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Comparison of the growth, fruit quality and physiological characteristics of cucumber fertigated by three different nutrient solutions in soil culture and soilless culture systems

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Global warming and declining rainfall in recent years have led to increased water and soil salinity in Iran agricultural lands. To address these challenges, greenhouse cultivation, particularly soilless culture, emerges as a critical solution for mitigating the effect of soil salinity and water scarcity on vegetable plant production in Iran. The aim of this experiment was to compare the growth and physiological responses of cucumber plants cultivated in both soil and soilless systems, using three distinct nutrient solutions. With this purpose, a factorial experiment carried out with two factors of cultivation system (Soil cultivation and soilless cultivation) and nutrient solution (Hoagland, Papadopoulos, and Commercial) in a completely randomized design with three replications in greenhouse conditions. Cucumber seeds of the Nagene 792 F1 variety were sown in cultivation trays filled with a mixture of perlite and cocopeat (in a 1:1 ratio) to produce seedlings, which were then placed in the growbag with the same substrate in greenhouse environment. Additionally, in soil-based cultivation, the seeds were first sown in cultivation trays and then transferred to 10-L pots containing soil medium. The results of this study showed that the soilless culture system increased vegetative and reproductive characteristics such as plant height (13%), number of nodes (9.4%), internode distance, number of leaves, leaf area (31.45%), fresh and dry mass of shoots, fresh (21%) and dry (33%) mass of roots, number of flowers (9.4%), number of fruits (10.12%), and fruit diameter (19.5%) in cucumber plants. Soilless cultivation increased the yield per plant and cultivation area (52%). The photosynthetic pigments (27.5% and 49.18% for Chl a and b, respectively), and fruit quality traits including fruit appearance color (the components a (16.42%), b (19.44%), and L (1.87%), hue angle (32.74%), and chroma (15.13%)), total soluble solids (TSS) (7%) and vitamin C (31.85%) increased compared to soil-grown plants. The results showed that the percentage of flower fall in soil-grown plants was higher than the plants in soilless medium. Hoagland nutrient solution had a more significant effect on increasing these parameters than other nutrient solutions. Although, the highest flowering rate was observed in nutrient solution of Hochmat and Papadopoulos. Overall, soilless cultivation using the Hoagland nutrient solution significantly enhanced growth and yield characteristics, as well as both the quantitative and qualitative traits of the fruit and physiological characteristics, compared to the other treatment methods.

Cucumber (*Cucumis sativus*L.) is an important crop produced under controlled conditions and has allocated a large area of greenhouse production outside of the Iranian season. Greenhouse cucumber plants exhibit rapid vegetative and reproductive growth rates, high water and nutrient absorption, and extensive root development[1]. Iran is one of the major producers of cucumbers in the west Asia and globally. According to the Food and Agriculture Organization of the United Nations (FAO), Iran produced approximately 1.4 million metric tons

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of cucumbers in 2019, making it one of the top cucumber-producing countries in the world. According to FAO statistics, in 2022, Iran was the 14thlargest cucumber producing country in the world with the production of about 400,000 tons of cucumbers[2]. Cucumber production in Iran is mainly concentrated in the northern and western regions of the country, where the climate is conducive to cucumber cultivation. Greenhouse cultivation of cucumbers is also common in Iran, allowing for year-round production and higher yields. Cucumbers are an important crop in Iran, both for domestic consumption and for export. Iranian cucumbers are known for their high quality and are sought after in international markets. The government of Iran has implemented various programs to support and promote cucumber production, including providing subsidies for farmers and investing in research and development initiatives to improve crop yields and quality. Overall, cucumber production plays a significant role in the agricultural economy of Iran, providing employment opportunities for farmers and contributing to the country's food security. The consistent production and high quality of Iranian cucumbers have helped establish Iran as a key player in the global cucumber market. Therefore, high quality and performance production of this crop in controlled conditions requires proper management. In recent years, the presence of some problems in soil cultivation such as salinity, improper soil structure, and limited water resources in some countries, especially Iran, has led to the development of soilless cultivation (hydroponics). Soil fertility decline, increased salinity, and the occurrence of soil-borne diseases after successive crops are observed. Therefore, the use of soilless cultivation as an alternative to soil cultivation is considered in many countries. Research has shown that if nutrients are provided to plants through fertigation/ nutrigation, the plant does not need soil for growth[3,4]. Hydroponics is a method in which plant growth and development can be well controlled, resulting in relatively high performance. A key advantage of this method is its applicability worldwide[5]. Sustainable agriculture is a type of agricultural system that aims to achieve desirable performance by using minimal inputs and external chemical factors. Additionally, sustainable agriculture minimizes harmful effects on the environment and enhances the quality of the environment and natural resources in the long term. With the increasing population and its substantial food needs, traditional and low-yielding agricultural methods are no longer sufficient to meet these demands. Furthermore, pollution of water and soil resources is another factor hindering the use of chemical fertilizers in the soil. In this context, soilless cultivation offers a sustainable alternative for vegetable production by optimizing agricultural inputs and achieving high yields, and reducing soil-related issues commonly found in traditional crop cultivation. This method has seen a significant increase in popularity in recent decades due to its ease of use and ability to create a more controlled growing environment. With the ability to manipulate water availability, pH levels, and nutrient concentrations in the root zone, soilless cultivation has proven to be highly effective for growing a variety of crops. Hydroponic systems have become increasingly popular in cucumber cultivation due to their numerous advantages over traditional soil-based methods. One of the key benefits of using hydroponics for cucumber cultivation is the ability to precisely control and optimize nutrient levels, water usage, and environmental conditions. This allows for increased yields, faster growth rates, and higher quality produce. Recent literature has highlighted the advantages of hydroponic systems for cucumber cultivation. A study found that cucumbers grown in a nutrient film technique (NFT) hydroponic system had higher yields and better fruit quality compared to soil-grown cucumbers[6]. The researchers attributed these improvements to the ability of hydroponic systems to provide plants with a more consistent and controlled environment. Another study compared the nutrient uptake and growth of cucumber plants grown in a hydroponic system versus traditional soil-based methods. The researchers found that hydroponically grown cucumbers had higher nutrient uptake efficiency and biomass production, leading to increased yields and improved plant health[6]. Overall, the research suggests that hydroponic systems offer numerous advantages for cucumber cultivation, including increased yields, improved fruit quality, and more efficient nutrient uptake. As a result, many growers are turning to hydroponics as a more sustainable and productive method of cucumber production. Studies have shown that different compositions of growing media can also have a significant impact on plant growth and yield. For example, research by Samadi[7]found that fine-grade perlite resulted in the best performance for cucumber cultivation. Additionally, cocopeat, a popular soilless growing medium, has been shown to have high water holding capacity and air-filled porosity, leading to high seed germination rates and producing strong, fibrous seedlings. Nutrient supply and environmental conditions such as light, temperature, and relative humidity are among the most important factors for successful management and cultivation of greenhouse cucumbers. Although research on the use of organic sources in hydroponic cultivation is expanding[8], continuous research on nutrient solutions is essential for identifying the best nutrient solutions for specific crops given the increasing greenhouse industry and production of greenhouse products. In hydroponics, careful attention must be paid to nutrient elements, as deficiencies of any element manifest quickly in this method[4]. Therefore, determining the best type and combination of nutrient solutions for achieving desirable performance serves as one of the key methods for managing the nutrition of products in controlled conditions[9].

Water and nutrients are essential inputs for plant growth, especially in soilless production systems, where their uptake occurs as two independent processes[10]. Fertigation, which involves dissolving fertilizers in irrigation water, enhances the efficiency of water and nutrient use in soilless cultivation[10]. This method allows for precise and uniform application of nutrients directly to the active root system[11]. Furthermore, protective cultivation can lead to reductions in water and nutrient consumption by 22% and 35%, respectively, in cucumber production[12]. Singh et al.[10]reported that cultivating off-season seedless cucumbers in soilless media within a naturally ventilated greenhouse, where environmental conditions were partially controlled, significantly enhanced nutrient and water use efficiency compared to conventional cultivation methods. One of the key indicators of a suitable nutrient solution is to supply the necessary elements in a way that the plant receives macro- and micro-elements in optimal amounts to avoid nutritional stress, and most importantly, its economic viability to ensure its acceptance among investors. Having sufficient knowledge of important nutrient solution formulations is crucial, but more importantly, knowing how to manage them is essential for successful production[13]. In soilless cultivation methods, all essential elements must be supplied to the plant in the form of soluble salts. A standard nutrient solution contains all essential nutrients at specified concentrations, and experts may modify or use different concentrations of standard solutions based on research components, cultivation conditions, and plant species. Considering that an element exists in various salt forms, the choice of salt or fertilizer type to supply that element depends on factors such as element ratios, solubility, pH, growing medium, cost, and the mechanisms by which that element affects[14]. Different countries around the world use different nutrient solutions based on cultivation type, environmental factors, and the cost of various fertilizers. In Iran, due to the relatively short history of hydroponic systems, the effects of different nutrient solutions on highly productive plants such as cucumbers have been less explored. Therefore, to achieve better performance and quality, it is necessary to study important nutrient solutions in order to select the most suitable ones economically, in terms of performance impact, and even environmental factors. It has been observed that different ratios of potassium and nitrogen in hydroponic conditions lead to changes in growth and performance indicators of cucumber plants, so that growth indicators such as stem length, leaf area, stem diameter, fruit length, fruit diameter, and fruit mass are affected by the application of different nitrogen and potassium concentrations[15]. The separate application of potassium, phosphorus, calcium, magnesium, and nitrogen in field conditions results in increased growth indicators of tomato plants through increased chlorophyll content and nutrient concentration in leaf tissue[16].

The following factors should be considered in preparing nutrient solutions: 1- Selecting a suitable formulation based on the type of cultivation, 2- Analyzing the mineral composition of irrigation water, 3- Choosing the type of mineral salts, and 4- Calculating the mass of mineral salts. Balancing between anions and cations should be maintained in the preparation of nutrient solutions, and precipitation should be avoided. The nutrient solution is directly related to the plant roots and its concentration changes rapidly as it is absorbed by the plant, and the absorption of elements depends on the nutrient ratios in the solution. With repeated use of the nutrient solution, not only its quantity decreases but also the balance between elements is disrupted. Some nutrients, such as nitrogen, are rapidly absorbed by the plant, while others like magnesium and calcium are absorbed more slowly. If the nutrient solution is used for a long time without renewal, it may lead to a deficiency in some nutrients.

In general, nitrogen is the first element that a plant becomes deficient in, and its symptoms are clearly evident on the plant. Another problem we may encounter with long-term use of solutions is that some elements such as iron or phosphorus may become inaccessible to the plant, and signs of their deficiency may be observed. Unlike soil cultivation, soilless cultivation requires more essential elements, including micronutrients, to be continuously provided due to the limited buffering capacity of the growing medium and limited availability of nutrients[17]. Although nutrient solutions for all purposes have been presented by Hoagland and Arnon13, many researchers and organizations have recommended specific nutrient compositions for different plants grown in soilless cultivation. However, in greenhouse cultivation, especially in hydroponic environments, environmental conditions such as nutrient elements have a significant impact on the growth, development, and quality of plants. In this method, each element quickly demonstrates its effect, so careful consideration should be given in selecting or creating a nutrient solution[18]. In an experiment[12], important nutrient solutions worldwide were compared, and it was observed that the nutrient composition of these widely used nutrient solutions significantly affects micronutrients[19]. In a study on the effect of three growing media, perlite, palm peat, and soil, on the growth of greenhouse cucumbers[20], showed that in palm peat medium, the weight of root biomass and fruit differs significantly compared to the perlite medium; the plant height, stem diameter, and leaf area of plants in the palm peat medium were higher than those in the other two media.

Proper nutrition management and selecting the best fertilizer source with the suitable combination and concentration of nutrients can be considered as a fundamental and scientific solution for cucumber production to increase yield and deliver a quality product to consumers[15]. Considering the increasing trend of soilless cucumber production in Iran, investigating the growth and physiological differences of cucumbers in soil and soilless cultivation, as well as identifying the best nutrient solution for them in Iranian climate conditions, seems essential. Therefore, an experiment was conducted with the following objectives: 1- Determining the best nutrient solution for cucumbers in soil and soilless culture systems 2- Comparing the growth and physiological characteristics of cucumber plants in soil and soilless cultivation 3- Determining the best nutrient concentration combination for performance and quality indicators of cucumber fruits in soil and soilless culture systems.

Materials and methods

Time and location of experiment

This research was conducted to evaluate the impact of different nutrient solutions on the growth characteristics and performance of cucumber plants, as well as to assess the growth and quantitative and qualitative characteristics of fruits in soil-based and soilless cultivation in a greenhouse located in Shahrbak, Iran. The average minimum and maximum temperatures were 24 ± 3 °C during the day and 21 ± 3 °C at night, and the average relative humidity was 54%. Additionally, this area is located at 55° and 8´ East longitude, and 30° and 7´ North latitude, at an elevation of 1834 m above sea level.

Experimental design and treatments

The experiment was conducted in a factorial design as a completely randomized design with three replications. The factors included cultivation systems at two levels (soil-based and soilless cultivation) and types of nutrient solution at three levels (Hoagland, Papadopoulos, and commercial nutrient solution). Each replication constituted 3 plants, and 54 plants were cultivated in total.

Preparation of growing media and nutrient solution

In soil-based cultivation, 10 L pots were used, with one plant grown in each pot. The pots were filled with greenhouse soil that was used commercially for cucumber production. The soil used was sandy clay soil containing 1.5% organic matter. The plants in soil-based cultivation were irrigated with the nutrient solution every 12 days based on the treatments, and to maintain moisture, the soil-based plants were also irrigated with city tap water every 4 days. In the hydroponic cultivation system, the cultivation bags in the experimental setup consisted of a mixture of cocopeat and perlite in a ratio of 50:50. The water required to prepare the nutrient solution was obtained from a RO system with 5 filters and an output EC of 14 µS/cm available in the greenhouse. In the hydroponic system, plants fertigated with nutrient solution twice daily up to 20% drainage. The nutrient solution used had a pH of 5.8–6.5 and an EC of approximately 1.7–2.2 $dS.m^{-1}$. Table 1 shows nutrient solution formulation and concentration in different treatments. The macronutrients provided by $Ca(NO_3)_2.4H_2O$, KNO_3, KH_2PO_4, K_2SO_4 and $MgSO_4.7H_2O$, in all nutrient solutions. The greenhouse grade of chemicals was used to make the nutrient solution. The concentration of micronutrients (20 µM Fe(III)-EDDHA-Na, 7 µM MnSO4. H2O, 0.7 µM ZnCl2, 0.8 µmM CuSO4.5H2O, 2 µM H3BO3, 0.8 µM Na2MoO4.2H2O) was the same in all nutrient solution treatments, while macronutrients concentration was different. The Hoagland nutrient solution contained 15 mM nitrogen, 1 mM phosphorous, 6 mM potassium, 6 mM Calcium, 2 mM magnesium, 4 mM Sulphur. The Papadopoulos nutrient solution contained 8.36 mM nitrogen, 1.13 mM phosphorous, 4.5 mM potassium, 2.37 mM Calcium, 1 mM magnesium, 1.84 mM Sulphur. The commercial nutrient solution contained 8.57 mM nitrogen, 0.97 mM phosphorous, 4.5 mM potassium, 2.5 mM Calcium, 0.82 mM magnesium, 1.19 mM Sulphur. Nitrogen, K, Ca, Mg and S were 107, 57, 129, 24 and 92 percent higher in Hoagland nutrient solution compared to Papadopoulos nutrient solution, and 102, 33, 124, 145 and 197 percent higher than commercial nutrient solution, respectively. Phosphorous was higher in Papadopoulos nutrient solution compared to other treatments.

Preparation of seedlings (tray cultivation) and planting

For this purpose, cucumber seeds of the Nagene 792 F1 (produced by Enza Zaden Company) variety were sown in cultivation trays filled with a mixture of perlite and cocopeat (in a 1:1 ratio) to produce seedlings, which were then placed in the greenhouse environment. Additionally, in soil-based cultivation, the seeds were first sown in cultivation trays and then transferred to 10-L pots. Fourteen days after sowing the cucumber seeds, when the seedlings had reached the 4–6 leaf stage and a height of 12 cm, the seedlings were transferred to cultivation bags (Growbags) for hydroponic cultivation and to 10-L pots for soil-based cultivation.

Parameters measurement

Growth parameters

The growth parameters measured in this experiment included plant height, number of nodes, internode distance, number of leaves, leaf area, fresh and dry mass of the shoots, and fresh and dry mass of the roots. These parameters were measured 120 days after the plant transfer to the cultivation systems. The biometric measurements performed on all plants. Plant height was measured using a ruler. Leaf area was measured using a Leaf Area meter (model CI 202), and the leaf area was calculated in square centimeters. Three mature leaf from each plant were taken to assess leaf area. For measuring the fresh mass, the plant was separated into shoot and root sections, washed, dried, and then weighed separately. Dry mass was measured after drying the all shoot and roots for 48 h at 70 ∘C.

Reproductive parameters

The reproductive parameters to be measured in this experiment included the number of flowers, number of fruit, percentage of flower drop, fruit diameter, fruit mass, cucumber yield per plant, and yield per hectare.

Leaf pigments

The levels of chlorophyll a, b, total chlorophyll and carotenoid were measured using the spectrophotometric by randomly sampling mature leaves and extracting with acetone[21], so that 0.25 g of fresh leaf sample was ground in a cold mortar with 10 mL of 80% acetone until a uniform solution was obtained, then the samples

Chemical component (mg.L-1)	Hoagland	Papadopoulos	Commercial
Ca(NO3)2.4H2O	1178.95	352.60	526.32
KNO3	427.97	176.93	277.45
KH2PO4	136.10	153.66	131.71
K2SO4	61.04	139.15	66.55
MgSO4.7H2O	500.00	255.10	204.08
Nutrient element (mg.L-1)			
N	242	117	120
P	31	35	30
K	232	175	175
Ca	224	95	100
Mg	49	25	20
S	113	59	38

Table 1. Chemical components and nutrient elements concentration (mg.L-1) in Hoagland13, Papadopoulos4 and commercial nutrient solution. Micronutrients were according to Hoagland and Arnon (1950).

were transferred to centrifuge tubes and centrifuged at 3500 rpm for 10 min, after separating the liquid phase from the solid, the liquid part was used for chlorophyll measurement. The light absorption of the solution was measured using a spectrophotometer device (PG Instruments Limited, England) at wavelengths of 663.2, 646.8, and 470 nm.

Chla = {12.25 (A663.2)−2.79 (A646.8)} × V/1000 × W.

Chlb = {12.21(A646.8)−5.10 (A663.2)} × V/1000 × W.

TChl = chlb + Chla.

Car = [1000 (A470)−1.8 (chla)−85.02 (chlb)/198].

Where: A: Absorbance readings, V: Volume of acetone used, W: Weight of the sample (g).

Measurement of fruit quality parameters

Total soluble solids

For the measurement of total soluble solids in the fruit extract, a digital refractometer (ATAGO model A. PAL-1, Japan) was used. After calibrating the refractometer with distilled water, a few drops of the fruit extract were placed on the glass plate of the refractometer, and the concentration of total soluble solids in the solution was read in ∘Brix.

Measurement of vitamin c

For the measurement of vitamin C, the iodine in potassium iodide method was used. To prepare iodine in potassium iodide solution, first, 1.27 g of iodine was dissolved in a few milliliters of ethyl alcohol. Then, 16 g of potassium iodide was dissolved in a portion of distilled water and made up to a volume of 300 mL with distilled water. These two solutions were mixed together and made up to a volume of 1000 mL with distilled water. To prepare a 1% starch indicator, 1 g of starch was dissolved in a portion of distilled water and made up to a volume of 100 mL with distilled water. Initially, the burette was filled with the iodine in potassium iodide solution, and then, inside a flask, 2 mL of fruit juice, 2 mL of 1% starch, and 20–25 mL of distilled water were mixed, and the flask was placed under the burette containing iodine in potassium iodide. The titration started by adding the iodine in potassium iodide solution from the burette to the solution in the flask. When the solution in the flask changed color (light gray), the burette was closed, and the amount of iodine in potassium iodide consumed for this color change was noted. By this definition, as 1 mL of iodine in potassium iodide is equivalent to 0.088 mg of vitamin C in the fruit juice, the amount of vitamin C consumed in 2 mL of fruit juice was calculated based on the amount of iodine in potassium iodide used in the experiment, and ultimately, the amount of vitamin C obtained per 100 mL of fruit juice was calculated.

Measurement of fruit color

To calculate the skin color of the fruit using a chroma Meter (Konica Minolta CR 400, Japan), the color of 4 different parts of the surface of 5 fruits from each replication was read. The chroma Meter provides color values in the form of three indices: a*, b*, and L*. The L* index represents the brightness of the fruit skin color, ranging from 0 (black) to 100 (white). The range of the a* index varies from + 60 (red) to −60 (green), with decreasing green color from −60 and increasing red color from + 60 towards the color diagram (0). The range of the b* index varies from + 60 (yellow) to −60 (blue), decreasing towards the color diagram (0) from + 60 for yellow and −60 for blue. The Chroma index indicates the intensity or purity of the color, with the value zero at the center of the color diagram, increasing as it moves away from the center. Chroma and Hue angle indices were calculated using the following formulas:

Chroma = √(a^2 + b^2).

Hue = tan^−1(b*/a*).

Data analysis

Statistical analyses were performed using the SAS software, and the comparison between the means was done using the Duncan test at a probability level of 5%, and the relevant graphs were plotted using Excel. Minitab software was used for data normalization.

Results

Vegetative growth

The height of cucumber plants in hydroponic cultivation was higher than in soil-based cultivation. Additionally, the Hoagland nutrient solution had a higher plant height compared to the commercial and Papadopoulos solutions, showing a significant difference between them. The results of investigating the interactive effects of cultivation system and nutrient solution showed that the tallest cucumber plant height was observed in the hydroponic cultivation medium with the simultaneous application of the Hoagland nutrient solution, while the lowest height was seen in soil-based cultivation with the simultaneous application of the Papadopoulos nutrient solution. So that the height of plants fed with Hoagland's solution in the hydroponic system increased by 13% compared to soil cultivation with Papadopoulos solution (Table 2).

The results indicated that the number of nodes in hydroponic cultivation was higher than in soil-based cultivation. Comparing the effects of cultivation system on the number of nodes of cucumber plants showed that the highest number of nodes was observed in the hydroponic cultivation medium with the simultaneous application of the Hoagland nutrient solution, and the lowest number of these parameters was observed in soil-based cultivation with the Papadopoulos nutrient solution. So that the number of nodes of plants fed with Hoagland's solution in the hydroponic system increased by 9.4% compared to soil cultivation with Papadopoulos solution (Table 2).

Cultivation system	Nutrient solution	Height (cm)	Node No. (Plant^{-1})	Internode Length (cm)	SFM (g.plant^{-1})	SDM (g.plant^{-1})	RFM (g.plant^{-1})	RDM (g.plant^{-1})
Hydroponics	Hoagland	278.65a	25.01a	10.42c	623.79a	81.79a	94.52a	41.62ab
	Papadopoulos	256.83 cd	23.44 cd	11.16a	599.93bc	63.74c	87.12b	37.49bc
	Commercial	262.27b	23.90b	10.87b	612.41a	71.78b	96.79a	45.10a
Soil	Hoagland	259.98bc	23.28de	10.73b	591.31c	63.27 cd	85.41bc	31.52d
	Papadopoulos	246.65e	22.85f.	11.22a	540.11e	54.90e	65.48d	25.62e
	Commercial	250.67de	23.05e	10.61c	558.35d	59.03de	81.23c	34.76 cd

Table 2. The interactive effects of cultivation system and nutrient solution on height, node number (Node No.), internode length, shoot fresh mass (SFM), shoot dry mass (SDM), root fresh mass (RFM) and rood dry mass (RDM) of cucumber plant. In each column, means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

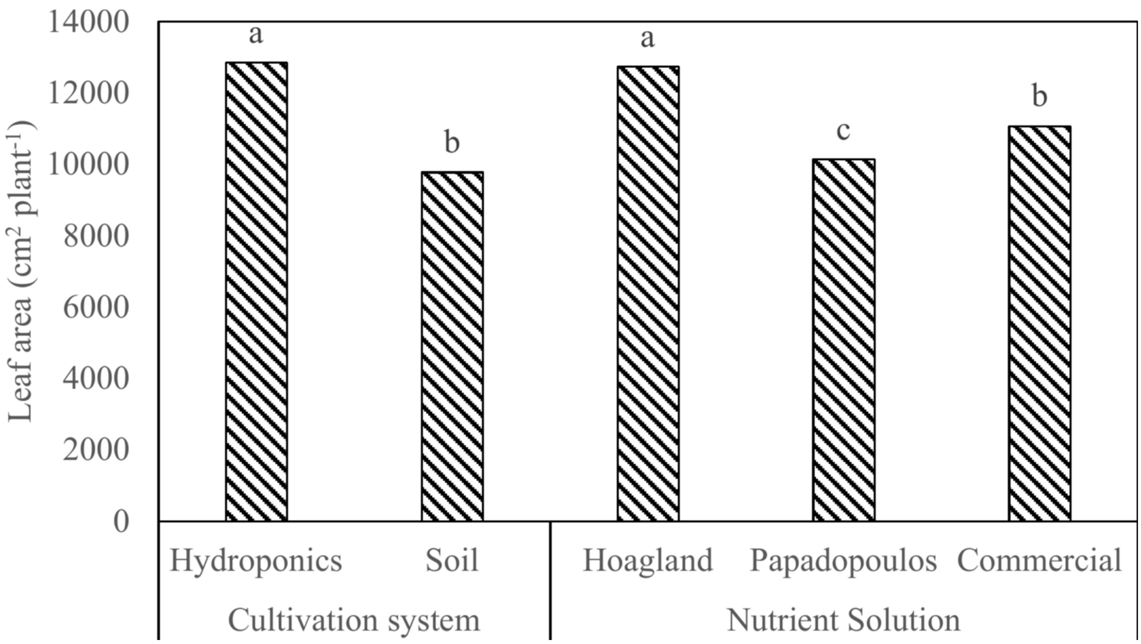

Fig. 1. Impact of cultivation system and nutrient solution on the leaf area of greenhouse cucumber. Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

The results showed that the plants irrigated with Hoagland nutrient solution in the hydroponic cultivation system had a lower internode length compared to other treatments (Table 2). In addition, among the nutrient solutions used, the Papadopoulos nutrient solution had the highest internode length in the both cultivation systems.

The highest leaf area of cucumber plants was observed in the hydroponic cultivation system, and the lowest was in plants grown in the soil-based cultivation system, as the leaf area in the hydroponic system increased by 31.45% compared to soil cultivation (Fig. 1). There was a significant difference between hydroponic and soil-based cultivation systems. The plants treated with the Hoagland nutrient solution had the highest leaf area, which was significantly different from the commercial nutrient solution and the Papadopoulos nutrient solution, which had the lowest leaf area.

The fresh and dry mass of the shoot in cucumber plants grown in the hydroponic cultivation system with the simultaneous application of the Hoagland nutrient solution was the highest. The lowest mass was found in plants grown in soil-based cultivation with the simultaneous application of the Papadopoulos nutrient solution. The cucumber plants fertigated with commercial nutrient solution in the hydroponic cultivation system also had the highest shoot fresh mass (Table 2).

The fresh and dry mass of the root in cucumber plants in the hydroponic cultivation system was higher compared to soil-based cultivation, with an increase of 21% and 33%, respectively. The plants grown in the hydroponic cultivation system showed respective increases in the mass of the dry roots. The results showed that the Hoagland nutrient solution in the hydroponic cultivation system increased the mass of the root by 35% compared to the soil-based cultivation (Table 2).

Reproductive growth

The number of flowers in cucumber plants grown in the hydroponic medium was higher than in soil-based cultivation, showing a significant difference. Also, the number of flowers in plants treated with the Hoagland nutrient solution was higher than in plants treated with the commercial and Papadopoulos solutions. The highest number of flowers in cucumber plants was observed in the hydroponic cultivation medium with the simultaneous application of the Hoagland nutrient solution, while the lowest number of flowers was observed in soil-based cultivation with the simultaneous application of the Papadopoulos nutrient solution, as the number of flowers of plants fed with Hoagland's solution in the hydroponic system increased by 9.4% compared to soil cultivation with Papadopoulos solution (Table 3).

The results showed that the percentage of flower abscission in soil-based cultivation plants was higher than in hydroponic cultivation plants. Additionally, in plants fertigated with the Papadopoulos solution, the percentage of flower abscission was higher compared to plants treated with the Hoagland nutrient solution. The highest percentage of flower abscission was in soil-based cultivation with the simultaneous application of the Papadopoulos and commercial nutrient solutions, and the lowest percentage was in hydroponic cultivation with the Hoagland nutrient solution, as the percentage of flower abscission of plants fed with Hoagland's solution in the hydroponic system decreased by 9.41% compared to soil cultivation with Papadopoulos solution (Table 3).

The number of cucumber fruits obtained from plants grown in the hydroponic cultivation system was higher than in plants grown in soil-based cultivation. Plants treated with the Hoagland nutrient solution also had a higher number of fruits compared to plants nourished with the commercial and Papadopoulos solutions. The highest number of fruits was observed in plants grown in the hydroponic cultivation system with the simultaneous application of the Hoagland nutrient solution, while the lowest number of fruits was in the plants grown in soil-based cultivation with the Papadopoulos nutrient solution, with 10.12% increase in fruit number in hydroponics (Table 3).

The largest diameter of fruit from plants grown in the hydroponic medium was 3.25 cm, while the smallest diameter was 2.72 cm in plants grown in the soil-based cultivation, so that the fruit diameter in the hydroponic system increased by 19.5% compared to soil cultivation (Fig. 2). The Hoagland nutrient solution had a higher fruit diameter compared to the commercial nutrient solution and Papadopoulos nutrient solution, showing a significant difference between the Hoagland and Papadopoulos nutrient solutions.

The yield per plant in cucumber plants grown in the hydroponic cultivation medium was higher than in plants grown in soil-based cultivation. Additionally, plants treated with the Hoagland and commercial nutrient solutions had a higher yield per plant compared to plants nourished with the Papadopoulos nutrient solution. The results showed that the highest yield of cucumber per plant was in plants grown in the hydroponic cultivation system and supplied with the Hoagland and commercial nutrient solutions, while the lowest yield of cucumber per plant was in plants grown in soil-based cultivation with the Papadopoulos nutrient solution, as the yield of plants fed with Hoagland's solution in the hydroponic system increased by 52.24% compared to soil cultivation with Papadopoulos solution (Table 3).

The plant yield per hectare in plants grown in the hydroponic cultivation system was higher than in plants grown in soil. The highest plant yield per hectare was in plants grown in the hydroponic cultivation system and supplied with the Hoagland and commercial nutrient solutions, while the lowest plant yield per hectare was in plants grown in soil-based cultivation with the Papadopoulos nutrient solution (Table 3).

Photosynthetic pigments

Plants grown in soil-based cultivation had a higher amount of chlorophyll compared to plants grown in hydroponic cultivation. Additionally, plants nourished with the Hoagland nutrient solution had a higher level of chlorophyll. The highest levels of chlorophyll a and b in plants grown in hydroponic cultivation was observed with the simultaneous use of the Hoagland nutrient solution, while the lowest levels of chlorophyll in plants grown in soil-based cultivation with the Papadopoulos nutrient solution, as the leaf chlorophyll a and b of plants fed with Hoagland's solution in the hydroponic system increased by 27.7% and 49.18% compared to soil cultivation with Papadopoulos solution, respectively (Figs. 3 and 4).

The highest amount of total leaf chlorophyll in cucumber plants grown in hydroponic cultivation with the simultaneous use of the Hoagland nutrient solution was observed, and the lowest amount was observed in plants grown in soil-based cultivation with the Papadopoulos nutrient solution (Fig. 5). Therefore, the total leaf

Cultivation system	Nutrient solution	Flower No (Plant^{-1})	Flower abscission (%)	Fruit No (Plant^{-1})	EFY (Kg.Plant^{-1})	Yield (Kg.ha^{-1})
Hydroponics	Hoagland	25.01a	11.99e	23.51a	3.42a	89866a
	Papadopoulos	23.44c	12.80c	21.94c	3.07c	71050c
	Commercial	23.90b	12.56d	22.40b	3.27ab	81667ab
Soil	Hoagland	23.28c	12.89bc	21.78 cd	2.90d	65856d
	Papadopoulos	22.85e	13.13a	21.35e	2.25e	59029e
	Commercial	23.05d	13.01ab	21.55d	2.75d	67228d

Table 3. The interactive effects of cultivation system and nutrient solution on flower number (Flower No.), flower abscission, fruit number (Fruit No.), early fruit yield (EFY) and yield of cucumber plant. In each column, means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

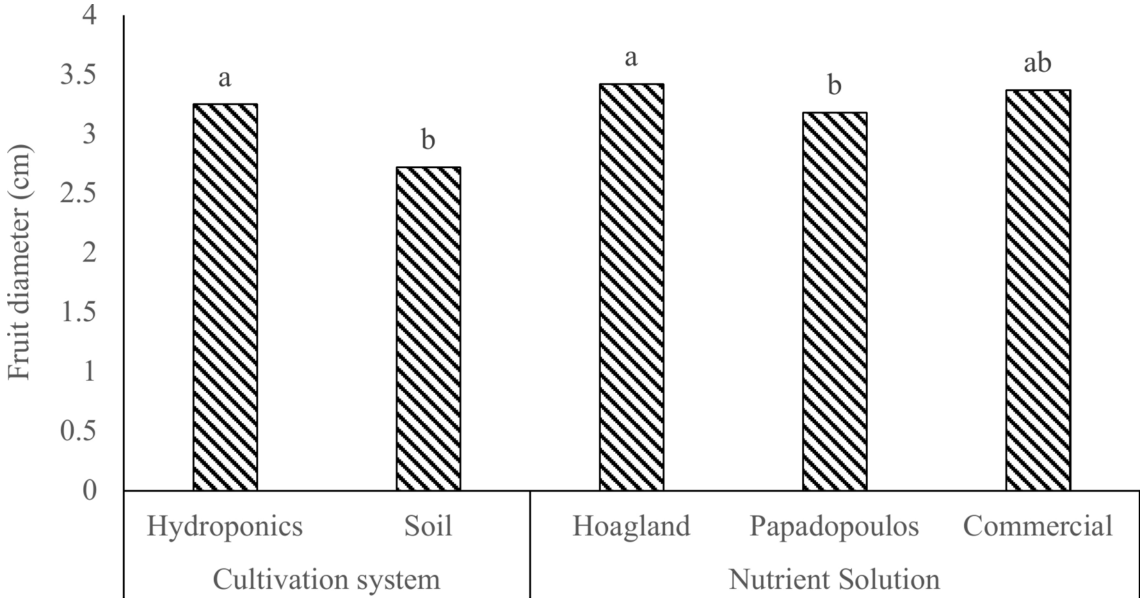

Fig. 2. The effect of cultivation system and nutrient solution on the diameter of cucumber fruit. Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

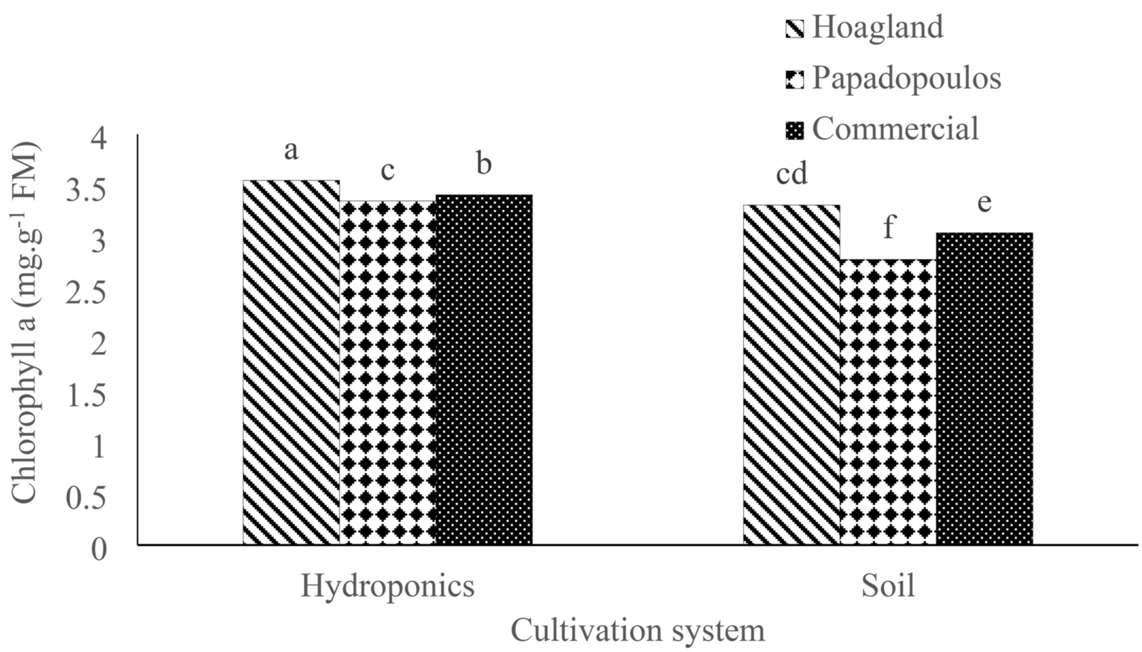

Fig. 3. The leaf chlorophyll a concentration in the interaction of cultivation system and nutrient solution. Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

chlorophyll content in plants grown in hydroponic cultivation was higher than in soil-based cultivation, and plants nourished with the Hoagland nutrient solution had more chlorophyll compared to the commercial and Papadopoulos solutions.

Plants grown in the soil-based medium had lower levels of carotenoids compared to plants grown in hydroponic cultivation (Fig. 6). The Hoagland nutrient solution had the highest leaf carotenoid content compared to the Papadopoulos solution, showing a significant difference between the Hoagland and Papadopoulos nutrient solutions (Fig. 6).

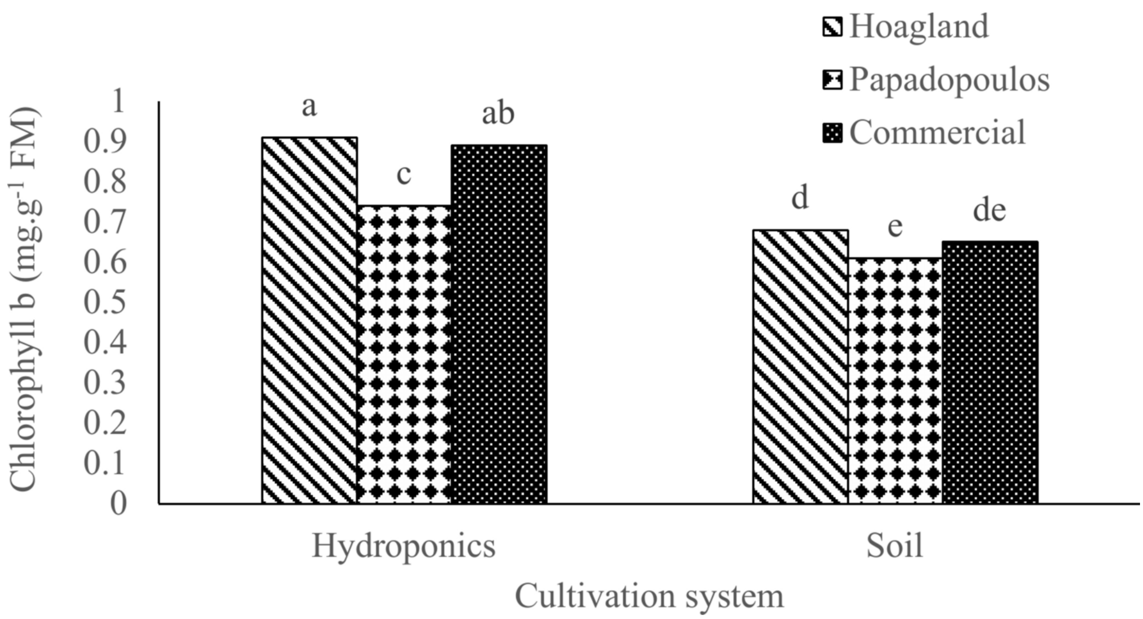

Fig. 4. The leaf chlorophyll b concentration in the interaction of cultivation system and nutrient solution. Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

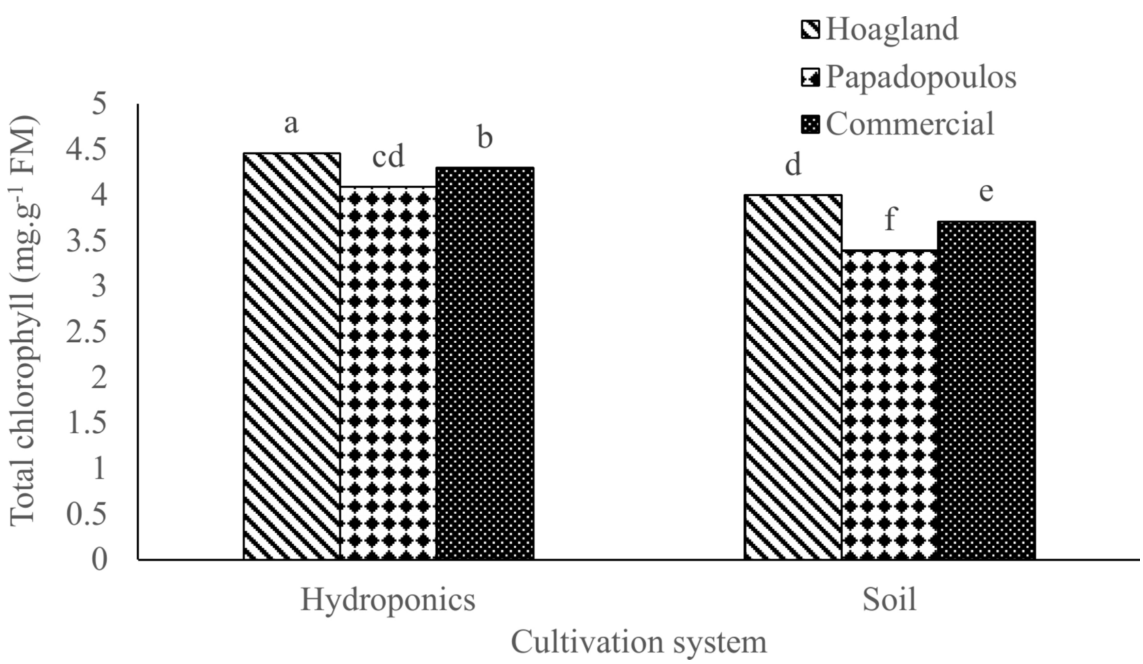

Fig. 5. The leaf total chlorophyll concentration in the interaction of cultivation system and nutrient solution. Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

Fruit quality

Soluble solids content

Plants grown in the hydroponic medium had a higher soluble solids content compared to plants grown in soil-based cultivation (Fig. 7). Additionally, the soluble solids content in plants treated with the Hoagland nutrient solution was higher than in plants treated with the Papadopoulos nutrient solutions, as the soluble solids content of plants fed with Hoagland's solution in the hydroponic system increased by 7% compared to soil cultivation with Papadopoulos solution.

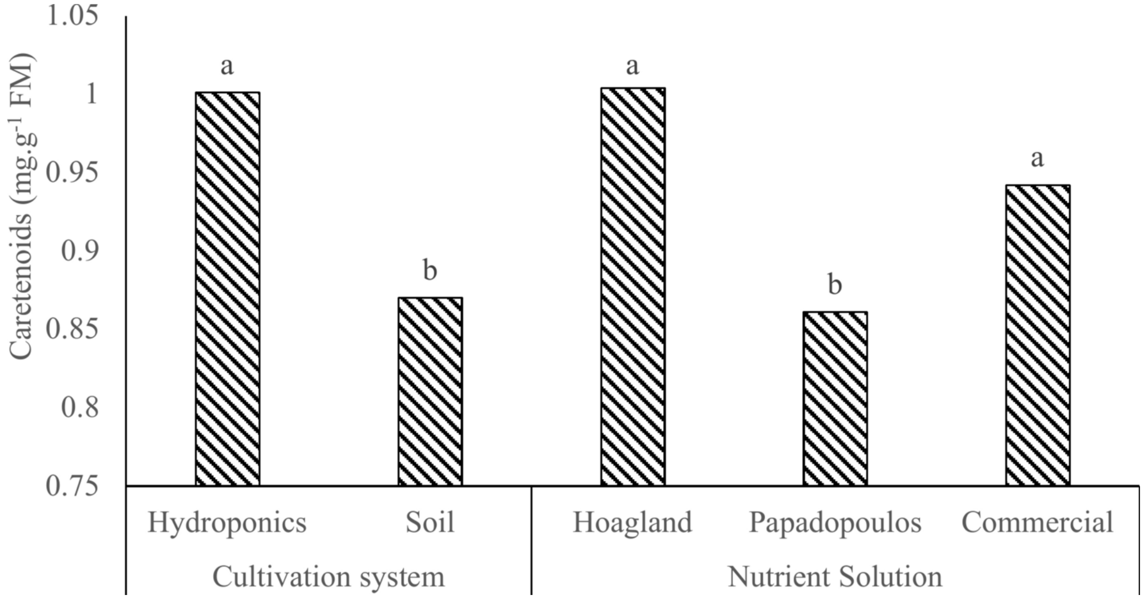

Fig. 6. Impact of the cultivation system and nutrient solution on leaf carotenoids in cucumber leaves. Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

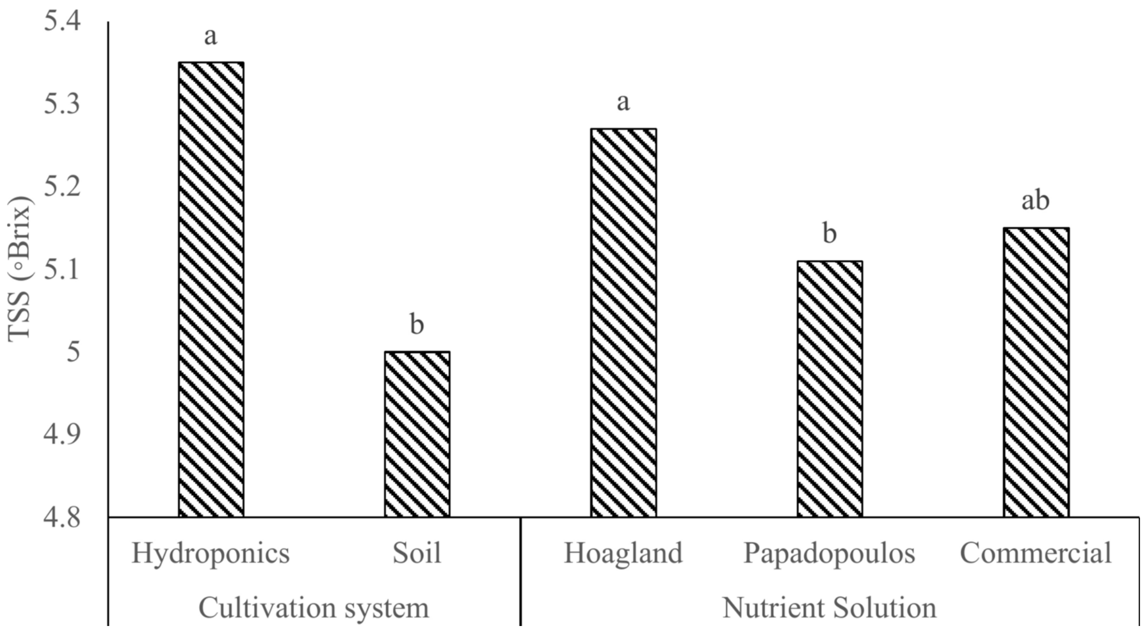

Fig. 7. Effect of cultivation system and nutrient solution on the soluble solids content of cucumber fruit. Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

Fruit color

The L* value represents the brightness and transparency of the fruit, calculating brightness from 0 for black to 100 for white. The a* value (green/red) indicates the amount of green color (-a*) and red color (+a*), while the b* value (blue/yellow) indicates the amount of blue color (-b*) and yellow color (+b*). The lowest and highest values of component a* were related to plants grown in the hydroponic and soil-based cultivation, respectively. so that the a* value in the hydroponic system increased by 16.42% compared to soil cultivation. Among the nutrient solutions, plants fed with the Hoagland nutrient solution had the lowest a* value, while those fed with the Papadopoulos and commercial nutrient solution had the highest value (Fig. 8). The highest amount of b* value in cucumber fruits grown in hydroponic cultivation with the simultaneous use of the Hoagland nutrient

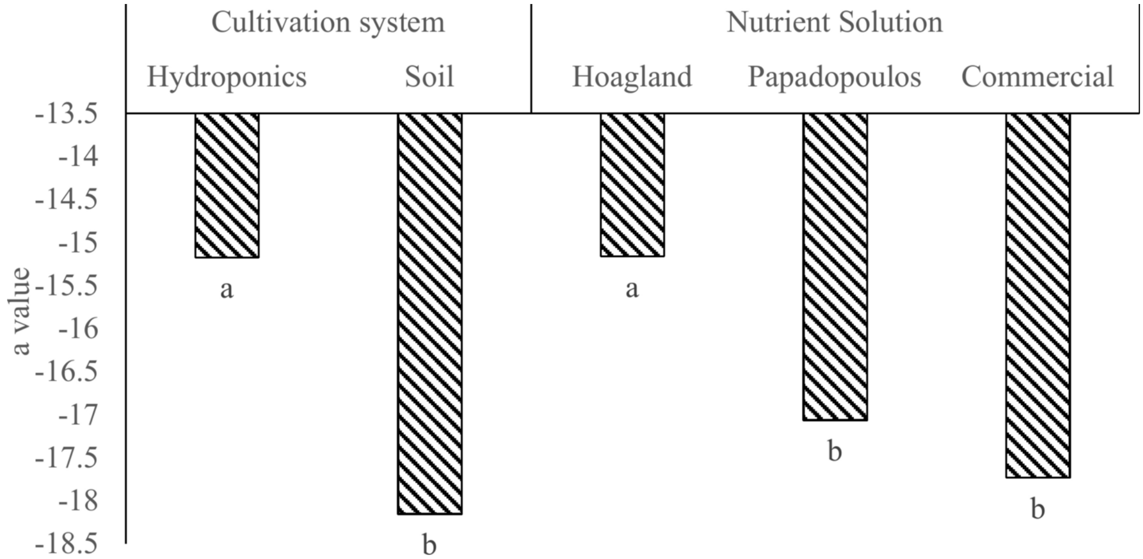

Fig. 8. Impact of cultivation system and nutrient solution on a component of cucumber fruit. Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

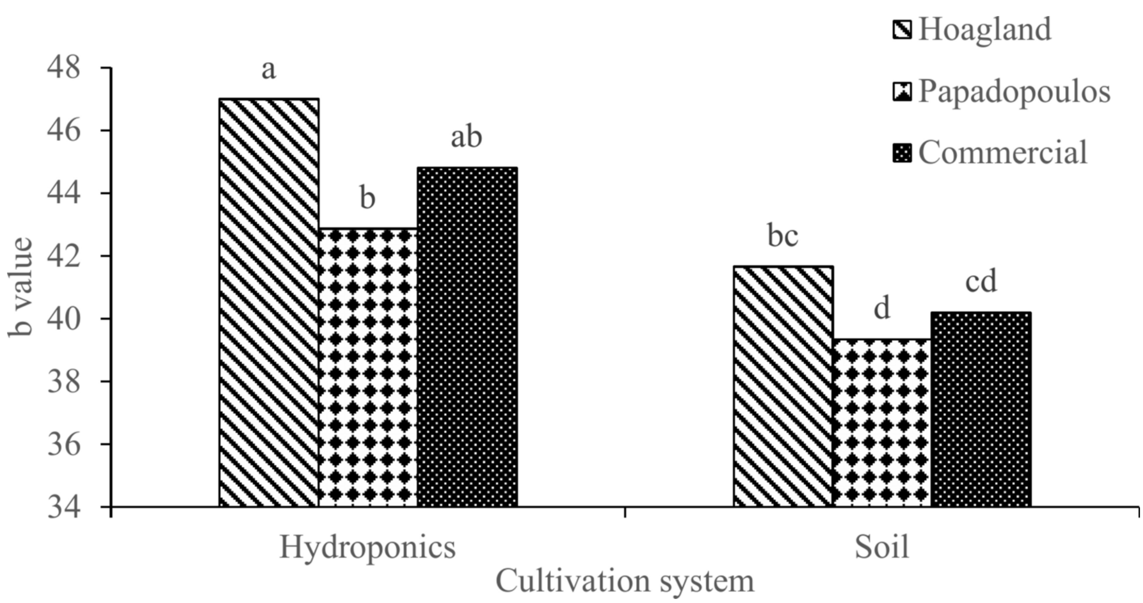

Fig. 9. The b value of fruit in the interaction of cultivation system and nutrient solution. Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

solution was observed, and the lowest amount was observed in plants grown in soil-based cultivation with the Papadopoulos nutrient solution, as the b* value of plants fed with Hoagland's solution in the hydroponic system increased by 19.44% compared to soil cultivation with Papadopoulos solution (Fig. 9). The highest value of component L* was observed in plants grown in the hydroponic medium and the lowest value in plants grown in soil-based cultivation, showing a significant difference between them. So that the L* value in the hydroponic system increased by 1.87% compared to soil cultivation. Among the nutrient solutions, plants treated with the Hoagland nutrient solution had a higher L* value, and plants treated with the Papadopoulos nutrient solution had a lower L* value. There was no difference between the commercial and Papadopoulos nutrient solution (Fig. 10).

The hue represents the intensity of color, with higher values indicating a darker fruit color. The Fruit Chroma indicates the degree of color saturation, which can vary from 1 to 60. According to Fig. 11, the highest hue angle was obtained from plants grown in the hydroponic cultivation medium, while the lowest hue angle was observed in plants grown in soil-based cultivation, as the fruit hue angle in the hydroponic system increased

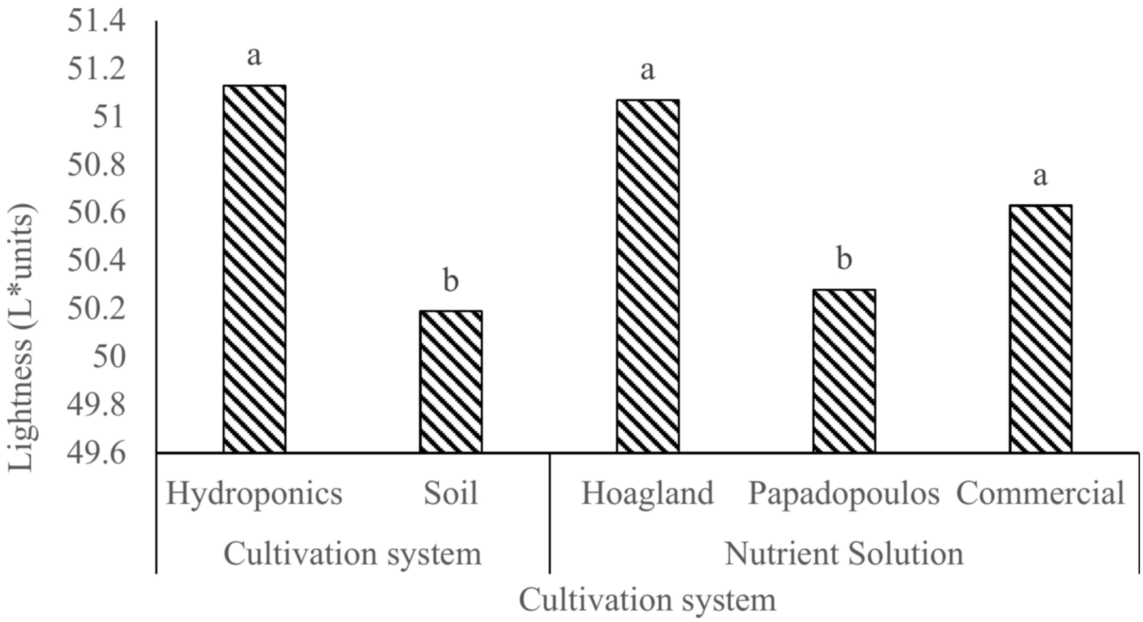

Fig. 10. The effect of the cultivation system and nutrient solution on the L component of cucumber fruit. Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

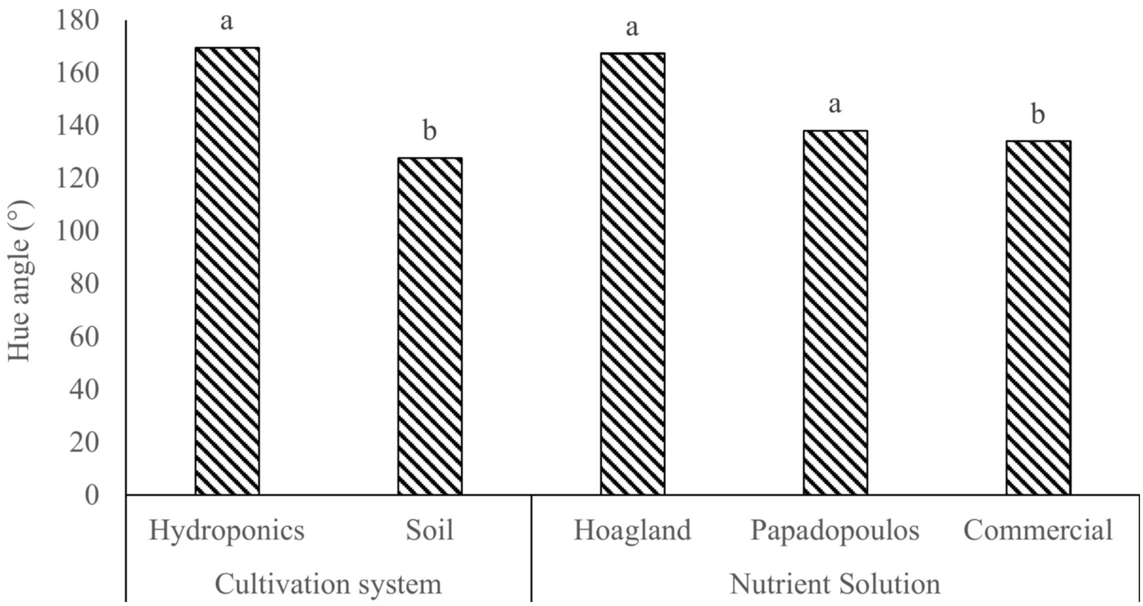

Fig. 11. Impact of the cultivation system and nutrient solution on the hue of greenhouse cucumber fruit. Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

by 32.74% compared to soil cultivation. Additionally, the Hoagland nutrient solution had the highest hue value, while the commercial nutrient solution had the lowest hue value. Furthermore, the highest chroma value was observed in plants grown in hydroponic cultivation system with the Hoagland nutrient solution and the lowest chroma value was in soil-based cultivation with the Papadopoulos nutrient solution, as the chroma value of plants fed with Hoagland's solution in the hydroponic system increased by 15.13% compared to soil cultivation with Papadopoulos solution (Fig. 12).

Vitamin C

The amount of vitamin C in cucumber fruits from plants grown in the hydroponic cultivation system was higher than in plants grown in soil-based cultivation, as the fruit vitamin C in the hydroponic system increased by

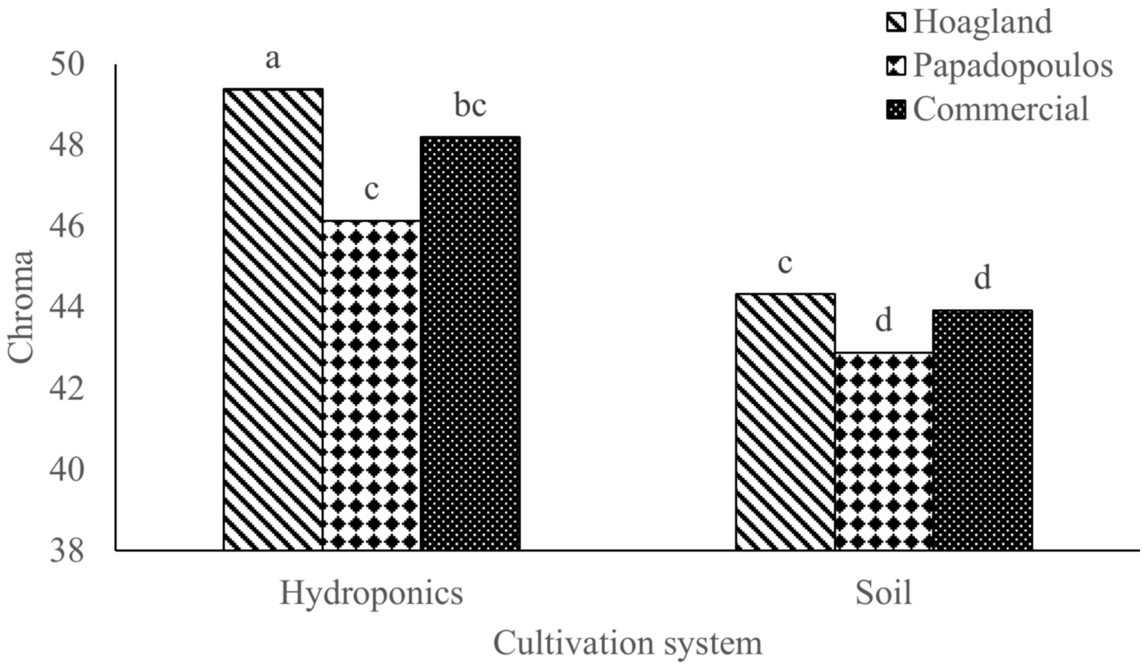

Fig. 12. Effect of the cultivation system and nutrient solution on the chroma of cucumber fruit. Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

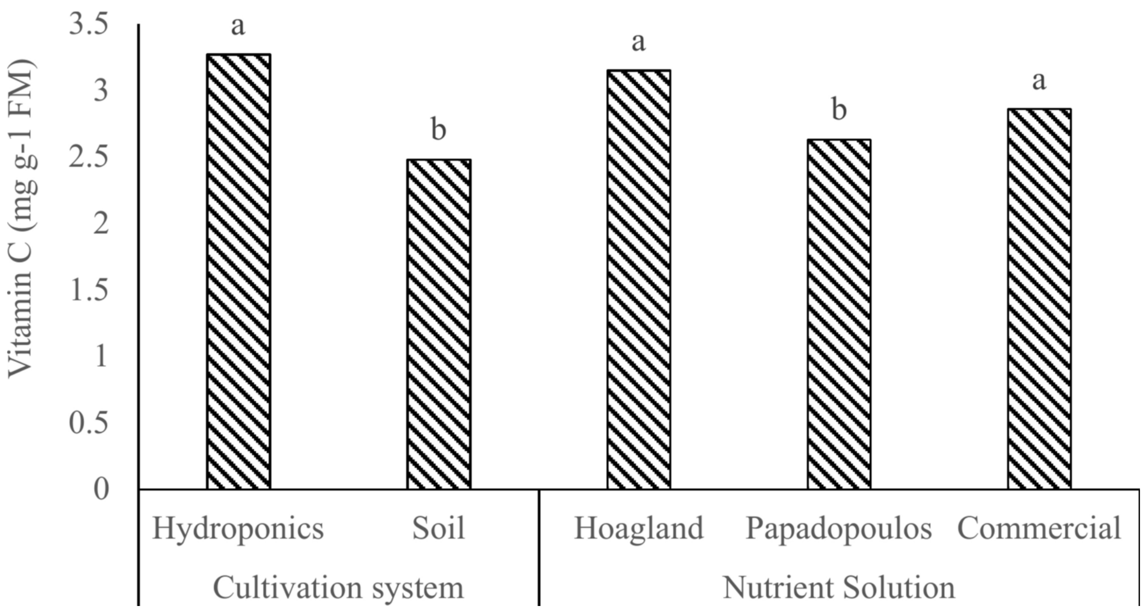

Fig. 13. The effect of the cultivation system and nutrient solution on the amount of vitamin C in greenhouse cucumber fruits Means with similar letters did not show a significant difference statistically at the 5% level in the Duncan's multiple range test.

31.85% compared to soil cultivation (Fig. 13). Fruits of cucumber plants fertigated with the Hoagland nutrient solution had the highest amount of vitamin C compared to fruits treated with the Papadopoulos nutrient solution. There was no a significant difference between the Hoagland, and commercial nutrient solutions.

Discussion

Plant growth

Awareness of favorable conditions for plant growth, such as optimal temperature, light, ventilation, variety, and soil, plays a significant role in increasing plant performance. In addition to the above conditions, the growing medium, especially in hydroponics, has a more effective role in providing favorable conditions for the growth and performance of plants. The growing medium provides a suitable environment for plants to receive water and nutrients and can also serve as suitable substrate for the spread of unfavorable factors such as soil fungi, pests, nematodes, and a seed bank rich in weeds. Due to the elimination of the mentioned unfavorable factors, the use of organic and mineral cultivation media such as perlite, leca, rice husk, peat moss, cocopeat, pomace, etc., has recently gained attention in Iran as well. One of the important solutions for achieving maximum yield in minimum time and with excellent quality is the cultivation of plants in soilless greenhouse systems. In the present study, it was found that the growth and reproductive traits of greenhouse cucumbers were influenced by the growing media, and hydroponic cultivation (cocopeat-perlite) led to an increase in growth and reproductive traits in cucumber plants compared to soil cultivation[22] reported that stem diameter and plant height of potato plants were greater in hydroponic cultivation media compared to soil-based cultivation, attributed to the better growth of seedlings in hydroponic media in terms of porosity and suitable aeration. The pH of the growing medium (5.8–6.5) in hydroponic culture was lower than soil medium (7.56), that can be part of the reason for higher growth of cucumber plants in cocopeat-perlite medium.

In a study on the effect of 8 growing media on tomatoes[23], stated that the growing medium had an impact on the growth factors of tomatoes. The study results clearly indicate that date-palm peat is an optimal choice for soilless cultivation due to its favorable physical and chemical properties, wide availability, and cost-effectiveness. The results showed that an increase in leaf number in greenhouse cucumbers in the cocopeat-perlite cultivation system was consistent with the results of Aslani et al.[24]. Plants grown in the hydroponic medium had the highest number of leaves, indicating the effective role of the hydroponic medium in providing water and nutrients, leading to better growth conditions for the plants[24]. They also reported that the dry mass of the aerial parts and fine root of potato plants in hydroponic systems was higher compared to soil-based media[25]. The effect of the cultivation system on increasing the fresh and dry masses of roots was in line with the results of Hatami et al.[26] in tomatoes, and Aghhavani Shajari et al.[27] in pepper plants.

Aslani et al.[24]demonstrated that the growing medium had a significant effect on the fresh and dry root masses. The significant porosity of perlite increases desirable root aeration and reduces water fluctuations in the root environment, maintaining water in the root environment due to its strong absorbent properties[28]. The presence of perlite along with cocopeat in the root environment contributes to an increase in drainage capacity of the medium and improvement in root aeration, which in turn played a role in increasing the wet mass of roots in the cocopeat-perlite medium. Tomatoes and cucumbers in the greenhouse had the highest wet and dry root masses in the cocopeat-perlite medium, indicating a greater effect of this medium on root mass. Proper nutrient absorption in the hydroponic system compared to soil cultivation, with improved plant photosynthesis and carbohydrate supply to the roots, played an important role in increasing leaf area by promoting better photosynthetic efficiency and root growth.

Borji et al.[20]demonstrated that the growing medium had a significant impact on the leaf area of cucumber plants. It has been reported that there is a significant difference in growth parameters such as average fruit mass, plant height, and leaf surface in perlite mixed with organic media compared to sole perlite medium[7]. The high water and nutrient retention capacity of coco peat improves growth conditions for plant growth, and can lead to an increase in plant leaf area. Adequate nutrition in the hydroponic system, along with sufficient potassium supply for improved leaf cell turgidity and leaf growth, has played an important role in increasing leaf area.

Aalaei et al.[29] compared the effects of growing media on the growth characteristics of the Persian violet flower and found the highest number of flowers in the cocopeat-perlite growing medium. Each plant requires good vegetative growth and sufficient reserves to achieve higher fruit production and appropriate fruit growth. This adequate growth will be achievable when all the physical conditions of the growing medium—such as porosity, water holding capacity, ventilation, etc. are optimal, along with its chemical conditions such as cation exchange capacity and electrical conductivity.

The present study showed that the highest reproductive traits in cucumber plants were achieved in the cocopeat-perlite cultivation system, which was consistent with Mami et al.[30] in tomatoes and Ghaimi et al.[31]in cucumbers. An increase in vegetative growth leads to an increase in the number of nodes in the plant, followed by an increase in the number of leaves, fruits, and flowers[32]. In media with higher nutrient retention capacity and higher cation exchange capacity, vegetative growth is increased[33]. The size and number of fruits determine the yield[34]. Each plant requires good vegetative growth and sufficient reserves for higher fruit production. It seems that improving the conditions of the cocopeat-perlite growing medium in the absorption and retention of essential nutrients has an effective impact on vegetative growth, which in turn affects reproductive growth and increases fruit production.

The results of this study indicate that the cultivation system has a significant impact on plant performance, which is consistent with the findings of Dalvand et al.[35]in tomatoes and Abdipour and Alamzadeh Nasiri[36]in cucumbers[23] examined the effects of 8 growing media on tomato performance and did not observe a significant difference between treatments statistically, but the highest performance was obtained from the perlite-based growing medium, and the lowest performance from the palm peat + perlite medium. It seems that growing media, with their physical, chemical characteristics, and elements, have a significant impact on plant performance, with suitable nutritional conditions and moisture in the root environment playing a critical role in enhancing performance, which is more effective in the cocopeat-perlite cultivation system than in soil cultivation.

Water and soil pollution are significant inhibiting factors in the use of chemical fertilizers in the soil8. In soilless cultivation systems, plants are fertigated through nutrient solutions made from various mineral salts, where each element quickly demonstrates its effects, so care must be taken in selecting or preparing the nutrient solution 18. The results of the current experiment showed that the application of nutrient solutions in hydroponic and soil cultivation led to an increase in growth and reproductive traits in greenhouse cucumbers. This is consistent with the findings of Ahabbi Mayan et al.[37], who demonstrated that the use of Hoagland 1, Hoagland 2, UK, and Nop nutrient solutions in soilless cultivation increased growth and reproductive traits in greenhouse bell peppers. An experiment demonstrated that by varying the nutrient concentrations of nitrogen, potassium, and calcium in the Hoagland nutrient solution, an increase in the height of green and purple basil plants was observed[38]. These results are consistent with the observations of Namatullah Thani et al.[39], who had noted changes in height with certain Papadopoulos nutrient solutions. Feizi et al.[40]investigated the effects of three nutrient solutions—Hoagland, Cooper, and England—on the performance and quality of cultivated lettuce in soilless cultivation systems. They found that nutrient solutions led to an increase in traits such as leaf area, fresh and dry mass of the plant, and number of leaves in lettuce. The increase in nutrient solution concentrations not only affected dry matter accumulation but also influenced stem diameter and plant height in potato plants[41,42], with higher stem diameters reported in hydroponic systems with increased nutrient solution concentrations compared to soil cultivation[22], that was in agreement with the findings of this study. Higher macronutrients especially N in Hoagland nutrient solution increased vegetative growth traits of cucumber in the current experiment. Delshad et al.[43]reported that the application of nutrient solutions led to an increase in dry matter in the aerial parts and roots of tomato plants. Leaf area is an important factor in plant growth, with increased leaf area leading to higher photosynthesis, carbohydrate accumulation, and optimized use of light for increased plant growth and yields[44], which aligns with the results of this study. Significant increase in leaf area with special nutrient solutions can be another reason for the increased yield. The increased leaf area of bell pepper plants in treatments with Hoagland 1, Hoagland 2, UK, and Nap nutrient solutions has been reported[37], which was consistent with the results of the present study about Hoagland nutrient solution. Najm et al.[45]reported that linearly increasing nitrogen levels led to an increase in leaf area of potato plants. As nitrogen absorption increases, it positively impacts leaf expansion and development. Nitrogen absorption also influences chlorophyll concentration, photosynthesis, leaf number, and dry matter accumulation. Therefore, nitrogen plays a crucial role in canopy development, particularly in potato plants, where it affects dry stem mass and leaf area[45], aligning with the results of this study. In the current experiment the N concentration of Hoagland nutrient solution was almost two time of two other nutrient solutions.

Phosphorus deficiency can disrupt water transfer through roots, leading to insufficient water for cell expansion, resulting in stunted leaves and hindered aerial growth[46]. An increase in ammonium concentration in nutrient solutions resulted in an increase in fruit diameter in peppers and the production of wider fruits[47]. Khezri and Tabatabai[48]observed that the England and Hoagland nutrient solutions produced higher yields in cucumbers compared to Steiners, University of Tabriz, Nop, and Holland nutrient solutions, which was consistent with the results of the present study about Hoagland nutrient solution. These differences in plant performance among different nutrient solution treatments may stem from variations in the pH and electrical conductivity (EC), and higher macronutrients concentration in Hoagland nutrient solution. In an experiment, increasing potassium concentrations from one to 12 mM in the modified Hoagland nutrient solution linearly increased total biomass, fruit number, and plant mass, with the optimal concentration for performance being 6 mM[49], which was the same concentration of Hoagland nutrient solution of the current experiment. Mardanloo et al.[50]reported that the highest performance was achieved at a potassium concentration of 300 mg.L-1 in the nutrient solution. Increased yield due to increased potassium application has also been reported in other plants[51,52]. In a soil experiment, increasing potassium levels up to 450 kg.ha-1 led to increased yields in peppers and tomatoes.

Biochemical traits

Chlorophylls are the most important group of photosynthetic pigments responsible for light absorption in chloroplasts. Young leaves have the highest chlorophyll content, which decreases with leaf aging[53]. Plant density, plant nutrition status, environmental conditions, nutrient deficiencies, and diseases are among the factors that influence chlorophyll content in leaves[54]. An increase in chlorophyll content is associated with an increase in specific leaf mass[55]. The cocopeat-perlite cultivation system has been effective in increasing the levels of chlorophyll a, b, and total chlorophyll. It seems that the better nutritional conditions in this cultivation system have influenced the increased chlorophyll content in leaves. The enhancement of photosynthetic pigments (chlorophyll a, b, and total chlorophyll) in plants from cocopeat growing media in greenhouse cucumbers[36]and cocopeat-perlite in greenhouse tomatoes[35] has been reported. In the current experiment, N and Mg concentration was higher in Hoagland nutrient solution. These two macronutrients have important role in chlorophyll synthesis, and higher chlorophyll concentration in cucumber plants treated with Hoagland nutrient solution can be related to high N and Mg in this nutrient solution.

Carotenoids are plant pigments that act as antioxidants and essential components in the photosynthetic apparatus. The amount of carotenoids in green leaves depends on various factors such as plant species, variety, production factors, diversity, maturity, and environmental conditions including temperature, light, and soil properties[56]. Plant pigments play a role not only in coloration but also in fulfilling physiological functions for plant health[57]. It is possible that the higher presence of leaf carotenoids in the cocopeat-perlite cultivation system is a result of improved root environment conditions in this medium. In a study, the effect of four growing media (cocopeat, cocopeat-perlite, bagasse, and bagasse-perlite) on the carotenoid content of tomato plant leaves was investigated, with the cocopeat growing medium having the highest carotenoid content[35]. Ahabbi Mayan et al.[37]reported an increase in leaf chlorophyll in treatments with different nutrient solutions (Hoagland 1, Hoagland 2, UK, and Nap) in pepper plants, with the highest levels observed in the Hoagland 1 nutrient solution, which was consistent with the results of the present study. They reported that the chlorophyll content in leaves of seedlings fed with nitrates was lower compared to those fed with ammonium, suggesting that the use of nitrate fertilizers as a nitrogen source may result in lower nitrogen uptake due to difficulties in assimilation, possibly leading to lower chlorophyll content. They also reported that foliar urea spray increases chlorophyll in broccoli. Nitrogen is a significant factor in chlorophyll formation, with the type of nitrogen fertilizer likely playing a role[58]. It has been reported that leaf chlorophyll content increases with nitrogen treatments[59], which aligns with the results of this study. In a study, the increase in leaf chlorophyll and carotenoids in treatments with different nutrient solutions in greenhouse basil plants (*Ocimum basilicum*L.) was reported[60]. This increase in chlorophyll has also been observed in cucumber plants, confirming this finding[61].

Fruit quality

The color of cucumber fruits is an important factor in fruit quality for consumers[62]. The amount of L*, indicating lightness and transparency of the fruit, calculates brightness from 0 for black to 100 for white, with higher values indicating more brightness in the tissue. The a* component (green/red), where (-a*) represents the amount of green color and (+a*) represents the amount of red color, and b* (blue/yellow), where (-b*) indicates the presence of blue color and (+b*) signifies the amount of yellow color. The results of the current study showed that the cocopeat-perlite cultivation system and soil cultivation had a significant impact on the visual color of the fruit (a*, b*, and L* components) and the intensity and saturation of the fruit color, with the quality parameters in plants from hydroponic systems being higher than in soil cultivation. Chroma indicates color saturation, with values ranging from 1 to 10. Hue represents the intensity of color, with higher values indicating a darker color. Ahmadi Dehaj et al.[63] obtained the highest amount of the a* component in fruit grown in tea waste growing medium. Dalvand et al.[35]studied the effects of four different growing media (cocopeat, cocopeat-perlite, bagasse, and bagasse-perlite) on the visual color of greenhouse tomato fruit (a*, b*, and L* components) and the intensity and saturation of the fruit color, showing that the highest levels of the L* component and chroma were achieved from the bagasse-perlite cultivation system, while the lowest levels were from the cocopeat growing medium. Abdipour and Alamzadeh Ansari[36]also reported the highest value of the L* component in the perlite growing medium. In an investigation of the effects of different growing media on tomato fruit quality under controlled conditions in hydroponic greenhouse systems, tomatoes grown in a perlite-zeolite (2:1) growing medium had the highest solid matter content[64].

Vitamin C in fruits is influenced by factors such as plant nutrition, water storage, and light intensity, with nutrient concentrations being another reason for increased solid matter content, which results from increased salinity leading to water non-absorption and nutrient storage[30]. Increasing sugars and organic acids in fruit contribute to improving fruit quality[65], which is consistent with the results of this study. The higher solid matter content in cucumbers from hydroponic growing media can be attributed to the presence of nutrients in these media that have played a role in increasing solid content. The levels of vitamin C in tomatoes increase during the ripening process and are influenced by environmental conditions such as light intensity and plant nutrition[63]. It has been reported that greenhouse tomatoes have lower vitamin C levels compared to open-field tomatoes, which may be attributed to lower light intensity in the greenhouse. Mami et al.[30]also stated that fruits exposed to more light have higher vitamin C levels. It has been reported that the use of different nutrient solutions (Hoagland, Steiner, Nap, England, Holland, and Tabriz University) has led to an increase in solid matter content in cucumbers, specifically in the Negin and Catherine varieties, with the Hoagland nutrient solution having a greater impact on increasing solid matter content in the fruits[66], consistent with the results of the current study. The application of nutrient solutions has resulted in increased levels of vitamin C in bell peppers[50]. In another study, Mardanloo et al.[50] showed that the highest performance and fruit quality traits were obtained in treatments with 300 and 400 $mg.L^{-1}$potassium nutrient solution, respectively. Potassium improves chemical compounds by increasing protein, starch, solid matter, and vitamin C content in fruit, extending its storage life[66]. The solid matter content in strawberry plants increases with relative nitrogen addition. There is a direct correlation between sugar concentration and nitrogen content in fruits[67]. Phosphorus is an essential and highly utilized element that plays crucial roles in plants. Zahedi Far et al.[68] reported that increasing phosphorus by 60 $mg.Kg^{-1}$of soil increased spinach yield. Generally, increasing nutrient levels in strawberry cultivation only has a positive effect on fruit quantitative and qualitative characteristics up to a certain level[69].

Conclusion

Both growth and physiological characteristics of cucumber plants were affected by culture system as well as different nutrient solution, with a significant interaction. The results of this study indicate that the use of hydroponic systems and cocopeat-perlite as growing media in greenhouse cultivation of cucumbers leads to an increase in growth characteristics such as plant height, number of nodes, number of leaves, number of lateral branches, leaf surface area, mass of fresh and dry aerial and root parts, reproductive characteristics including number of flowers, number of fruits, fruit diameter, cucumber yield per plant, and yield per hectare, biochemical traits such as photosynthetic pigments (chlorophyll a, b, and total) and carotenoids, fruit quality traits such as fruit appearance color (components a*, b*, and L*), hue, and chroma, solid matter content, as well as an increase in vitamin C in plants compared to soil cultivation. However, the highest percentage of flower drop was observed in plants from soil cultivation. Hoagland nutrient solution had a more significant impact on increasing the aforementioned traits compared to other nutrient solutions. Overall, soilless cultivation using the Hoagland nutrient solution significantly enhanced growth and yield characteristics, as well as both the quantitative and qualitative traits of the fruit and physiological characteristics, compared to the other treatment methods, therefore it is recommended to use for cucumber production in Iran greenhouses.

Data availability

The data presented in this study are available on request from the corresponding authors. The data are not public.

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Declarations

Competing interests

The authors declare no competing interests.

Ethical statement

No plants were collected in this experiment. Cucumber seeds of Nagene 792 F1 (produced by Enza Zaden Company) variety were purchased from Sepahan Rooyesh Company, Iran. In the all experiments on plants/plant parts in the present study, the use of plants complies with international, national and/or institutional guidelines.

Additional information

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