacity, growth, stress tolerance, and also photoprotection (Shah et al., 2017). The increase in chlorophyll content due to the increase in the strength of the nutrient solution can be attributed to the availability of essential elements (N, P, K, Mg, Fe, Zn, and Mn) in chlorophyll synthesis (Hörtensteiner and Kräutler, 2011). Carotenoids usually contribute to membrane stabilization, cell development, and a reduction of oxidative radicals in chloroplasts when stressors are at work (Ben Abdallah et al., 2016). Our results showed that the B light increased chlorophyll and carotenoid content, compared to the R light. In the case of cucumber, Hogewoning et al. (2010) also reported that an increase in the B light from zero to 50% led to enhancements in photosynthetic capacity. Proteins play an important role in plant adaptation (Du et al., 2010). Protein level is influenced by light quality. In this regard, the RB light led to a higher amount of protein production. In some cases of research, the B light increased the amount of amino acids, especially aspartic acid and glutamic acid, as well as soluble proteins (Barro et al., 1989), whereas the R light increased the soluble sugars and starch (Warrington and Mitchell, 1976). Proline, as a source of carbon and nitrogen, is also helpful in the adaptation process, and the production of proline can assist in overcoming undesirable conditions (Ashry et al., 2022). Our results showed that the RB light, along with a higher EC level, caused the production of a higher amount of proline and probably improved plant resistance to stress after transplanting the seedlings in the greenhouse. Moreover, the R light caused the lowest amounts of proline, protein and carotenoids. In tomato seedlings, the R light also resulted in the lowest proline content (Rehman et al., 2020). These results illustrated that the RB light caused a substantial increase in the amount of plant pigments and osmoprotectants, i.e. proline and soluble proteins, in the cucumber seedlings. According to the results of this study, seedlings with a high-quality index were more efficient in using carotenoids, soluble proteins and proline to regulate the RWC.

Potassium has an essential role in physiological functions, such as stomatal activity, cell development, enzyme structure, membrane integrity, chlorophyll structure and osmotic adjustment (Wang et al., 2013). Since phosphorus has a vital role in enzyme activity, auxin signalling, root expansion and abiotic stress tolerance, its uptake is a substantial factor in seedling growth and wellbeing (Hou et al., 2022). In cucumber, membrane integrity, respiratory metabolism, photosynthetic capacity, and yield are highly defined by the amount of phosphorus absorption (Wang et al., 2021). As the EC increases, the adsorption of elements (K and P) tends to decrease (Loupassaki et al., 2002), which is consistent with the present results. Accordingly, it was observed that monochromatic R light stimulated potassium uptake in the roots, whereas the B light enhanced potassium agglomeration in the leaves of cucumber. Additionally, our results confirmed that the R light treatment assisted in phosphorus accumulation in the leaves. In comparison, RB and B lights had a crucial role in encouraging the roots to improve phosphorus uptake. Meanwhile, the optimization of nutrients for seedling growth can largely contribute to seedling quality and improve seedling survival after transplantation in the greenhouse (Grossnickle and MacDonald, 2018). Overall, it appears that the R and the B lights can contribute to nutrient delivery to seedling leaves and roots (Fig. 8). There is evidence that providing the plant with more nutrients increases its growth and biomass production (Yadav et al., 2020).

For six weeks, the seedlings of the first experiment were grown under only natural light in the greenhouse. The results of seedling performance revealed that under different light regimes and EC levels, the plants showed different fruit fresh weights and plant dry weights. The RB light along with 1.7 ds m^{-1} EC produced higher amounts of fruit fresh weight and plant dry weight. Moreover, in contrast to the conventional seedling production, yield and biomass production increased by 70% and 92%, respectively, in the transplanting phase, resulting from a better uptake, higher biomass distribution, and low vegetative growth in the seedling production phase. The SI and DQI correlated strongly with crop yield, indicating that a high-quality seedling is more likely to have better fruit yield. Previous studies have shown the positive effects of the B and RB lights on biomass production in lettuce (Johkan et al., 2010), thereby confirming the general concepts of the current results.

Conclusions

In this study, the combined effects of light quality (B, W, RB, and R) and EC value of the nutrient solution (1, 1.7, and 3 ds m-1) were evaluated on shaping seedling growth, a number of quality traits, as well as physiological and biochemical parameters. The effects of light regime on seedling growth, quality and yield depended on the EC value of the nutrient solution. In this experiment, the simultaneous application of RB light and irrigation at EC 1.7 ds m-1 resulted in seedlings with the highest quality indicators and balanced growth efficiency. The plant allocates biomass to its roots and cotyledons instead of promoting vegetative growth, thereby increasing the chances of success in the transplantation stage. Meanwhile, the plant accumulates useful phytochemicals such as proline, soluble proteins and plant pigments to control the RWC and photosynthetic activity. High quality seedlings are capable of higher phosphorus and potassium uptake that improve root structures. In the transplanting phase, seedlings treated with the RB light along with EC 1.7 showed the best yield and biomass production compared to the control. According to our results, seedling quality is one of the most important factors in plant yield, especially in fruit vegetables. Taken together, the EC value of the nutrient solution should be considered decisively when formulating an optimal light spectrum for cucumber seedling growth.

Author Contributions

NA led and coordinated the experiment. SG, NA performed the experiment. NA, HM and AS designed the experiment. RG drafted the manuscript as the leader of authors. NA, SG, HM, AS, and RG analysed the data and revised the manuscript. All authors read and confirmed the submitted version of the manuscript.

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Conflict of interest

The authors indicate no conflict of interest for this work.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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