



Cultivation Possibilities for Pak Choi (*Brassica rapa* var. *chinensis*) Growing in Different Nutrient Solutions in Floating Water Culture

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Abstract: For this study, two different pak choi (*Brassica rapa* var. *chinensis*) cultivars, a standard cultivar ‘Black Summer’ and a mini cultivar ‘Little Shanghai’, were cultivated in floating water culture utilizing two different nutrient solutions. Plants were evaluated for agromorphological development, yield, leaf quality characteristics, and water consumption. The plants were grown in either Hoagland nutrient solution or Alberici nutrient solution, which has a partially reduced macroelement content. Cultivation was carried out in a greenhouse in horizontal troughs containing aerated nutrient solutions; seedlings obtained from seeds sown in a peat medium were transplanted into foam boards and floated on the nutrient solutions in the troughs. Each trough contained 11 seedlings. Air was supplied to the nutrient solution via a compressor to ensure oxygenation of the plant root zone. The seedlings, grown in the hydroponic system for one month, were harvested at a single time for subsequent measurements and analyses. According to the findings, no significant differences were observed between the two nutrient solutions. It was determined that the Alberici nutrient solution, which has a lower element concentration, but is less popular than the Hoagland solution, could be utilized as an alternative solution in hydroponic pak choi cultivation instead of the higher salts concentration Hoagland solution. In the cultivar-based evaluation, distinct genotypic differences were detected. The ‘Black Summer’ cultivar exhibited a significantly superior performance compared to the ‘Little Shanghai’ cultivar in terms of leaf area, total fresh/dry weight, plant height, and yield per unit area. On the other hand, the ‘Little Shanghai’ cultivar stood out in terms of visual quality, characterized by a higher seed emergence rate, a greater number of fresh leaves, and higher brightness and color chroma values. In conclusion, the use of Alberici nutrient solution is recommended in hydroponic pak choi production to prevent excessive fertilizer utilization, to ensure environmental sustainability, and to reduce production costs. Depending on the production targets, the use of the ‘Black Summer’ cultivar grown in Alberici nutrient solution was found to be most suitable for higher tonnage and larger leaves.

Keywords: Pak choi, hydroponic, floating water culture, nutrient solution

INTRODUCTION

In addition to yield losses and environmental constraints encountered in conventional agriculture, soilless cultivation systems, where environmental conditions such as light, temperature, and nutrients can be precisely controlled, have become central to modern Agriculture [1, 2]. Soilless cultivation is practiced in two primary forms: water culture (hydroponics) and substrate culture. While substrate culture is preferred for fruit-bearing

vegetable species in commercial production, water culture systems are utilized for leafy vegetables, medicinal and aromatic plants, and exotic greens. Water culture is implemented in various forms (e.g., static water culture, recirculating water culture, nutrient solution methods) depending on the application method of the nutrient solution to the root zone. Particularly for leafy vegetable production, aerated deep water culture (floating systems)—where plant roots develop freely in nutrient solution and are continuously aerated by air pumps—and the nutrient film technique (NFT)—where a thin film of nutrient solution flows through the root zone—emerge as highly effective and practical production models [3].

In hydroponic systems, cultivated species include lettuce and basil, as well as spinach, mint, green onion, arugula, sorrel, parsley, and cilantro. The system's ability to provide clean produce in a short duration increases the interest in cultivating greens via water culture, leading to the adoption of alternative species. In this context, species such as pak choi, mizuna, tatsoi, chives, and lamb's lettuce stand out. Among these alternative species, pak choi has recently become popular and is highly sought after, particularly by luxury restaurants.

Pak choi (*Brassica rapa* var. *chinensis*) is an annual vegetable belonging to the Brassicaceae family, originating from East Asia, and is characterized by a short growth period, rapid development, and suitability for cool climate conditions [2, 4]. In literature, it is referred to by names such as "napa cabbage," "kimchi cabbage," "Chinese cabbage," "white Chinese cabbage," or "Beijing cabbage." It generally features light green, wide-veined leaves; green or white, crunchy, wide petioles; and a loose or tight head structure. The pak choi plant is very rich in healthy compounds [5]. Its nutritional value is high due to its content of vitamins (A, K, B2, B6, B9, and C), dietary fiber, minerals such as calcium, potassium, and iron, and antioxidants [4, 6-7]. Beyond being a new vegetable species for Turkish agriculture, it possesses great production potential as an alternative green crop for soilless cultivation systems due to its clean, efficient, high-quality, short-duration production and multiple harvest possibilities.

Due to pest infestation, low plant density per unit area, dependency on climatic conditions, and a long vegetation period (2-3 months) in open-field cultivation, pak choi is commercially grown primarily in greenhouses and water culture systems. Studies on pak choi in our country are quite limited [8]. Therefore, it is necessary to establish procedures for the cultivation of pak choi, a new species for Turkey, in water culture under local conditions.

In hydroponic systems, plant physiology, growth, and harvest quality fundamentally depend on the concentration (EC) and elemental content of the applied nutrient solution [6, 7]. Plants convert these inorganic nutrients into energy throughout their life cycles, facilitating mass accumulation and biochemical development [2]. Although modified standard solutions are frequently used for plant nutrition studies in literature, the intensive use of these solutions can lead to various problems in leafy vegetables with short vegetation periods [6]. The Hoagland solution, the most widely used solution for every species in soilless cultivation, was originally prepared for fruit-bearing vegetable species. Its application to leafy vegetables results in fertilizer waste. Furthermore, nutrient solution concentration above the optimum level can lead to toxicity, osmotic stress, a decrease in photosynthesis rate, and nitrate accumulation in leaves, which poses a serious risk to human health; additionally, it causes environmental pollution as unused fertilizer becomes waste [6, 7].

To overcome such negative effects, reduce nitrate levels in leaves to safety limits for human health, and ensure sustainable and economic production, limiting and modifying nutrient solutions is a critical research topic in modern agriculture [6].

Physiological responses of different genotypes and commercial vegetable varieties to varying nutrient levels in hydroponic systems can differ [7]. Accordingly, this study aimed to cultivate two different types and varieties of pak choi, 'Black Summer' and 'Little Shanghai', in aerated static water culture using standard Hoagland nutrient solution and Alberici nutrient solution, which is recommended for leafy greens. It further aimed to determine the effects of the tested factors (solution and cultivar) on plant earliness, morphological development, yield, and quality parameters and make production recommendations as appropriate.

MATERIALS AND METHODS

The research was conducted in the educational and research greenhouses of the Department of Horticulture, Division of Protected Vegetable Cultivation, Faculty of Agriculture at Ege University (EU) located within the EU campus (Bornova/İzmir). The bitunnel greenhouse utilized in the study measured 16.5x50 m and was covered with a polyethylene (PE) plastic sheeting material. Cultivation was performed within an approximately 10 m² section of the greenhouse.

The plant material consisted of the standard cultivar 'Black Summer', characterized by normal green leaf and petiole color, and the mini cultivar 'Little Shanghai' of pak choi (*Brassica rapa* var. *chinensis*) obtained from Johnny's Selected Seed (USA). Since pak choi is an annual cool-season species with low heat tolerance, the experiment was executed during the cool climatic period, taking greenhouse indoor temperatures into consideration. Seeds of the imported cultivars were sown in 128-cell foam trays filled with a peat medium. To prevent moisture loss post-sowing, the trays were wrapped in stretch film and maintained in a dark climate chamber at 18 ± 2 °C temperature, 80% relative humidity for 3 days. At the end of this period, the stretch film was removed, the trays were transferred to the adaptation greenhouse, and the seedlings were irrigated solely from above using watering cans with rose-heads until they reached the 1-2 true leaf stage (approximately 7 days). During the seedling stage, data regarding the emergence period required for 50% seed germination (days), the emergence rate representing the percentage of sown seeds converting to seedlings (%), and the duration from seed sowing to transplanting (days) were recorded.

Seedlings with two true leaves that reached the transplanting stage were transferred to the aerated static water culture system established in the greenhouse. In this system, plants were grown on foam boards floating freely on the surface of the nutrient solution. Sixteen plastic troughs measuring 80 x 44 x 19 cm with a volume capacity of 52 liters were utilized for cultivation; each trough was filled with nutrient solution up to a height of 15 cm (40 L). Root-washed pak choi seedlings were placed into 0.5 mm planting holes opened on the foam boards. Eleven seedlings were transplanted into each trough. To ensure oxygenation of the plant root zone, an air stone was placed in the center of each trough, supplied via mini valves and aquarium hoses connected to a 5-meter-long main air hose attached to a compressor. The aeration compressor was connected to a timer set to a cycle

of 60 minutes running / 60 minutes resting. As the nutrient solution within the troughs decreased, replenishment was calculated on a volumetric basis to consistently maintain the water volume in the troughs at the 40 L level.

Two different nutrient solutions were evaluated in the experiment. Out of the 16 troughs, 8 contained the modified "Alberici greens recipe" recommended by Alberici et al. [9] for the hydroponic production of leafy greens [N:160, P:80, K:180, Ca:140, Mg:34, S:86, Fe:2.2, Mn:0.50, Zn:0.05, B:0.50, Cu:0.02, Mo:0.01 ppm]. The remaining 8 troughs received the standard "Hoagland recipe"[10] - [N:210, P:31, K:235, Mg:48.6, S:64, Fe:1, Mn:0.11, Zn:0.023, B:0.11, Cu:0.014, Mo:0.018 ppm]. Under each nutrient solution application, 4 troughs were assigned to the 'Black Summer' cultivar, and the other 4 troughs were assigned to the 'Little Shanghai' cultivar. The electrical conductivity (EC) of both recipes was adjusted to 1.8 - 2.0 dS/m and the pH values were maintained between 5.5 and 6.5. Control measurements were performed twice a week using an EC and pH meter (Mettler Toledo, Switzerland).

Throughout the research period, greenhouse indoor temperature and light intensity data were recorded at 15-minute intervals using a HOBO-Pendant-MX2202 device, while relative humidity values were monitored using a HOBO-U9 device (A Li-Cor Brand, OnSet Comp., USA).

At the end of the 30-day cultivation period in water culture, yield, growth, and quality parameters were examined in 4 randomly selected plants from each replicate (trough). The harvested plants were weighed to determine the number of unmarketable leaves (pieces), unmarketable leaf weight (g), total yield (kg/m²), and average head weight (g/plant). Canopy width (cm), canopy length (cm), leaf length (cm), leaf width (cm), petiole length (cm), stem length (cm), stem diameter (cm), and plant height from the root collar to the growing tip (cm) were measured using a ruler. The number of leaves (pieces) was determined by counting fully developed, healthy leaves. Plant diameter (cm) was measured using a caliper (Mitutoyo, Japan), and leaf thickness (mm) was measured using a micrometer (Mitutoyo, Japan). Leaf area (cm²) was calculated utilizing an image processing technique. The shoots and cleaned roots of the plants were initially weighed fresh, and then dried in an oven at 65 °C for 3 days to determine their total biomass (fresh and dry weight, g/plant).

Leaf sap was extracted from the sampled plants to measure EC (dS/m) and pH values, and the total soluble solids content (TSS, %) was determined using a digital refractometer. Titratable acidity (TA, mval/100 mL) was determined via titration with 0.1 N NaOH. Leaf color measurements (L, a*, b*) were performed using a colorimeter (CR-300 Chroma Meter, Konica Minolta, Japan). Vitamin C (mg/100 mL) [11] and nitrate content (mg/kg) [12] of the leaves were determined in fresh leaf samples using spectrophotometric methods.

The study was established according to a completely randomized experimental design with 2 factors (Factor A: nutrient solution, Factor B: cultivar) and 4 replications. The quantitative data obtained from the experiment were subjected to a one-way analysis of variance (ANOVA) in a computer environment using the JMP statistical package program. Student's t-test was employed for grouping the statistical differences between the means.

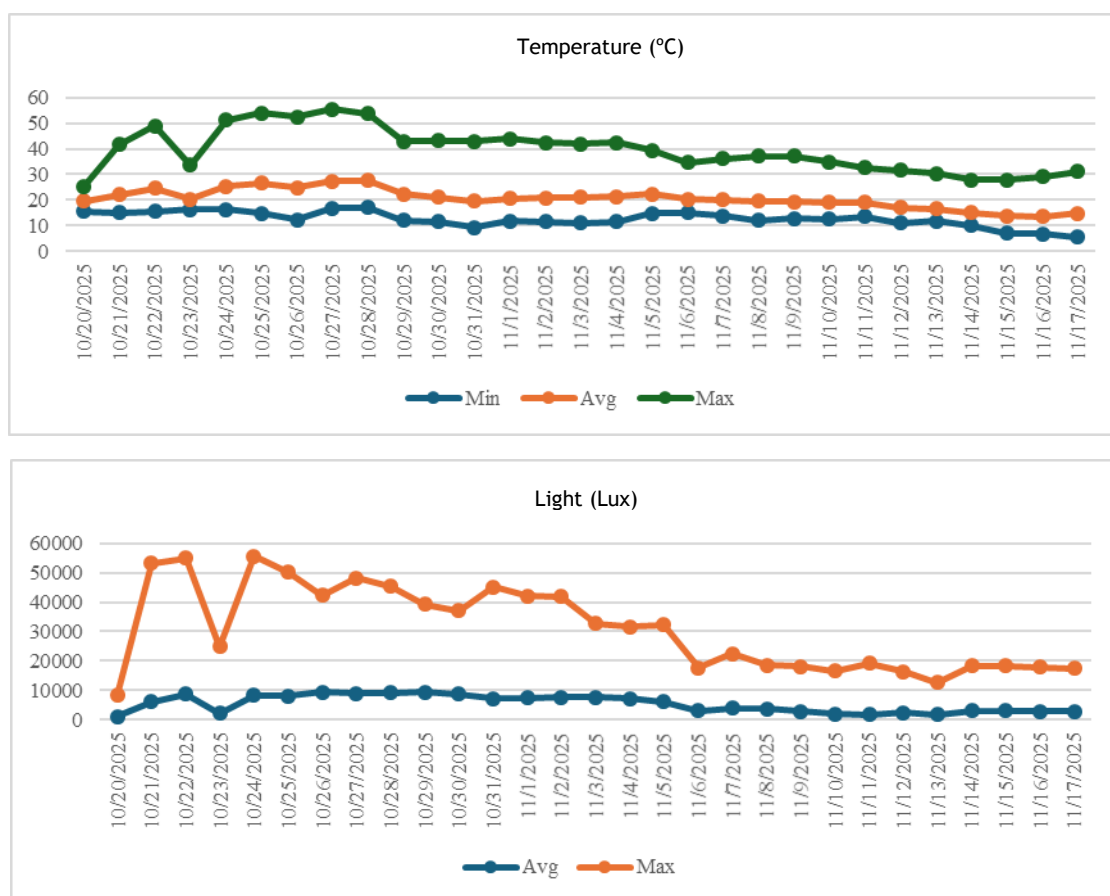
RESULTS

Germination and Seedling Emergence

The number of days required for 50% seed germination (emergence) of pak choi was determined to be 3 days across all treatments, independent of cultivar differences. The germination-emergence rates in the peat medium were determined as 85% for the 'Black Summer' cultivar and 97% for the 'Little Shanghai' cultivar. The duration from seed sowing to seedling transplanting was 6 days for both cultivars.

Greenhouse Indoor Climate Data

The graphs representing the greenhouse environmental values obtained throughout the production period are illustrated in Figure 1. The maximum temperature ranged between 30.0 °C and 56.0 °C, the minimum temperature fluctuated between 5.0 °C and 17.0 °C, and the average temperature values varied from 13.0 °C to 28.0 °C. The overall mean maximum, minimum, and average temperature values were recorded as approximately 42.0 °C, 12.0 °C, and 21.0 °C, respectively. The maximum relative humidity ranged from 64% to 100%, the minimum relative humidity ranged from 15% to 38%, and the average relative humidity fluctuated between 35% and 75%, with overall mean relative humidity values determined as 82%, 20%, and 58%, respectively. The recorded light intensity values varied between a maximum of 12.000 lux and 56.000 lux (with a mean maximum of 32,000 lux), while the average daily light intensity ranged from 1.500 lux to 9.500 lux (with an overall mean of 5.000 lux).



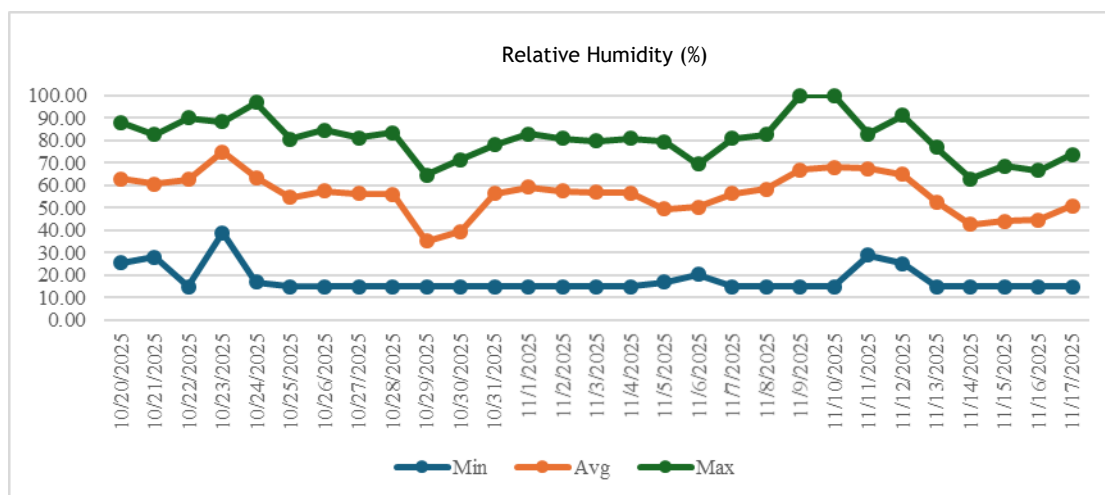


Figure 1: Greenhouse indoor climate data

Agromorphological Characteristics

The canopy width, canopy height, plant diameter, plant length, stem diameter, and stem length of pak choi plants were not significantly affected by the differences in nutrient solutions. However, cultivar variations significantly influenced canopy width, canopy height, plant diameter, plant length, and stem length, with the ‘Black Summer’ cultivar exhibiting higher values across all these measured parameters. The interaction between the nutrient solution recipes and cultivars was found to be statistically non-significant for these parameters. Although not statistically significant, the application of the Alberici nutrient solution increased canopy width, plant length, and stem diameter (Table 1).

Table 1: Effects of different nutrient solutions and cultivar applications on some agromorphological growth parameters of pak choi plants

Receipt	Cultivar	Canopy		Plant		Stem	
		width (cm)	length (cm)	diameter (mm)	length (cm)	diameter (mm)	length (mm)
Hoagland		29.58	17.18	56.52	23.92	8.84	17.92
Alberici		31.69	17.14	61.33	23.57	9.29	19.92
<i>p</i>		0.0685	0.9269	0.1029	0.6243	0.3673	0.4903
	Little Shanghai	25.66 b	12.35 b	58.15	18.26 b	8.98	15.64 b
	Black Summer	35.62 a	21.98 a	59.69	29.24 a	9.16	21.47 a
	<i>p</i>	<0.0001	<0.0001	0.5819	<0.0001	0.7211	0.0064
Hoagland	Little Shanghai	24.02	12.13	54.58	18.26	8.52	15.89
Alberici	Little Shanghai	27.28	12.56	61.72	18.26	9.43	15.39
Hoagland	Black Summer	35.14	22.24	58.45	29.59	9.16	19.96
Alberici	Black Summer	36.09	21.72	60.93	28.89	9.14	22.99
<i>p</i>		0.2916	0.3642	0.4085	0.6181	0.3413	0.3393

The effects of different nutrient solutions on the total number of leaves, single leaf width, single leaf length, petiole length, leaf thickness, and leaf area were found to be statistically non-significant. However, cultivar differences significantly affected the evaluated leaf characteristics. The ‘Little Shanghai’ cultivar resulted in a higher total number of leaves, whereas the ‘Black Summer’ cultivar exhibited significantly higher values for single leaf width, single leaf length, petiole length, and leaf area. The interaction

between the nutrient solution recipes and the cultivars was found to be non-significant for all evaluated leaf traits (Table 2).

Table 2: Effects of different nutrient solutions and cultivar applications on leaf characteristics of pak choi plants

Receipt	Cultivar	Total leaf number (no)	Leaf width (cm)	Leaf height (cm)	Petiole length (cm)	Leaf thickness (mm)	Leaf area (cm ²)
Hoagland		11.53	10.12	22.52	9.82	0.464	328.99
Alberici		11.78	10.44	22.32	9.56	0.475	319.93
<i>p</i>		0.6376	0.5928	0.7183	0.4844	0.705	0.7374
	Little Shanghai	12.56 a	8.07 b	16.83 b	6.43 b	0.446	238.98 b
	Black Summer	10.75 b	12.49 a	28.00 a	12.95 a	0.494	409.95 a
	<i>p</i>	0.0044	<0.0001	<0.0001	<0.0001	0.102	<0.0001
Hoagland	Little Shanghai	11.81 ab	7.61	16.67	6.48	0.425	236.29
Alberici	Little Shanghai	13.31 a	8.54	17.00	6.37	0.467	241.66
Hoagland	Black Summer	11.25 b	12.63	28.37	13.16	0.504	421.69
Alberici	Black Summer	10.25 b	12.34	27.63	12.75	0.483	398.21
<i>p</i>		0.0325	0.3188	0.3451	0.6900	0.2700	0.5949

Biomass

Plant biomass was significantly affected only by cultivar variations. The ‘Black Summer’ cultivar exhibited a higher biomass in terms of shoot fresh weight, shoot dry weight, dry matter content, and root fresh and dry weights compared to the ‘Little Shanghai’ cultivar (Table 3). A similar trend was observed for total plant biomass; while the differences in nutrient solutions did not significantly influence total fresh and dry weights, cultivar differences had a significant effect, with ‘Black Summer’ achieving higher total biomass. Under the interaction effect, the Hoagland x ‘Black Summer’ combination produced the highest biomass, which was followed by the Hoagland x ‘Little Shanghai’ combination within the same statistical group (Figure 2).

Table 3: Effects of different nutrient solutions and cultivar applications on the biomass of pak choi plants

Receipt	Cultivar	SHOOT			ROOT		
		Fresh Weight (g/plant)	Dry Weight (g/plant)	Dry Matter (%)	Fresh Weight (g/plant)	Dry Weight (g/plant)	Dry Matter (%)
Hoagland		164.99	6.918	4.18	9.22	0.481	5.212
Alberici		166.66	6.515	3.89	10.42	0.526	5.08
<i>p</i>		0.9204	0.4402	0.3396	0.3167	0.4033	0.6187
	Little Shanghai	126.68 b	4.590 b	3.71 b	8.39 B	0.412 b	4.95
	Black Summer	204.97a	8.843 a	4.36 a	11.24 a	0.595 a	5.34
	<i>p</i>	0.0005	<0.0001	0.0417	0.0286	0.0047	0.1644
Hoagland	Little Shanghai	115.38	4.390	3.90	7.30	0.376	5.16
Alberici	Little Shanghai	137.99	4.790	3.52	9.48	0.447	4.74
Hoagland	Black Summer	214.59	9.447	4.46	11.13	0.585	5.26
Alberici	Black Summer	195.34	8.240	4.27	11.34	0.606	5.42
<i>p</i>		0.2274	0.138	0.745	0.4056	0.6484	0.288

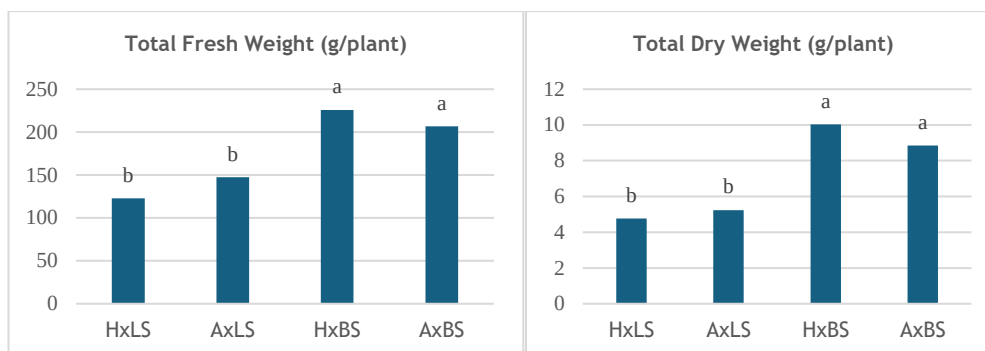


Figure 2: Effects of different nutrient solutions and cultivars on the total fresh and dry weights of pak choi plants at harvest. (HxLS - Hoagland ‘Little Shanghai’, AxLS - Alberici ‘Little Shanghai’, HxBS - Hoagland ‘Black Summer’, AxBS - Alberici ‘Black Summer’)

Yield Parameters

The nutrient solution utilized significantly affected the number of unmarketable leaves, whereas cultivar variations significantly influenced head weight, yield per unit area, and the number of unmarketable leaves (Table 4). Although not statistically significant, the application of the Alberici nutrient solution increased plant yield. Among the cultivars, ‘Black Summer’ exhibited higher yield values and a lower number of unmarketable leaves. Under the interaction effect, total yield values ranged between 3.67 and 6.32 kg/m², with the highest value determined in the Alberici nutrient solution x ‘Black Summer’ cultivar combination. This was followed by the Hoagland x ‘Black Summer’ combination, which was placed within the same statistical group. The number of unmarketable leaves was found to be highest in the Hoagland nutrient solution ‘Little Shanghai’ cultivar combination (Table 4).

Table 4: Effects of different nutrient solutions and cultivar applications on yield parameters of pak choi plants

Receipt	Cultivar	Total weight (g/plant)	Total yield (kg/m ²)	Number of discarded leaves (no)	Weight of discarded leaves (g)
Hoagland		146.01	4.56	2.7 a	4.76
Alberici		175.13	5.47	2.2 b	4.45
<i>p</i>		0.0885	0.0885	0.0311	0.631
	Little Shanghai	132.70 b	4.15 b	2.9 a	4.99
	Black Summer	188.44 a	5.88 a	1.9 b	4.19
	<i>p</i>	0.0040	0.0040	0.0001	0.1709
Hoagland	Little Shanghai	117.51 c	3.67 c	3.4 a	5.56
Alberici	Little Shanghai	147.88 bc	4.62 bc	2.5 b	4.42
Hoagland	Black Summer	174.50 ab	5.45 ab	2.0 bc	3.89
Alberici	Black Summer	202.38 a	6.32 a	1.8 c	4.48
<i>p</i>		0.9381	0.9381	0.1058	0.1421

Quality Parameters

The effects of the treatments on the leaf sap EC, pH, TSS, TA, vitamin C, and nitrate content of pak choi plants were found to be statistically significant for certain parameters. The

nutrient solution utilized significantly influenced the leaf sap pH value, whereas cultivar variations significantly affected the total soluble solids content (TSS) (Table 5). The highest leaf sap pH was recorded in the Alberici nutrient solution, while the 'Black Summer' cultivar achieved the highest TSS values. Furthermore, the interaction effect was found to be statistically significant for TSS and Vitamin C values. The combination of both nutrient solutions with the 'Black Summer' cultivar resulted in higher TSS and Vitamin C content. Although not statistically significant, the application of the Alberici nutrient solution increased the amount of Vitamin C and reduced nitrate accumulation in the leaves.

Table 5: Effects of different nutrient solutions and cultivar applications on some quality parameters of pak choi plants

Receipt	Cultivar	EC (mS/cm)	pH	TSS (%)	TA (mval/100 mL)	Vitamin C (mg/100 g)	NO ₃ (mg/kg)
Hoagland		1.28	6.24 a	2.76	1.43	26.34	682.70
Alberici		1.12	5.97 b	2.72	1.61	27.68	645.79
<i>p</i>		0.1379	0.039	0.7886	0.2844	0.0972	0.5834
	Little Shanghai	1.24	6.12	2.57 b	1.55	26.4	643.14
	Black Summer	1.16	6.11	2.91 a	1.48	27.63	685.34
<i>p</i>		0.4314	0.9314	0.0296	0.675	0.124	0.5316
Hoagland	Little Shanghai	1.30	6.30	2.50 b	1.46	25.98 b	659.93
Alberici	Little Shanghai	1.17	5.93	2.65 ab	1.65	26.70 ab	626.35
Hoagland	Black Summer	1.25	6.22	3.03 a	1.40	26.81 ab	705.46
Alberici	Black Summer	1.07	5.99	2.80 ab	1.46	28.55 a	665.22
<i>p</i>		0.8102	0.5877	0.1954	0.9401	0.5068	0.9603

The nutrient solutions utilized did not create a significant difference in the leaf blade color values. However, cultivar variations significantly influenced leaf lightness (L*), greenness (a*), yellowness (b*), color saturation (Chroma, C*), and hue angle (h°); the 'Little Shanghai' cultivar exhibited lighter and more saturated green leaves. The interaction between the nutrient solution and the cultivar was also found to significantly affect the color parameters. The 'Little Shanghai' cultivar achieved higher color values under both nutrient solution applications (Table 6).

Table 6: Effects of different nutrient solutions and cultivar applications on leaf colour parameters of pak choi plants

Receipt	Cultivar	Leaf Colour					
		L*	a*	b*	a*/b*	h°	C*
Hoagland		39.20	-13.44	17.94	-0.76	142.68	22.43
Alberici		37.83	-13.02	17.26	-0.77	142.52	21.64
<i>p</i>		0.3086	0.1838	0.2432	0.8043	0.7635	0.2098
	Little Shanghai	40.56 a	-15.45 b	21.77 a	-0.71 a	144.64 a	26.70 a
	Black Summer	36.46 b	-11.02 a	13.43 b	-0.82 b	140.56 b	17.37 b
<i>p</i>		0.008	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Hoagland	Little Shanghai	39.94 a	-15.52 b	22.02 a	-0.70 a	144.81 a	26.94 a
Alberici	Little Shanghai	41.19 a	-15.37 b	21.53 a	-0.71 a	144.47 a	26.46 a
Hoagland	Black Summer	38.47 a	-11.35 a	13.86 b	-0.82 b	140.57 b	17.92 b
Alberici	Black Summer	34.47 b	-10.68 a	12.99 b	-0.82 b	140.55 b	16.82 b
<i>p</i>		0.0647	0.3843	0.7379	0.7325	0.7311	0.6148

Water Consumption

Throughout the production period, a total of 65 L of nutrient solution was uniformly supplied to each of the cultivation troughs. At the end of the production period, the volume of nutrient solution discharged from the troughs ranged between 30.04 and 45.50 L. On average, 25.3 L of the applied nutrient solution was consumed by the 'Little Shanghai' cultivar, and 30.4 L was consumed by the 'Black Summer' cultivar; consequently, 39.7 and 34.6 L of nutrient solution were discharged from the troughs for the 'Little Shanghai' and 'Black Summer' cultivars, respectively. Plant water consumption was not significantly affected by the differences in nutrient solutions, but it was significantly influenced by cultivar variations. While the 'Black Summer' cultivar consumed 3.48 L of nutrient solution per plant, the water consumption of the 'Little Shanghai' cultivar was 19.3% lower. Depending on the water consumption values, the ratio of discharged nutrient solution was also significantly affected by cultivar differences. Of the total applied nutrient solution, 61.0% was discharged in the 'Little Shanghai' cultivar, whereas 53.2% was discharged in the 'Black Summer' cultivar. Water use efficiency (WUE) was not significantly affected by the main effects of cultivar or nutrient solution. However, under the interaction effect, plant water consumption, the ratio of discharged solution, and water use efficiency exhibited statistically significant differences. The Alberici nutrient solution x 'Black Summer' cultivar combination achieved the highest water consumption and water use efficiency, while exhibiting the lowest ratio of discharged solution (Table 7).

Table 7: Effects of different nutrient solutions and cultivar applications on nutrient solution consumption and WUE values of pak choi plants

Receipt	Cultivar	Plant water consumption (L/plant)	Drained ratio (%)	WUE (kg/m ³)
Hoagland		3.02	58.14	53.32
Alberici		3.27	56.15	47.78
<i>p</i>		0.2527	0.5403	0.1644
	Little Shanghai	2.81 b	61.04 a	54.20
	Black Summer	3.48 a	53.24 b	46.90
	<i>p</i>	0.0069	0.0296	0.075
Hoagland	Little Shanghai	2.75 b	61.89 a	42.44 b
Alberici	Little Shanghai	2.87 b	60.20 ab	51.36 ab
Hoagland	Black Summer	3.29 ab	54.39 ab	53.12 ab
Alberici	Black Summer	3.66 a	52.09 b	55.29 a
<i>p</i>		0.5564	0.9250	0.3853

EC and pH Value of Nutrient Solution

Throughout the production period, the measured electrical conductivity (EC) values of the nutrient solutions ranged between 1.59 and 2.37 dS/m, with an average of 2.05 dS/m in the Hoagland solution. In the Alberici solution, the EC values fluctuated between 1.00 and 1.94 dS/m, averaging 1.59 dS/m. Regarding the pH values of the nutrient solutions, the Hoagland solution exhibited a maximum pH of 8.08, a minimum of 6.28, and an average of 7.28. Meanwhile, the Alberici solution reached a maximum pH of 7.59, a minimum of 6.34, and maintained an average pH of 6.93 (Figure 5).

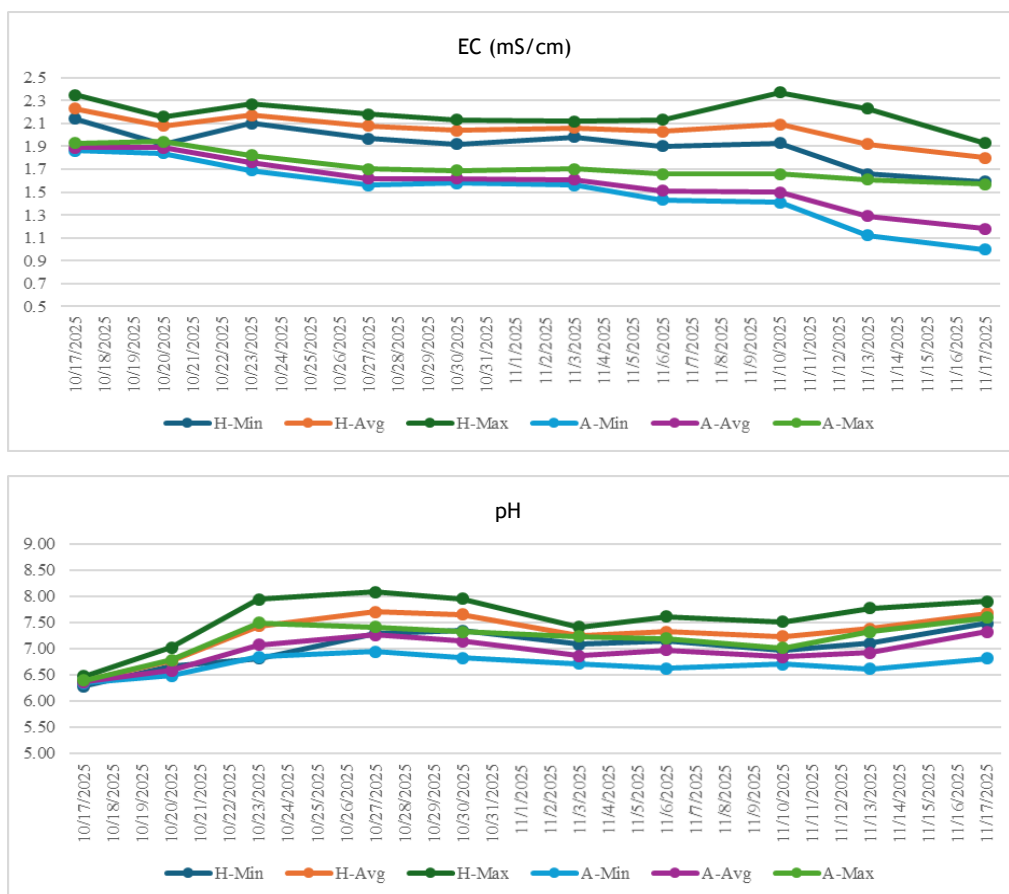


Figure 1: Effects of different nutrient solutions and cultivar applications on changes in nutrient solution EC and pH values of pak choi plants throughout the production period. (H - Hoagland, A - Alberici)

DISCUSSION AND CONCLUSIONS

In this study, the effects of different nutrient solutions (Hoagland or Alberici) on the agromorphological characteristics, yield, quality, and plant water consumption of two different pak choi cultivars ('Little Shanghai' and 'Black Summer') grown in an aerated static water culture system were investigated. Pak choi is a cool-season annual vegetable that exhibits optimum growth at day temperatures of 20-25 °C and night temperatures of 10-18 °C [6, 13]. In this 1-month water culture cultivation, the indoor greenhouse average temperature was recorded as 21 °C and the relative humidity was 58%, both of which were found suitable for pak choi cultivation. Indeed, Park et al. [13] achieved high biomass in a climate-controlled vertical soilless cultivation system under a 23±1 °C day and 18±1 °C night temperature regime. Those researchers determined the average relative humidity as 60±10%. Similarly, Zou et al. [14] stated that the relative humidity for pak choi should ideally range between 65% and 85%. Although pak choi prefers full sunlight, it is a vegetable that can tolerate partial shading [15]. In the current study, the average indoor light intensity was 5.400 lux, which was sufficient for pak choi cultivation. Supporting this data, Frede et al. [16] and Park et al. [13] identified ambient light intensities of 80 μmol/m²s to 120 μmol/m²s (corresponding to approximately 4.571-6.857 lux) in their studies. Previous literature confirms that the cultivation period chosen here was highly favorable for pak choi production.

Compared to conventional open-field cultivation, this soilless cultivation study provided significant earliness. Sowing pak choi under open-field conditions, Wu et al. [15] reported a duration of 68 days from seedling transplanting to harvest. In our hydroponic study, however, the period required for the plants to reach harvest maturity was only 30 days from transplanting. Thus, a 38-day earliness was achieved through soilless cultivation. Supporting this finding, various studies conducted with different leafy vegetable species in water culture have demonstrated that soilless cultivation provides substantial earliness compared to soil-based cultivation [17-19].

Although no statistically significant difference was observed between the tested nutrient solutions, the Alberici application numerically increased total yield and certain plant growth parameters. The Alberici nutrient solution has a reduced content compared to the Hoagland solution, particularly in terms of N, K, and Mg. Setiawati et al. [1] indicated that a reduced use of inorganic fertilizers provides adequate nutrition without inhibiting plant morphogenesis, which is highly critical for sustainable agriculture and minimizing environmental impacts. Furthermore, the Hoagland solution was originally designed by Dennis R. Hoagland and Daniel I. Arnon specifically to optimize tomato cultivation [10]. From this perspective, it is thought to exhibit lower performance in leafy vegetables. For these reasons, the reduced Alberici recipe is recommended for hydroponic pak choi cultivation. Ding et al. [6] showed that as the ambient nutrient concentration (EC) increases beyond what is required, nutrient absorption can become difficult; the accumulation of high elemental concentrations in the root zone without being fully consumed can cause osmotic and salinity stress, thereby inhibiting the development of leafy vegetables. This phenomenon explains why the higher fertilizer input provided by the standard Hoagland solution in the present study did not yield an extra increase in plant growth and yield, and even partially suppressed the yield. Consequently, the higher EC values measured in the Hoagland nutrient solution further corroborate this result. This situation was also documented by Oliveira et al. [7], who revealed that the growth and physiological responses of different genotypes to hydroponic conditions and varying EC levels differ significantly.

Considering the solutions discharged from the troughs at the end of production, it is suggested that excessive fertilizer application can induce environmental pollution. Therefore, research on eco-friendly nutrient management in water culture systems is of paramount importance.

The different pak choi cultivars grown in the hydroponic medium significantly influenced plant morphology and yield. When compared to 'Little Shanghai', the 'Black Summer' cultivar was placed in a statistically superior group regarding total fresh/dry weight, canopy width, and yield per unit area. This distinct variation stems from the differing morphological structures of the two plant cultivars; while 'Black Summer' is a standard-sized cultivar, 'Little Shanghai' is a mini-type cultivar. Conversely, the 'Little Shanghai' cultivar excelled in leaf number and visual quality values such as color lightness and saturation. Previous studies [15] have similarly demonstrated that different genotypes significantly affect yield and plant development.

In conventional soil-based agriculture taken as a standard reference, pak choi yield generally remains around 1.64 kg/m² [20]. Da Silva [21], in a mulching application study, stated that the use of mulch in the open field significantly increased yield, reaching 6.37 kg/m² in the mulched plot compared to 6.21 kg/m² in the unmulched plot. Oliveira et al.

[7], in a study comparing different hydroponic systems, determined the yield per plant as 228.45 g/plant. Chu et al. [22] recorded a yield of 2.65 kg/m² in an aeroponic system. In our study, yield values ranged between 3.67-6.32 kg/m² and 117.5-202.4 g/plant. Compared with earlier literature, these results show a lower head weight per plant but a higher total yield per unit area. It should be noted that the obtained yield values can vary depending on the cultivation period, the plant type and cultivar grown, planting density, and harvest time.

When examining the visual quality and color values (L^* , a^* , b^*) of pak choi grown in soilless culture systems, Oliveira et al. [7] found that different electrical conductivity (EC) levels did not create a statistically significant effect on leaf color parameters. Zheng et al. [23] determined that leaf color and pigmentation depend more on the applied light quality and cultivar genetics than on nutrient concentration. The color results obtained in our study demonstrate that the eco-friendly Alberici solution with reduced fertilizer content does not adversely affect the visual market quality of the plant; color and quality variations were driven by cultivar differences rather than high EC values linked to nutrient solutions.

Under greenhouse conditions without supplemental lighting, the vitamin C (ascorbic acid) content of pak choi was measured at levels around 0.2 mg/g fresh weight (approximately 20 mg/100 g) [23]. Ding et al. [6], investigating the effects of different EC levels in a hydroponic system, noted that vitamin C ranged within the 0.71 to 0.82 mg/g fresh weight band at optimum EC levels (1.8-2.4 dS/m). In the current study, the vitamin C content of the pak choi plants varied between 25.98 and 28.55 mg/100 g, which was aligned with standard values under greenhouse conditions. Moreover, the Alberici solution, which features lower elemental concentrations and lower EC values, did not lower the vitamin C accumulation of the plant compared to the intensive Hoagland solution; instead, it appeared to cause a partial increase in nutritional quality.

Among the critical quality criteria determining the flavor of pak choi leaves are TSS, TA, EC, and pH values. In this study, only the pH value was influenced by the nutrient solution concentration difference, whereas the TSS value was affected by cultivar variations. The TSS value, which has a major impact on taste, was affected by the concentration of the nutrient solution in a previous study [6] and decreased significantly due to accelerated respiration rates and osmotic stress as the EC value rose. Similarly, Oliveira et al. [7] confirmed this result. The absence of such a difference in our study is attributed to maintaining the EC levels of the utilized nutrient solutions within the optimum range. The variation was directly induced by the genotype, and the 'Black Summer' cultivar was found to be superior in terms of flavor characteristics.

From a food safety perspective, nitrate accumulation is one of the most critical quality criteria in leafy vegetables. The European Commission Regulation (No: 1258/2001) established the maximum limit for greens in fresh consumption as 3,500 mg/kg [24]. Ding et al. [6] found the leaf nitrate content in pak choi to range between 297 and 1,250 mg/kg, noting that as the nutrient solution EC and nitrogen concentration increased, nitrate accumulation in pak choi leaves rose drastically, lowering food quality. Shang and Shen [25] found the nitrate content of pak choi leaves to be 380-600 mg/kg, while Chen et al. [26] found it between 1,100 and 2,700 mg/kg. The leaf nitrate contents obtained in our study were well below the threshold values specified in the European Commission Regulation and were compatible with previous literature. In the Hoagland solution, where the nutrient concentration was higher, the leaf nitrate content was found to be partially higher than

that of pak choi leaves grown in the more dilute Alberici solution, although this difference was statistically non-significant. These results demonstrate once again that leaf nitrate content varies depending on cultivation conditions, growing season, and cultivar.

In closed-system soilless pak choi cultivation, water consumption per plant ranged between 0.95 and 2.8 L, saving up to 74% of total water compared to conventional cultivation, with water use efficiency reaching levels of 63.8 g/L in these systems [22]. The water consumption and WUE values obtained in our study were found to be consistent with this previous work.

Accurate adjustment of the EC ($1.8\text{--}2.0 \pm 0.2$ dS/m) and pH (5.5–6.5) values of the nutrient solution in closed soilless farming systems is of great importance, especially in greens cultivation [27]. For optimum development, flavor components, and low nitrate content in pak choi cultivation, the EC of the nutrient solution should range between 1.8 and 2.4 dS/m [6]. Taste quality can be negatively affected by an increase in the EC level [6–7]. In this research, the EC value changes and mean values of both tested nutrient solutions were found suitable for pak choi cultivation. However, due to its inherently lower formulation content, the EC values in the Alberici recipe ran lower than those in the Hoagland recipe. It is concluded that this partially lower EC level is more appropriate for high biomass and yield in pak choi plants.

When evaluating all data obtained from the research, it is clear that nutrient solution optimization and cultivar selection have substantial effects on plant development. According to the experimental data, considering the economic dimension for commercial production, the Alberici x ‘Black Summer’ combination is recommended due to the prominent higher yield and biomass value of the ‘Black Summer’ cultivar and the lower input costs of the Alberici solution.

The reduced-content Alberici solution is not yet seen as a mainstream application as widespread as Hoagland in literature. However, its use as an alternative to standard recipes in hydroponic production offers an eco-friendly solution to prevent fertilizer waste and protect groundwater. Yet, considering that the genetic structures of plants and climatic conditions vary, it is certain that the nutrient response of every cultivar will not be identical. Therefore, it is suggested to expand this study through future research conducted in different seasons (summer/winter) and with varying levels of EC doses.

Declaration

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