TRANSACTIONS ON SCIENCE AND TECHNOLOGY

Efficacy of Column Hydroponic System for Increasing Growth and Yield of Pak-choy (*Brassica rapa* L.) per Unit Area

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ABSTRACT Increasing the domestic production of *Brassica* vegetables is important to sustain the local food supply, maintain the healthy diets of the population, reduce the country's foreign exchange, and improve the local economy. In this study, a column hydroponic system (CHS) of 1.2 m L × 1.2 m W × 1.5 m H was built and tested to increase *Brassica* vegetable production per unit area. There were 16 rectangular polyvinyl chloride tubes (10.2 cm L × 5.1 cm W × 1.5 m H) positioned upright (PVC columns) at 30.0 cm apart in four rows. Each column had 36 planting cups (4 lines × 9 levels). The seeds of curly dwarf Pak-choy were germinated on mop yarns in the cups. The nutrient solution was supplied using a 0.5HP non-submersible pump. Data were recorded on day 37 by measuring the vegetable yield, development, growth, and quality. The data were analyzed using Microsoft Excel®2019 by performing one- and two-way ANOVAs, followed by post-hoc tests (α = 0.05). The vegetable yield/area of the CHS (12.7 kg/m^2, or 400 plants/m^2) was 60% higher than that of a raft hydroponic system (5.1 kg/m^2, or 63 plants/m^2), but the mean weight/plant was 62% lower than that of the latter system (31.3 g/plant vs. 82.1 g/plant). There were statistically significant ($P < 0.05$) effects of column horizontal position (CHP) or vegetable vertical location (VVL) on the parameters studied. However, the effects of CHP × VVL was statistically significant only on yield and leaf area. Pak-choy in outer columns facing the morning and afternoon sunlight directly or at the top were heavier (39.2 - 71.7 g/plant) than those in inner columns or at the bottom (8.8 - 20.3 g/plant). The CHS can be used effectively to increase *Brassica* vegetable production/area, but its full potential is yet to be achieved. Research is recommended to determine the ideal column spacing to achieve the best balance between plant/area and weight/plant to increase further the system's growth, yield, and quality of vegetables.

KEYWORDS: *Brassica rapa* L.; vegetable growth and yield; vertical farming system; column culture; hydroponics.
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Original Article

INTRODUCTION

Brassicas, a group of leafy vegetables native to China, have become important diets in the world. The demand is high, especially in the cities where the Asian population is significant (Tay & Toxopeus, 2016). The global import value of cabbages and other brassicas in 2018 was USD1.87B (Anonymous, 2018). The USA were the leading importers (USD332.83–389.02M), followed by Canada (USD314.88–328.19M), Hong Kong (USD223.35M), Germany (USD180.71–195.96M), and Vietnam (USD103.39M). Malaysia was six or eight globally with USD67.71M (Anonymous, 2018; FAO, 2018). Specifically, RM87.0M (USD20.19M) worth of *Brassica rapa* L., or Pak-choy, were imported to Malaysia to meet this variety's demand (FAMA, 2017). In Sabah, vegetable imports, including Pak-choy were RM149.0M (USD34.57M) (DOA, 2016). *Brassica* vegetables are known to be important for a healthy diet. A 100-g raw flesh of Pak-choy contains water, vitamin, energy, carbohydrate, protein, sugar and various minerals (USDA, 2019). *Brassica* vegetables also produce anticarcinogenic and antioxidant compounds (Park *et al*., 2014). Consuming these vegetables will lead to glucosinolate digestion and absorption into our system (Barba *et al*., 2016). The breakdown products of glucosinolates will block mutagenic or genotoxic effects in living cells (Soundararajan & Jung, 2018), leading to a general improvement of one's health condition. Considering the above factors and the impact of the Covid-19 pandemic, it is increasingly important to improve the domestic production of *Brassica* vegetables. The improvement will sustain the local food supply, maintain a healthy diet of the people, enhance the economy, and balance the foreign exchanges.

The production of leafy vegetables per unit area can be intensified using hydroponics in particularly the vertical models (Eigenbrod & Gruda, 2015). There are various structural designs available around the world, from the pyramid (PHS), suspended grow-bag, stacked (SHS) to column (CHS) models (Liu *et al*., 2004; Hayden, 2006; Neocleous *et al*., 2010; Mahdavi *et al*., 2012; Touliatos *et al*., 2016), or to plant factory concept (Kozai, 2018). Also, the nutrient solution is supplied in various ways, such as the nutrient film (NFT), raft or deep-water culture and its deep flow variation (RHS or RHT), wick (WS), ebb and flow or ebb flood and flood drain (EBBF), drip, which is almost similar to fertigation system, and aeroponic techniques. The systems can also be combined with fish farming, which is called aquaponics. Of the various models, the CHS is of particular interest because the vegetables are cultivated on upright polyvinyl chloride tubes (PVC columns), allowing the plant to be cultivated in four lines rather than in one line per tube as in PHS and SHS. In CHS, vegetable number/area is increased by lowering the land area/column. In the vegetable industry, however, the leafy vegetable yields in PHS, SHS and CHS are seldom compared, except for a few studies (Liu *et al*., 2004; Touliatos *et al*., 2016), and less attention is given to yield/area as a basis to choose the best system. Little biological or technical information is available about CHS in the literature. This situation leaves local farmers to select the model introduced to them first, for example, the readily available model, namely the SHS. Farmers also select it based on personal liking, where a few of them prefer NFT rather than RHT. Since RHT cannot be used in CHS, the choice can only be either PHS or SHS, which means the selection has not been based on the system with the best yield/area.

Mathematically, the yield/area of PHS, SHS and CHS can be calculated to identify the best system. In CHS, at 15.0 cm vertical plant spacing, 53 leafy vegetables can be planted on a 2.0-m tall, 5.1 cm × 10.2 cm, rectangular PVC column. For the same column, only 13 vegetables can be produced in PHS or SHS, that is, 75% lower. In CHS, the land area/column (52.0 cm^2/column) is smaller than that in PHS and SHS (2,040.0 cm^2/column) since the tubes are upright rather than laying down. In 2,040.0 cm^2 (200.0 cm × 10.2 cm), 318 leafy vegetables can be produced in CHS when the 2.0-m tall columns are placed at 30.0 cm apart. This figure can be further translated to 848 plants/m^2, as 16 of the 2.0-m tall columns can be fitted at 30.0 cm apart in 1.0 m^2 (100.0 cm × 100.0 cm). In PHS and SHS of 16 columns, the density will only be 208 plants/m^2, and the 2.0-m long columns need to be cut into halves and stacked to fit in the 1.0 m^2. The yield is even lower in SHS of RHT, because only 67–167 plants/m^2 were recommended for this system (Cho & Son, 2005; Wiangsamut & Koolpluksee, 2020).

The total vegetable yield per unit area in CHS was higher than that in SHS (Touliatos *et al*., 2016). However, specifications and operation regimes of most vertical farming systems seen online or used in the industry are rarely published for others to use. Although the reason can be to protect the systems' intellectual property, general information for knowledge development, namely yield, growth, and quality of the vegetables across the columns, horizontally and vertically, of a CHS is seldom reported. In the primary food production industry, this information's absence is the missing link to the broader application of a great technology such as the vertical hydroponic system to solve the shortage of leafy vegetable supply. With little biological or technical information available on their hands, farmers do not have the opportunity to use the systems to increase leafy vegetable production per unit area and mitigate the burden to import this food as well as to address the negative environmental impacts of conventional farming. Thus, it is noteworthy to generate information about the fundamental features of CHS to form the foundation to improve this system for effective vegetable production.

The objective of the present study was to evaluate the differences in the yield, development, growth and quality of 576 curly dwarf Pak-choy across the columns and the levels in a CHS of 30.0-cm column spacing, 150.0-cm column height, and 1.2 m × 1.2 m ground area (*i.e.*, 400 plants/m^2, or double to the 208 plants/m^2 stated above). This dimension was chosen as a starting point since there is no complete technical information about CHS available in the literature to be used. The specific interest in this study was to assess the effects of columns horizontal position (*i.e.*, East to West, or sun orientation), vegetable vertical location on the columns (*i.e.*, the position from the lower to the upper section of the columns), and interaction between those two factors on yield (fresh and dry weights of shoot and root), development (leaf number), growth (plant height, leaf blade length, petiole length, root length and leaf area), and quality as chlorophyll (Chl-) content of the Pak-choy.

MATERIALS AND METHODS

The data used in this study were pooled from intensive trials carried out from June to September 2019 in an insect-proof shelter in the Faculty of Sustainable Agriculture, Universiti Malaysia Sabah, Sandakan, Sabah (5°55′54.93″ N, 118°00′14.69″ E). Each trial took 37 days. The same study was carried out again in 2021 as part of the faculty project to increase marketable-vegetable/area to improve students' financial well-being and employability ratings and increase the net profit of potential CHS users, especially smallholder vegetable farmers. The monthly precipitation at the study area ranges from 107.3 mm to 461.8 mm. The daily temperature is between 28 °C and 32 °C. In the shelter, the temperature averages 30 °C during the daytime.

Column Hydroponic System (CHS) Construction

A CHS of 1.2 m L × 1.2 m W × 1.5 m H was built (Figure 1). Sixteen (16) rectangular PVC tubes (10.2 cm L × 5.1 cm W × 1.5 m H) were arranged upright in four rows at a 30.0 cm distance one to another. There were nine vertical plant locations on each column and four planting cups at each location, *i.e.*, 36 planting cups per column. Each location was 15.0 cm apart. Overall, there were 576 cups in the system. The columns were placed on a 170-L nutrient solution tank, and the nutrient supply tube was connected to a 0.5HP non-submersible pump to complete the CHS. The power of the pump was controlled using a 13A-Eurosafe power-timer.

System Operation

The media were 100% cotton mop yarns; a 3.5 g and 60.0 cm long mop yarn was placed in each planting cup. The stock solutions A and B were prepared following the complete chemical composition recommended by Maludin *et al*. (2020) and Resh (2013). The stock solutions were then diluted to attain the final nutrient solution (NS) of 2.2 mS/cm electric conductivity (EC) and 5.9 pH. The average temperature of the NS was 28 °C. A total of 470 L NS was used per production cycle. The NS was circulated 15 minutes/session every 30 minutes from 7:00 AM to 6:00 PM and every two hours from 6:00 PM to 7:00 AM.

Vegetable Production

High quality seeds of curly dwarf Pak-choy (*Brassica rapa* L.) were purchased from a local authorized seed supplier. About five (5) seeds were sown on the mop yarns. On day 10, the seedlings were thinned to two seedlings per cup. On day 20, the seedlings were reduced to a single plant per cup. System maintenance carried out daily was measurements and correction (if necessary) of the NS's EC, pH and supply. The EC and pH were measured using a portable EC meter (HI98318 Hanna Instrument) and pH meter (Eutech pH6+ Thermo Fisher Scientific), respectively. Pest and disease problem were not encountered during this study. The vegetables were harvested on day 37.

Figure 1. The column hydroponic system in the study

Data Collection

On day 37, after sowing, data were collected from Pak-choy planted on hydroponic columns 2, 3, 6, 7, 10, 11, 14 and 15. Chl-content was measured before harvesting using a chlorophyll meter (SPAD-502Plus Konica Minolta). The data were then converted to Chl-content (ηmol/cm^2: Ling *et al*., 2011; and mg/g: Jiang *et al*., 2017). Plant growth was measured such as plant height (using a standard ruler as the length from the base of the Pak-choy to the tip of the last youngest leaf), leaf number (counted), leaf blade length (using a standard ruler as the average length from the bases to the tips of the largest, medium-size, and smallest leaf blades), petiole length (measured using a standard ruler as the length from the base of the petiole to the base of the leaf blade), leaf area (measured using C1202 Leaf Area Meter, CID Bio-Science Inc.), and root length (using a standard ruler as the length from the base of the roots to the tip of the longest roots). The yield was measured as fresh weight (FW) and dry matter weight (DW) of the shoots and roots. The root/shoot ratio was calculated as root-DW/shoot-DW. For DW assessment, the samples were dried in an oven at 70 °C for three days. The samples were then weighed using Mettler Toledo balance PL202-S. When this study was carried out, ten (10) ponds of raft hydroponic system (RHS) were operated in the same shelter, and thus, the productivities of the CHS and RHS were compared descriptively. Each pond was 2.0 m L × 1.2 m W × 0.13 m H (2.4 m^2; 220L capacity) with 12.0 cm × 15.0 cm plant spacing. The vegetables were floated using Styrofoam. The NS concentration was similar to that in the CHS. There were ten (10) other mini versions (3L capacity) of the raft hydroponic system (mRHS) operated in the shelter and in an air-conditioned greenhouse (ambient: 25 °C - 27 °C; NS: 25 °C), respectively, to raise only a single Pak-choy per system. The mRHS was operated to assess the highest growth and yield of the Pak-choy variety used in this study.

Data Analysis

The data of each parameter were organized based on (i) the column horizontal position (CHP, *i.e.*, East to West) from the first row (facing morning sunlight: MS1) to the second (after the first row: MS2), second last (before the last row: AS2) and last rows (facing afternoon sunlight: AS1) of columns, and (ii) the vegetable vertical location (VVL) from the lower (Level 1) to the upper section (Level 9) of the columns. Prior to analysis, the data were tested for compliance with the assumptions for ANOVA, *i.e.*, normally distributed (Shapiro-Wilk's test; Box Plot Analysis), independent, and homoscedastic (Levene's test); the tests revealed that the data fulfilled those requirements. Two-way ANOVA was performed to compare the differences between the means of yield, development, growth or Chl-content of the Pak-choy across the CHP and VVL, and whether those properties were affected by the interaction between the two factors. The simple-effects analysis was carried out to break down significant interaction effects (Field, 2018). One-way ANOVA was performed to compare the differences between yield, development, growth or Chl-content of the Pak-choy between CHPs at a specific VVL. The ANOVAs were performed at $\alpha = 0.05$, followed by Post-hoc tests (Tukey's HSD). The statistical analyses were carried out using Microsoft Excel® 2019, following the methods explained by Zaiontz (2020) and Field (2018).

RESULTS

Vegetable Yield

There were 400 plants/m^2 of Curly Dwarf Pak-choy harvested from the CHS. The average merchantable yield was 12.7 kg/m^2. The FW/plant ranged 7.2–80.4 g, where the mean was 31.3 g/plant. Ninety-five percent (95%) of the Pak-choy were lighter than the mean FW/plant. The average total yield/row in MS1, MS2, AS2, and AS1 was 5.5, 3.4, 3.0, and 6.4 kg, respectively (total: 18.3 kg). Total yield/row was affected by CHP (one-way ANOVA: $F_{3,\ 7} = 8.289$, $P = 0.034$). The differences between the means of yield/row were not significant between MS1 and AS1 (Tukey's HSD, $P = 0.676$), the two outer rows, or between MS2 and AS2 (Tukey's HSD, $P = 0.969$), the two inner rows, but the differences were marginal between MS2 and AS1 (Tukey's HSD, $P = 0.063$) and were significant between AS2 and AS1 (Tukey's HSD, $P = 0.045$). From the raft hydroponic system (RHS), 63 plants/m^2 of the same Pak-choy were harvested. The average yield was 5.1 kg/m^2 (total: 12.3 kg). Mean FW/plant was 82.1 g. In the mini raft hydroponic system (mRHS), however, this Pak-choy variety achieved 168.0 g/plant at 25 °C - 27 °C (NS and ambient temperatures) and 85.0 g/plant at 28 °C - 32 °C (NS and ambient temperatures).

Means of shoot yield (FW/plant or DW/plant) per location in AS1 were higher than those in other CHPs (Figure 2). Means of shoot yield per column at L9 were above those at other VVLs (Figures 3). The raw data showed that shoot FW across CHP and VVL was 8.8–20.3 g at L1 and 39.2–71.7 g at L9 (Figure 4). Shoot yield was significantly affected by CHP × VVL (two-way ANOVA, FW: $F_{24,\ 108} = 3.106$, $P < 0.001$; DW: $F_{24,\ 108} = 3.198$, $P < 0.001$). The simple-effects analysis indicated that the effects of CHP × VVL on shoot yields were statistically significant starting at L6 for MS1 ($F_{1,\ 108} = 5.360$, $P = 0.019$), L8 for MS2 ($F_{1,\ 108} = 21.365$, $P < 0.001$) and AS2 ($F_{1,\ 108} = 5.456$, $P = 0.021$), and L7 for AS1 ($F_{1,\ 108} = 10.965$, $P = 0.001$). Trends of shoot mean yields were AS1 > MS1 > MS2 = AS2 (Figure 2) and L9 > L8 > L7 > L1–L6 (Figure 3). Shoot yields/VVL in outer columns were almost all above those in inner columns (Figure 4).

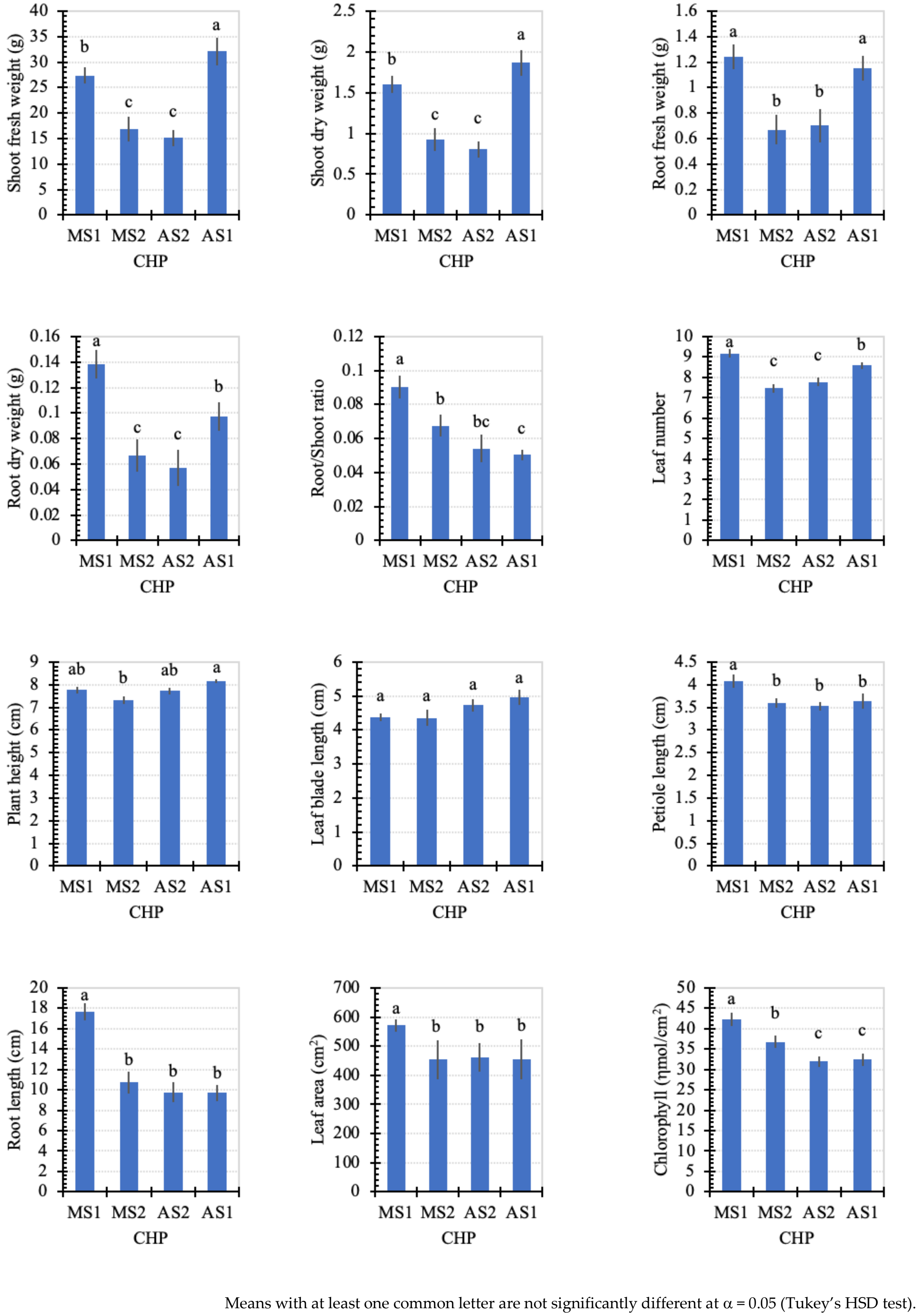
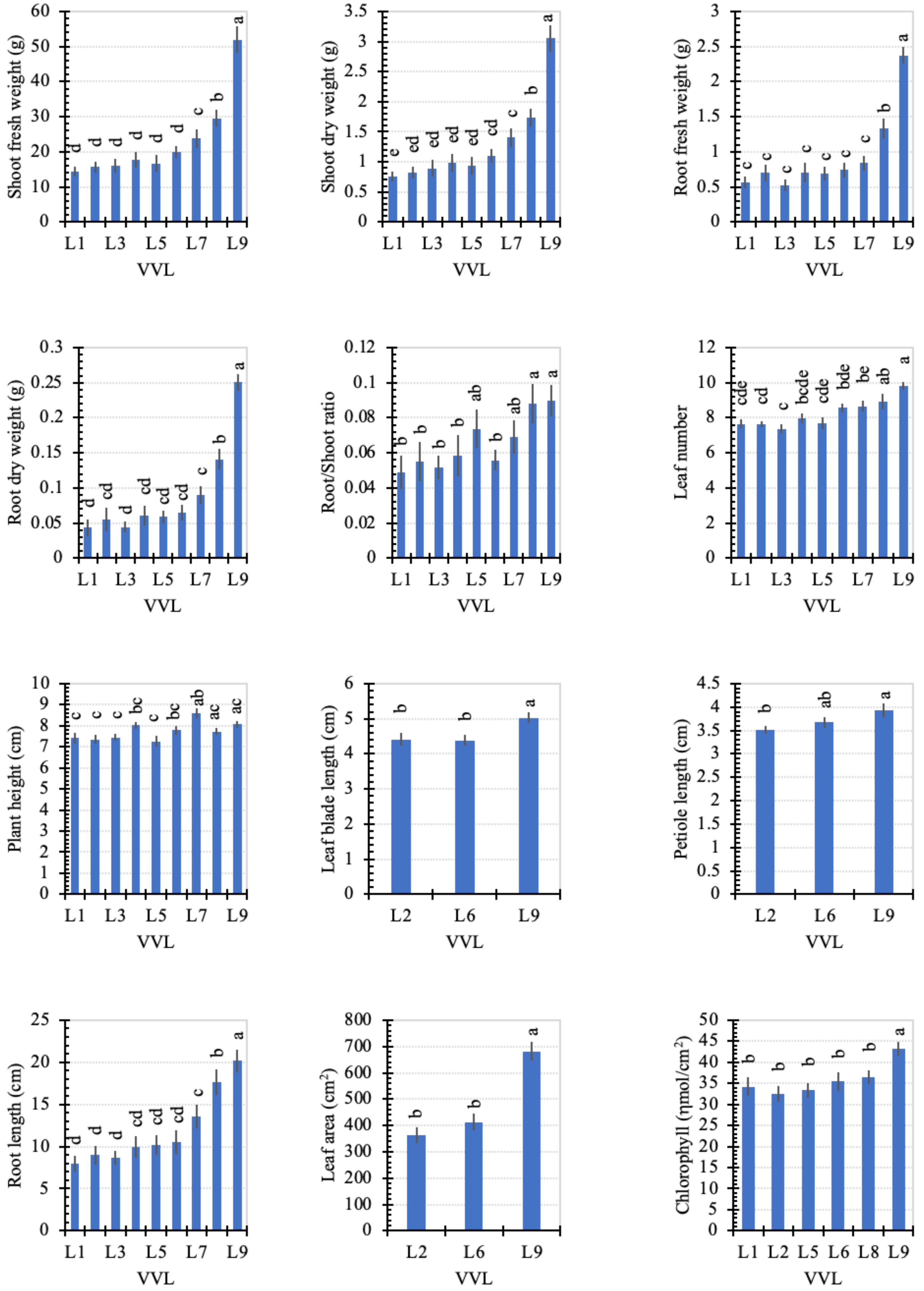


Figure 2. Means (±SE) of shoot and root weight (FW, DW), root/shoot ratio, leaf number, plant height, leaf, petiole and root length, leaf area, and Chl-content across CHPs.



Means with at least one common letter are not significantly different at α = 0.05 (Tukey's HSD test).

Figure 3. Means (±SE) of shoot and root weight (FW, DW), root/shoot ratio, leaf number, plant height, leaf, petiole and root length, leaf area, and Chl-content across VVLs.

Means of root yield (FW/plant or DW/plant) per location in MS1 and AS1 were higher than those in MS2 and AS2 (Figure 2). Means of root yield per column at L9 were above those at other VVLs (Figure 3). The raw data showed that root FW at L1 was 0.26–0.99 g and this was 2.26–2.54 g at L9 (Figure 4). Root yield was not significantly affected by CHP × VVL (two-way ANOVA, FW: $F_{24, 108}$ = 1.134, P = 0.321; DW: $F_{24, 108}$ = 1.361, P = 0.145). The non-significant effects of CHP × VVL on root yield were not expected because at L1–L7, differences between the means of root yield across CHPs were significant (one-way ANOVA, FW: $F_{3, 12}$ = 5.303–13.575, P = 0.001–0.015; DW: $F_{3, 12}$ = 7.125–20.791, P = 0.001–0.005), and the differences were not significant only at L8 ($F_{3, 12}$ = 0.114, P = 0.949) and L9 ($F_{3, 12}$ = 0.210, P = 0.887). Differences between the means of root yield were significant across CHPs (two-way ANOVA, FW: $F_{3, 108}$ = 24.237, P < 0.001; DW: $F_{3, 108}$ = 34.335, P < 0.001) or across VVLs (FW: $F_{8, 108}$ = 41.642, P < 0.001; DW: $F_{8, 108}$ = 51.160, P < 0.001). Trends of root mean yields were MS1 = AS1 > MS2 = AS2 (Figure 2) and more-or-less L9 > L8 > L1–L7 (Figure 3). Root yield trends at L8–L9 (Figure 4), which were identical, seemed to have cancelled out the trends at L1–L7 where yields/plant in outer columns were above those in inner columns.

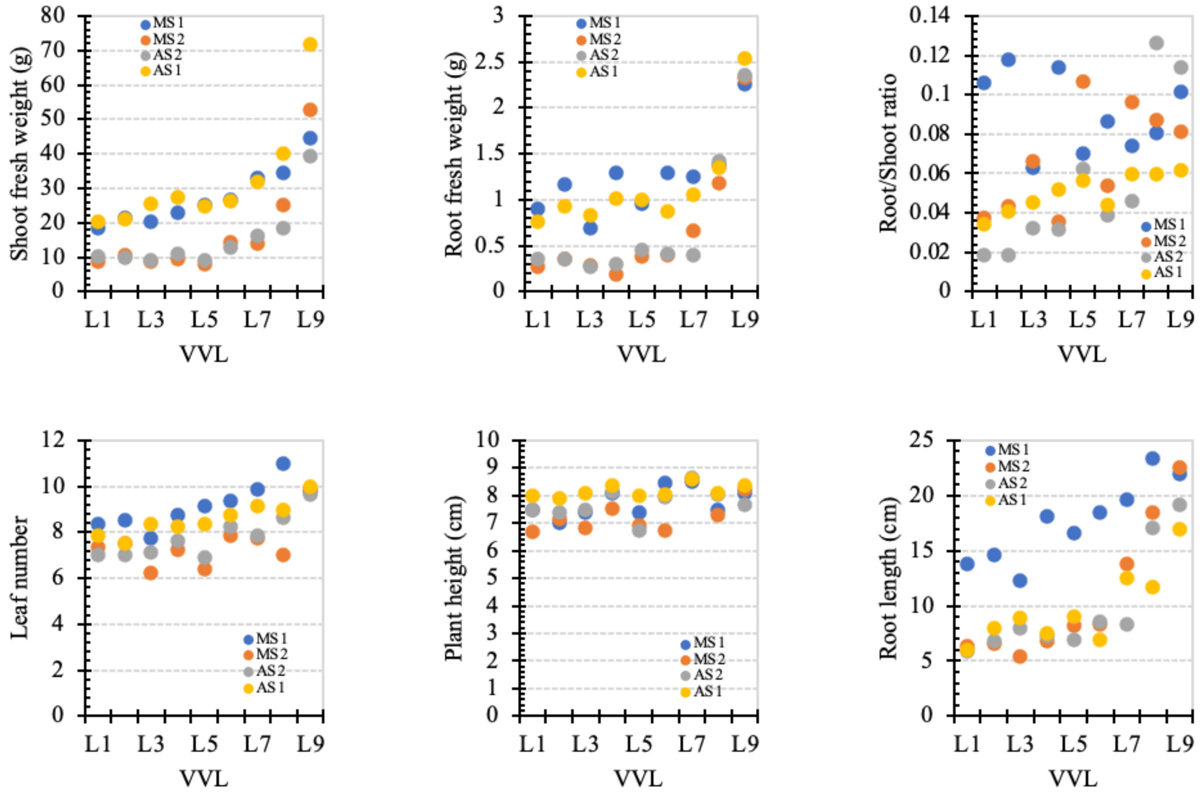


Figure 4. Trends of the mean shoot and root fresh weights, root/shoot ratio, leaf number, plant height, and root length across VVLs. Trends of the shoot and root dry weights are similar to those of fresh weights.

Vegetable Growth

Means of leaf formation (leaf-number/plant) per location in MS1 were higher than in other CHPs (Figure 2). Means of leaf formation per column at L9 were above those in other VVLs (Figures 3). Leaf formation was not significantly affected by CHP × VVL (two-way ANOVA, $F_{24, 108}$ = 1.499, P = 0.083). The non-significant effects of CHP × VVL on leaf formation were expected because at L2, L3, L5, L7 or L8, the differences were significant across CHPs (one-way ANOVA: $F_{3, 12}$ = 4.867–9.834, P = 0.001–0.019) but not at L1, L4, L6 or L9 ($F_{3, 12}$ = 1.418–1.636, P = 0.233–0.286). Leaf formations in outer columns were more-or-less above those in inner columns (Figure 4), but at any VVL, differences between the means of leaf formation across CHPs did not show a significant trend. Differences between the means of leaf formation were significant across CHPs (two-way ANOVA, $F_{3, 108}$ = 25.445,

$P < 0.001$) or across VVLs ($F_{8, 108} = 12.010$, $P < 0.001$). Trends of leaf mean formation were MS1 > AS1 > MS2 = AS2 (Figure 2) and more-or-less L9 = L8 > L8 = L7 = L6 > L5–L1 (Figure 3). In the raft system, leaf formation was 17 at 25 °C - 27 °C (mRHS) and 14 at 28 °C - 32 °C (RHS).

Means of stem elongation (height/plant) per location in MS1 were more-or-less similar compared to those in other CHPs (Figure 2). Means of stem elongation per column at L7 were higher than those at other VVLs (Figures 3). There were no statistically significant effects of CHP × VVL on stem elongation (two-way ANOVA, $F_{24, 108} = 0.707$, $P = 0.834$). This non-significant CHP × VVL on stem elongation was expected because the differences between the means of stem elongation at any VVL were significant across CHPs only at L6 (one-way ANOVA: $F_{3, 12} = 6.042$, $P = 0.009$). Differences between the means of stem elongation were significant across CHPs (two-way ANOVA, $F_{3, 108} = 6.413$, $P < 0.001$) or across VVLs ($F_{8, 108} = 4.713$, $P < 0.001$). However, Tukey's HSD results were difficult to interpret. The trends were more-or-less AS1 > MS2 (Figure 2; Figure 4) and L7 > other VVLs (Figure 3). In the raft system, stem elongation was 13.6 cm at 25 °C - 27 °C (mRHS) and 13.4 - 14.1 cm at 28 °C - 32 °C (RHS).

Figure 2 and 3 show the means of leaf elongation (petiole-length/plant and leaf-blade-length/plant) per location, or per column. There were no statistically significant effects of CHP × VVL on petiole length (two-way ANOVA, $F_{6, 36} = 1.589$, $P = 0.179$) and leaf blade length ($F_{6, 36} = 1.638$, $P = 0.165$). The non-significant effects of CHP × VVL on leaf elongation were expected, as the differences between the means at any VVL were significant across CHPs only for petiole length at L9 (one-way ANOVA: $F_{6, 36} = 4.871$, $P = 0.019$) and not any for leaf blade length. Differences between the means were significant across CHPs for petiole length (two-way ANOVA, $F_{3, 36} = 4.325$, $P = 0.011$) but not for leaf blade length ($F_{3, 36} = 2.794$, $P = 0.054$). The differences were significant across VVLs for both petiole length (two-way ANOVA, $F_{2, 36} = 4.204$, $P = 0.023$) and leaf blade length ($F_{2, 36} = 5.924$, $P = 0.006$). Trends of petiole mean length were more-or-less MS1 > MS2 = AS2 = AS1 and L9 > L2. Trends of leaf blade mean length were MS1 = MS2 = AS2 = AS1 (Figure 2; although there was a tendency that AS1 > AS2 > MS2 = MS1) and L9 > L6 = L2 (Figure 3).

Means of leaf expansion (leaf-area/plant or leaf-area/leaf) per location in MS1 were higher than those in other CHPs (Figure 2). Means of leaf expansion per column at L9 were above those at other VVLs (Figures 3). There were statistically significant effects of CHP × VVL (two-way ANOVA, $F_{6, 36} = 4.454$, $P = 0.002$) on leaf expansion. Although leaf area was less varying across VVL (545.0–601.8 cm^2/plant), the significant effects of CHP × VVL on leaf expansion were expected because leaf area was varying across columns (283.2–738.1 cm^2/plant). The simple-effects analysis indicated that the effects of CHP × VVL on leaf expansion were statistically significant only in MS2 ($F_{1, 36} = 32.962$, $P < 0.001$), AS2 ($F_{1, 36} = 10.787$, $P < 0.001$), and AS1 ($F_{1, 36} = 31.212$, $P < 0.001$) at L9. Trends of leaf mean expansion were MS1 > MS2 = AS2 = AS1 (Figure 2) and L9 > L6 = L2 (Figure 3), which was true only for MS2–AS1 (simple-effects analysis). In the raft system, leaf expansion was 1,904.0 cm^2/plant (122.0 cm^2/leaf) at 25 °C - 27 °C (mRHS) and 739.5–1029.5 cm^2/plant (51.0–71.0 cm^2/leaf) at 28 °C - 32 °C (RHS).

Means of root elongation (root-length/plant) per location in MS1 were higher than those in other CHPs (Figure 2). Means of root elongation per column at L9 were above those at other VVLs (Figures 3). Root elongation was not significantly affected by CHP × VVL (two-way ANOVA, $F_{24, 108} = 1.400$, $P = 0.124$). The non-significant effects of CHP × VVL on root elongation were not expected because at L1–L8, the differences between the means were significant across CHPs (one-way ANOVA: $F_{3, 12} = 3.889$–29.528, $P = 0.001$–0.037) and insignificant only at L9 ($F_{3, 12} = 0.905$, $P = 0.467$). Differences between the means of root elongation were significant across CHPs (two-way ANOVA,

$F_{3,\ 108}$ = 41.688, $P < 0.001$) or across VVLs ($F_{8,\ 108}$ = 23.327, $P < 0.001$). Trends of root mean elongation were MS1 > MS2 = AS2 = AS1 (Figure 2) and more-or-less L9 = L8 > L7–L1 (Figure 3). Pak-choy in the columns facing the morning sunlight and at the upper section of all columns invested more into root elongation (Figure 4). In the raft system, root elongation was 28.4 cm at 25 °C - 27 °C (mRHS) and 20.3 - 23.4 cm at 28 °C - 32 °C (RHS).

Means of root/shoot per location in MS1 were higher than those in other CHPs (Figure 2). Means of root/shoot per column at L8–L9 were above those at other VVLs (Figures 3). Root/shoot was significantly affected by CHP × VVL (two-way ANOVA, $F_{24,\ 108}$ = 2.444, $P < 0.001$). The root/shoot trends did not show a clear-cut pattern where at L1, L2, L4 and L6, the differences between the means were significant across CHPs (one-way ANOVA, $F_{3,\ 12}$ = 4.481–18.648, P = 0.001–0.025) but insignificant at L3, L5, and L7–L9 ($F_{3,\ 12}$ = 1.146–1.988, P = 0.169–0.370). The data, however, were varying (Figure 4), and thus, the significant effects of CHP × VVL on root/shoot were expected. Trends of mean root/shoot were MS1 > MS2 = AS2 (AS2 = AS1) (Figure 2) and more-or-less L9–L8–L7, L5 > L6, L4–L1 (Figure 3).

Chlorophyll Content

Means of chlorophyll (Chl-) content (ηmol/cm^2 of leaf; mg/g plant FW) per location in MS1 were higher than those in other CHPs (Figure 2). The average was 35.8 ηmol/cm^2 (1.24 mg/g). Means of Chl-content per column at L9 were above those at other VVLs (Figure 3). Chl-content was not significantly affected by CHP × VVL (two-way ANOVA, $F_{15,\ 72}$ = 0.607, P = 0.859); this trend was expected because at almost all VVLs, the differences between the means of Chl-content were not significant across CHPs (one-way ANOVA: $F_{3,\ 12}$ = 1.234–3.189, P = 0.063–0.340). Differences between the means of Chl-content were significant across CHPs (two-way ANOVA, $F_{3,\ 72}$ = 12.607, $P < 0.001$) or across VVLs ($F_{5,\ 72}$ = 5.515, $P < 0.001$). Trends of mean Chl-content were MS1 > MS2 > AS2 = AS1 (Figure 2) and L9 > L8, L6, L5, L2 and L1 (Figure 3). In the raft system, Chl-content was 38.6 ηmol/cm^2 (1.37 mg/g) at 25 °C - 27 °C (mRHS) and 62.3 ηmol/cm^2 (2.61 mg/g) at 28 °C - 32 °C (RHS).

DISCUSSION

Total Vegetable Yield

With a yield of 2.5 times higher than that of the RHS, the CHS can be considered to be productive. Extrapolation of the data shows that 127 tons/ha of curly dwarf Pak-choy can be produced in the system. This amount is 2.3 times higher than the best yield/ha reported by Wiangsamut and Koolpluksee (2020) for a deep flow system. Touliatos *et al*. (2016) reported that vegetable yield in CHS could be 13.8 times higher than that in SHS. Ninety-five percent of the Pak-choy in the CHS, however, were lighter than 31.3 g/plant. If the 168.0 g/plant in the mRHS is considered to be the growth-and-yield potential of the Pak-choy, the weight/plant in the CHS is 5.4 times lower than it should be. This means the high vegetable yield in the CHS is due to the higher plant/area rather than the higher weight/plant. A similar trend was reported by Touliatos *et al*. (2016).

The data implied that increasing the average weight/plant is one of the immediate steps to increase the system's vegetable yield. The closest target is 70.0–82.0 g/plant, because Pak-choy at L9 was 71.7 g/plant on average, which also matches the 71.0 g/plant reported by Maludin *et al*. (2019) for the same Pak-choy variety, and Pak-choy in the RHS was 82.1 g/plant on average. If that target is achieved, 40.3–47.2 kg of curly dwarf Pak-choy could be produced in the system, or 58% higher than the current total yield. Aiming for 168.0 g/plant will be remarkable, but the data from the mRHS indicated that this is difficult to achieve where the system has to be modified and operated in 25 °C -

27 °C ambient and NS temperatures, which can be achieved only in an air-conditioned greenhouse or at highlands.

A few factors are contributing to the variation of total vegetable yield in the system. One of the factors is NS formulation and concentration. Overall, the NS was suitable for the Pak-choy because it supported the plants to grow even to 168.0 g/plant. However, there is a possibility that plants at the lower section of the system had received fewer nutrients (Touliatos *et al*., 2016). In MS1, for example, all plants faced the morning sunlight, which meant light intensity was the same for all plants, yet weight/plant was gradually decreased from top to base (Figure 4). There is a logic that plants on the top had received a much higher amount of nutrient, as the nutrient solution was supplied from the top of the system. The second factor is the vegetable growth potential. Vegetables of good growth potential at the lower or inner section will still outperform vegetables of poor growth potential at the upper or outer section. The Box Plot Analysis revealed that of the yield data, 12 or 8% were outliers; 58% of the outliers were in inner columns. The outliers were too small to impact the ANOVA's results, but biologically, they have contributed to the variation in vegetable productivity. The impact will be higher when thousands of the Pak-choy are produced in a large-scale system. The third factor is the irrigation frequency. It affects plants' Chl-content (Yeganehpoor *et al*., 2016), a pigment that is important in photosynthesis. In this study, the nutrient solution was supplied every 30 minutes during the daytime, and the media in the cups was still wet within that gap. The media was also still wet within the two hours gap during the night time. However, nutrients in the media could have been depleted during those gaps, meaning growth and Chl-biosynthesis were suppressed intermittently during the production cycles. The effects of the 30-minute and two-hour gaps of irrigation on plant growth, yield and Chl-content in the CHS need to be further studied. This problem could be solved with a continuous rather than an intermittent supply of NS. This tactic could also increase the chances for the plants at the base to receive more nutrients.

Vegetable Density and Yield

Plant density in the CHS (400 Pak-choy/m^2) is 6.3 times higher than that in the RHS. For a raft system, 67–167 plants/m^2 were recommended to achieve the best marketable yield (Cho & Son, 2005; Wiangsamut & Koolpluksee, 2020). The high plant density is a disadvantage of the CHS when plant management and weight/plant are considered. High density means many plants have to be managed per unit area at a particular time and increases labour as well as material costs. It also increases the risk of loss when there is a disease outbreak. The weight/plant (31.3 g) in the system is 62% and 81% lower than the 82.1 and 168.0 g/plant in the RHS and mRHS, respectively. It is 42% lower than the 54.2 g/plant reported by Wiangsamut and Koolpluksee (2020). In CHS, column spacing will determine plant density (Touliatos *et al*., 2016), which means the 30.0 cm column spacing in this study needs to be re-evaluated to achieve better plant management and weight/plant.

Vegetable Growth and Yield

Plants in shaded areas have higher leaf-area/leaf as a strategy to capture more sunlight energy (Setiawati *et al*., 2018; Johnson *et al*., 2005). Plants in open areas have lower leaf-area/leaf to reduce leaf temperature, transpiration and leaf photosystem injury (Setiawati *et al*., 2018; James & Bell, 2000). This nature explains that leaf expansion as leaf-area/plant in the CHS is 31%–73% lower, and the leaf-area/leaf is 35%–73% higher than that in the raft system (RHS and mRHS). Pak-choy in the CHS had fewer (low leaf number) but broader leaves and thus a lower leaf-area/plant but a higher leaf-area/leaf. Pak-choy in the raft system had many but smaller leaves and thus a higher leaf-area/plant but a smaller leaf-area/leaf. It further explains the situation that the leaf-area/plant in MS1 and at L9 was high (Figure 2 & 3), but the leaf-area/leaf was low. Pak-choy in MS1 were well exposed to morning sunlight and had a more-or-less similar leaf expansion rate as indicated by the simple-effects analysis. While those at L9 were exposed to both morning and noon sunlight, meaning leaf expansion is higher, although at varying degrees. Pak-choy in AS1 were well exposed to afternoon sunlight where the light quality was lower but still much better than that in the centre of the system. Pak-choy in the inner columns (MS2 and AS2) and at the lower section were not well illuminated, and thus, both leaf-area/plant and leaf-area/leaf were low. The data from the mRHS also indicated that for Pak-choy in a cooler environment, the leaf-area/plant increases even though under direct sunlight, meaning when the risks associated with excessive leaf temperature, transpiration and leaf photosystem injury are elevated, leaves expand more than the size that the leaves could attain when under warm ambient temperature. Hence, to some extent, shade pattern has shaped leaf expansion in the CHS where at the same VVL but at different CHPs, Pak-choy in partial shade will have a higher leaf expansion rate than Pak-choy in full sunlight because those in partial shade are under slightly lower temperature. This scenario explains the situation that CHP × VVL significantly affected leaf-area/plant, and the strong effect of CHP × VVL on leaf area contributes to the significant effects of CHP × VVL on shoot yield.

Leaf-number/plant in the CHS is 39%–50% lower than that in the raft system. This indicates a slow leaf formation rate in the system. An establishment process of leaves is complex, but light is one factor that could affect its progress (Malinowski, 2013). Sunlight energy is absorbed in plants mostly by Chlorophyll *a* to be converted to chemical energy and used again in the biosynthesis of chlorophylls (Wettstein *et al*., 1995). This process is a circular biosynthesis that will lead plants to generate more chemical energies for the formation and development of leaves to meet the plants' ever-increasing chemical energy and chlorophyll demand while growing. Plants facing morning sunlight are expected to have higher biosynthesis of chemical energy for leaf formation and development. Photosynthetic rate and quality in the morning are better than those in the afternoon (Mohotti & Lawlor, 2002; Ibrahim & Jaafar, 2011; Koyama & Takemoto, 2014). *Brassica rapa* exposed to white colour light has a higher leaf number (Acero, 2013). This situation explains the trends that leaf formations were MS1>AS1>MS2=AS2 and L9 > L8–L1. Leaf formation at L9 was similar between the columns, as this area was exposed equally to both morning and afternoon sunlight, meaning plant photosynthetic activity was comparable, and thus plant growth was also similar. Pak-choy in MS1, AS1 and L9, however, did not form leaves as many as those in the raft system. This matter could be because of the short photoperiod effect. During morning–noon, Pak-choy in AS1 were in full shade, and during noon–afternoon, it was the turn for the Pak-choy in MS1. The ideal photoperiod for Pak-choy (*Brassica rapa* L.) has not been specifically reported, but the vegetation period of *Brassica rapa* is stated to be 28–30 days at 8.0–8.4 sunshine hours and 43–47 days at 6.0–6.4 sunshine hours (Kalisz, 2011), meaning more than 6 hours photoperiod will expedite the growth of this *Brassica*. Some brassicas can be a neutral day (Rabbani *et al*., 1997), but *Brassica rapa* is not one of the varieties judging from the study by Falik *et al*. (2014). A short day (short photoperiod) will retain vegetative growth, and a long day (long photoperiod) will stimulate flowering in *Brassica rapa* (Falik *et al*., 2014).

Stem length in the CHS is 42%–48% lower than that in the raft system, showing a low plant stem elongation in the system. Leaf formation will lead to stem elongation to accommodate the new leaves on the stem. However, differences in plant height were not significant irrespective of CHPs and VVLs (Figure 2 & 3). The data from the raft system can explain this trend. In the raft system, leaf number was 14 at 28 °C - 32 °C (ambient and NS temperature) and 17 at 25 °C - 27 °C, and stem height was 13.4 - 14.1 cm at 28 °C - 32 °C but only 13.6 cm at 25 °C - 27 °C. In other words, the stems elongated only a little, even for those that formed many leaves. This trait reflects the variety being named "dwarf". The data have also implied that stem elongation is not sensitive to ambient and NS temperatures, unlike leaf formation.

Once formed, the leaf will elongate and expand. Petiole elongation trends across CHPs and VVLs were closely similar to the leaf formation trends. The elongation trends across CHPs and VVLs were almost similar to the plant height trends for leaf blades. These traits could mean that once the leaf is formed, the petiole elongates first rather than the leaf blade. This scenario indicates an attempt to reach more sunlight, which also implies the function of the petiole. Unlike petiole, the leaf blade is likely to expand rather than elongate, at least for the studied Pak-choy variety. There is a trend that leaf blade elongation increased from East (MS1) to West (AS1) (Figure 2), indicating a weak effect of light quality associated with morning and afternoon sunlight on leaf blade elongation. Contrary to petiole elongation, leaf blade elongation was more-or-less affected by VVL alone. This trend could mean blade elongation at some parts of the CHS has resulted solely from the response to noon sunlight.

As stated earlier, the shoot yield (weight/plant) in the CHS was 62%–81% lower than that in the raft systems. At the same time, root elongation (root length/plant) was 28%–60% lower than that in the raft systems. Even in the MS1, root yield (8%) was also lower than the 25%/total mass reported by Niklas and Enquist (2002). The VVL patterns of the shoot and root yields were also similar; both decreased from top to base. Even so, for the outer columns, Pak-choy in AS1 had higher shoot yield and thus a lower root/shoot ratio, while those in MS1 had higher root yield and thus a higher root/shoot ratio. Shoot and root growth processes are complex with several competing explanations available in the literature, but generally, it is affected by nutrient, water and/or competitor availability (McNickle & Brown, 2014; Zhang *et al.*, 2019). When nutrients are abundant, plants use more energy and resources into shoot production and, when nutrients are deficient, into root production (Tilman, 1985). The trend of reaction can be due to a response to nutrients only or both nutrients and competitors, and some species overproduce root when in a competition (McNickle & Brown, 2014). Those factors could explain the trend of yield in MS1 and AS1. The higher root elongation can be attributed to root production increment as a response to nutrient competition and transpiration associated with higher ambient temperature. The competition, however, is expected to be less stiff in the CHS because every plant grows in its independent cup, compared to that in the RHS. The non-significant effect of CHP × VVL on root growth is considered as a non-meaningful no-interaction. Statistically, the effects at L8 and L9 have cancelled out those at L1–L7 and thus, CHP × VVL was indicated to have not affected root growth. Biologically, CHP × VVL has a marked effect on root growth as was shown at L1–L7 (Figure 4).

In MS1, the sunlight had better quality, and the Chl-content was higher. Logically, the shoot yield was MS1 > AS1. However, that was not the trend. The explanation could rest on the temperature at different sections of the system. This reason was also mentioned earlier for the leaf expansion. The temperatures at different parts of the system were not measured, but the data from the mRHS indicated that in a cooler environment, the Pak-choy were more productive even if having lower Chl-content. Shoots in 25 °C - 27 °C were heavier than those in 28 °C - 32 °C, although the Chl-content was 38% lower than that in the latter. In other words, higher Chl-content does not necessarily mean higher yield. The yield is conditional to NS and ambient temperatures too. Thus, the greater shoot yield in AS1 is expected to be due to a cooler temperature and the late-afternoon surge of photosynthetic rate, which can happen for plants in greenhouse condition (Ibrahim & Jaafar, 2011). During afternoon–evening, the study site's temperature is 30.8 °C compared to 33.3 °C during the morning–noon. It has been reported that photosynthetic activity will be suppressed faster in the morning due to the increased ambient temperature (Koyama & Takemoto, 2014). MS1 was situated on the eastern side, and the columns are also expected to be much warmer. Moisture in the media decreases a little faster as evaporation is higher, especially approaching noontime. As a result, the Pak-choy in MS1 invested more into root production to increase water uptake. A similar explanation is applicable for Pak-choy at the upper-section of the system. The greater shoot yield at L9 in AS1 is expected to be the benefit of productive photosynthesis at a cooler temperature, and the higher root yields at L8 and L9 irrespective of columns resulted from the response of the Pak-choy to increase water uptake, as the upper section was directly under the noon sunlight. It has been reported that along the balanced growth path, a plant has a root/shoot ratio that maximizes the daily net photosynthesis for given total biomass (Iwasa & Roughgarden, 1984). The data from the mRHS also showed, however, that in a cooler environment, root growth will be much higher, meaning root growth in AS1 can also be higher than that in MS1. This situation did not occur probably because of the condition stated by Tilman (1985) that under a favorable condition, which was the situation in AS1, plants will invest into shoot production. This situation could be stated as the partial root/shoot ratio principle in CHS, that is, growth and yield will depend on the location of the vegetables in the system.

Overall, the growth and yield data supported previous major CHS findings reported by Liu *et al*. (2004) and Touliatos *et al*. (2016). The high production was due to the high vegetable number/area rather than the high weight/plant. Column spacing (CHP) was critical for good vegetable growth and yield. From top to base (VVL), the growth and yield decreased. There were effects of shade and probably nutrient gradients from top to base on the yield. The data, however, indicated new things about CHS that need further attention. Shade created a cooler environment for better growth and yield. Sunlight orientation affected the yield, where the shoot on the western side was heavier. Photoperiod associated with morning and afternoon sessions also affected the yield.

Chlorophyll Content and Vegetable Quality

Chl-content of the green-leaf Pak-choy in the CHS is 36% lower or 19% higher than the reported values in the literature. Green-leaf Pak-choy in the fresh market had 44.0–52.4 SPAD-values (Limantara *et al*., 2015). These numbers are equal to 38.8–50.8 ηmol/cm^2 (1.38–1.94 mg/g). Others reported 1.0–1.1 mg Chl/g for green-leaf Pak-choy and 1.0–1.80 mg Chl/g red-leaf Pak-choy (Zheng *et al*., 2018). These differences, however, need be taken with caution, as a few varieties are naturally low or high in Chl-content. Chl-content in the CHS is lower than that in the raft system, depending on the ambient and NS temperatures. It is 43% lower at 28 °C - 32 °C but only 7% lower at 25 °C - 27 °C even under direct sunlight. The latter trend also explains why the average Chl-content in this study was low. Pak-choy in the inner and lower-side columns were in a cooler environment, as these areas were in the shade to some degrees for most times.

Chlorophyll leads a role in photosynthesis and natural biosynthesis in plants. It absorbs light energy to be converted to chemical energy. A part of the energy is used again for chlorophyll's biosynthesis (Wettstein *et al*., 1995). In other words, light intensity and quality increment enhance chemical energy and chlorophyll biosynthesis. This fact explains the high Chl-content in MS1 and at the upper section (L9) of the system. Pak-choy in these parts were exposed to higher light intensity and quality. Photosynthetic rate varies throughout the day, but the peaks are during the morning–noon. It peaks at 9:00–10:00 AM in the open field (Mohotti & Lawlor, 2002; Koyama & Takemoto, 2014) and 12:00–1:00 PM in the greenhouse (Ibrahim & Jaafar, 2011). There is sometimes a second peak at 3:00–4:00 PM (Ibrahim & Jaafar, 2011). As mentioned earlier, Pak-choy in AS1 were in full shade in the morning, and it was the turn for Pak-choy in MS1 in the afternoon. That means photoperiod had also affected Chl-content in the system to some extent. Chl-content at any VVL across the columns was insignificantly different. In other words, Pak-choy at L1 in outer and inner columns had a closely similar Chl-content. This trend is difficult to explain based on the available data and needs to be investigated.

The simple quality indicator of leafy vegetables is greenness (Ahmed *et al*., 2002). This trait depends on Chl-content. Compared to the Chl-values from the raft system and those reported by Limantara *et al*. (2015) and Zheng *et al*. (2018), the quality of the Pak-choy in the CHS is moderate. It is a little higher than average for Pak-choy in outer and upper-section columns. The 62.3 ηmol/cm^2 (2.61 mg/g) at 28 °C - 32 °C in the RHS are higher than those reported in the literature for green-leaf Pak-choy.

CHS Design Adjustment Consideration

Certain features of the system need to be modified to balance high plant/area and high weight/plant so that the system's best vegetable yield can be attained. (1) The 30.0 cm column spacing is insufficient to allow more sunlight to reach the centre and lower section. Thus, space needs to be expanded beyond 30.0 cm to improve light penetration to those areas. The suggestion for future study is 40.0 cm. (2) Once the space between the columns is increased, the system's width will expand. Plants in inner columns are difficult to access and manage. Hence, the system's width from the centre to the outer columns has to be reduced to arm-length. (3) The columns need to be shortened until sufficient noon sunlight reaches the lower section. A caution is this will reduce vegetable number/column. (4) LED lights are installed between the inner columns (Touliatos *et al*., 2016) so that light intensity and photosynthetic rates at these areas are increased. (5) The yield of Pak-choy in outer columns (MS1 vs. AS1) was not homogeneous. Hence, the system may have to be built to rotate systematically a few degrees every few minutes. This will expose equally vegetables in outer columns to morning and afternoon sunlight. (6) The nutrient solution is supplied continuously into the system. (7) Those six approaches are combined to some degrees either all included or some are, and some are not. These modifications will incur a cost in different ways. Increasing the space between the columns will increase the structural cost. Shortening the columns will reduce structural cost but may reduce the vegetable number, which is also a cost. Using LED lights and continuous nutrient supply will add accessorial and energy cost, and building the system to rotate will increase both structural and accessorial costs.

Implications to Vegetable Production Sustainability

CHS increased leafy vegetable yield/area to 60% (2.5 times) higher than that in RHS. It was 13.8 times more than that in SHS (Touliatos *et al*., 2016) or 129%–200% higher than that in conventional farming (Liu *et al*., 2004). However, its effect on the food production and supply chain is more than just increasing vegetable yield/area. In this study, there were no application of weedicide and pesticide and no nutrient solution waste. These advantages show increment in vegetable production at a reduced area used and reduced potential negative environmental impact associated with vegetable farming. CHS was a tourist attraction as well (Liu *et al*., 2004), providing extra income to the farmers. CHS is also a good device for students to learn environmentally, friendlier vegetable farming. The experience will give them a basis to advocate acceptable agricultural practices. The technical information of CHS in this study has been shared with the students to spread its application. To date, CHS is commonly mentioned in the media, but the technical information is seldom revealed for others to use.

CONCLUSIONS

Column Hydroponic System (CHS) can be used effectively to increase vegetable production per unit area. The yield was still high, even if the CHP was less than ideal. As were reported by previous researchers, CHP, VVL, CHP x VVL and column spacing were found to affect vegetable yield in the system. The data, however, had also indicated that sun orientation, photoperiod, and vegetable genetic potential were also affecting the yield. Other factors were Chl–temperature–photosynthesis–

yield, root/shoot ratio, and shade-effect. The immediate action to improve the model used in this study is to increase the weight/plant by reducing the plant/area. It is recommended that the column spacing is expanded beyond 30.0 cm, and the width of the system from the center to the outer columns is reduced to arm length. Other improvements suggested are the column height is reduced, the light intensity between the inner columns is enhanced with LED light addition, the nutrient is supplied continuously, and the system is built to rotate. One other option is that those approaches are combined to a certain degree. As major modification will incur a significant cost, the ideal column spacing is investigated first. There is a possibility that more sunlight will arrive at the lower and inner sections of the system at the best column spacing. In that case, some of the other recommendations will be less critical.

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