Net Houses Effects on Microclimate, Production, and Plant Protection of White-fleshed Pitaya

Yen-Chieh Chien and Jer-Chia Chang¹

Department of Horticulture, National Chung-Hsing University, No. 145, Xingda Road, Taichung 40227, Taiwan, Republic of China

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Abstract. To evaluate the comprehensive response of commercial cultivation of the white-fleshed pitaya (*Hylocereus undatus* ‘VN White’) under net house in Taiwan, experiments were conducted during the natural reproductive period (from June to Sept. 2016) with fruits grown within net houses (either 16 or 24 mesh insect-proof netting, without fruit bagging) or in an open field (the control, without netting, with fruit bagging). The effects of netting on microclimate, phenological period, flowering (floral bud emergence) of current and noncurrent cladodes (shoots) (2- to 3-year-old), fruit quality, market acceptability, pests and diseases control, and level of sunburn were investigated. Indoor solar radiation in the 16 and 24 mesh net houses were 78.12% and 75.03%, respectively, and the sunlight intensities [photosynthetic photon flux density (PPFD), $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$] were 76.03% and 73.00%, respectively, that of control. The maximum daily temperature for the 16 and 24 mesh net houses was greater than that of the control. However, there were no significant differences in daily average temperature, minimum temperature, or relative humidity (RH). The first flowering cycle (12 June 2016) and last flowering cycle (11 Sept. 2016) in both net houses were the same as those in the control. The accumulative flowering of current cladodes was unaffected by net covering, but that of noncurrent-year cladodes in both net houses was lower than that in the control. Although the L^* and C^* values of fruit color in the 16 and 24 mesh net houses were lower than those in the control, the fruits still had commercial value. The average fruit weight of the 16 mesh net house was significantly greater than that of the control. Average total soluble solid (TSS) content, TSS content at the fruit center, and titratable acidity were unaffected. In addition, the 16 mesh net house blocked some large pests without exacerbating disease or sunburn. Our findings suggest that 16 mesh net houses may be useful for white-fleshed pitaya cultivation during its natural reproductive period in subtropical Taiwan.

Pitaya (*Hylocereus* spp.), also known as pitahaya, strawberry pear, or dragon fruit, is a fruit crop native to Central and South America that is now cultivated worldwide (Ortiz-Hernández and Carrillo-Salazar, 2012; Zee et al., 2004). The main cultivars include the white-fleshed pitaya (*H. undatus*), red-fleshed pitaya (including purple-fleshed pitaya) (*H. ocamponis*, *H. costaricensis*, and *H. polyrhizus*), yellow pitaya (*H. megalanthus*), and their hybrids, and they are commercially cultivated in tropical and subtropical regions (Mizrahi, 2015; Mizrahi et al., 1997; Ortiz-Hernández and Carrillo-Salazar, 2012). The white-fleshed pitaya ‘VN White’ is one of the major cultivars in southeastern Vietnam

and Taiwan (Chiu et al., 2015; Food and Fertilizer Technology Center, 2018). Pitaya is regarded as a long-day plant (Jiang et al., 2012), and thus, in southern Taiwan, the natural reproductive period for white-fleshed pitaya is from summer until fall, with the first flowering typically in early May and the last in late September (Chiu et al., 2015; Hsu, 2004).

Individual fruit bagging is a widely used practice in the open-field cultivation of white-fleshed pitaya in Taiwan to minimize the impact of pests on fruit appearance and to benefit peel coloration (Tran et al., 2015a). However, individual bagging is labor and cost intensive. Further, if opaque kraft paper bags are used, it is difficult to assess fruit maturity. In addition, poor ventilation and susceptibility to sooty mold (*Phaeosaccardinula javanica*) can further increase labor cost for postharvest cleaning (Chiu et al., 2015). Thus, alternatives to individual bagging are needed.

Net houses are used in the cultivation of many fruits in Taiwan, including papaya (*Carica papaya* L.) (Wang, 2004), Indian jujube (*Zizyphus mauritiana* Lam.) (Chang and Wang, 2004), and guava (*Psidium guajava* L.) (Chu and Chang, 2017; Wu et al., 2017). As a protected facility, net house helps prevent diseases and pests and can substitute fruit

bagging. The use of net houses for pitaya cultivation had become a trend in the industry (Tseng and Yu, 2015); however, facility conditions and cultivation management are specifically adjusted for the local climate and the varieties being cultivated. For example, in Israel (which receives 50 $\text{mol}\cdot\text{m}^{-2}$ per day of daily light integral in the summer), the recommended shading for white-fleshed pitaya was 30% to 60% to achieve satisfactory biomass accumulation (Raveh et al., 1998) and flowering (Khaimov and Mizrahi, 2006). Since the cladodes (shoots) of pitaya are sensitive to high temperature and strong sunlight in summer, they are prone to sunburn (Chang et al., 2016; Chu et al., 2015; Hsu, 2004; Zee et al., 2004), which may reduce yield (Chen and Lin, 2016). Thus, the use of shade screens in net house can help minimize sunburn (Mupambi et al., 2018) and maximize fruit yield and quality during the natural reproductive period.

A preliminary study reported by Lai (2017) showed that the use of 32 mesh net house in Taichung, Taiwan, significantly reduced radiation and sooty mold without affecting fruit quality of *H. undatus*. However, the maximum and average air temperatures inside the net house in summer were greater than those in open field, and such environmental conditions are not favorable for the flowering of *H. undatus*. Lower mesh specifications, such as 16 mesh or 24 mesh, may be helpful to combat the heat accumulation problem and provide proper light intensity in facilities cultivating white-fleshed pitaya.

This study aimed to comprehensively evaluate the complete response/feasibility of using net houses for commercial production of white-fleshed pitaya. During the natural period of flowering and fruiting, the effects of white 16 mesh and 24 mesh insect-proof screens on the microclimate within net houses, flowering performance, fruit quality, cladode sunburn, and pests and diseases incidence of ‘VN White’ white-fleshed pitaya field grown plants were investigated. The results we obtain will provide guidelines for further use of net house cultivation in industry and ecophysiology research.

Materials and Methods

Plant materials and treatments during flowering period

Experiments were conducted on 6-year-old *H. undatus* ‘VN White’ plants in a commercial orchard in Waipu District, Taichung City, central Taiwan (lat. 24°20’N, long. 120°41’E). All plants were under normal cultivation management, their tree vigors were maintained even, and they were capable of flowering (floral bud emergence) and fruiting. Selected cladodes were labeled in Dec. 2015 and experiments were carried out from June to Sept. 2016, which is the natural flowering and fruiting period. Cladodes that developed after Dec. 2015, which were less than 1-year-old during investigation, were labeled as current-year cladodes. Cladodes aged 2 to 3 years, which had robust developmental status and possessed

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¹Corresponding author. E-mail: jerchiachang@dragon.nchu.edu.tw.

areoles capable of outgrowth, were labeled as noncurrent-year cladodes. No cladodes older than 3-years-old were retained in the plant because they have been thinned out by farmer after harvest due to lower light interception for photosynthesis inside the canopy and the number of areoles per cladode to produce flower buds had almost been exhausted (Chen, 2017; Jiang et al., 2012). Thus, two types of cladodes were labeled: current-year and noncurrent-year cladodes.

The *H. undatus* ‘VN White’ has complete self-compatibility (Tran et al., 2015b), meaning that flowers can set fruit after flowering. During the natural reproductive period in Taiwan, 10 to 12 flowering waves generally were obtained, and regulation of only one fruit per cladode was retained after fruit setting to ensure fruit quality in accordance with standard cultivation practices in Taiwan (Chen, 2017).

Mesh size of net houses and bagging treatment

The net houses were covered with 16 mesh or 24 mesh white insect-proof screens (3 m height). The area of each net house was ≈ 0.5 to 0.6 ha. Fruits within net house were not bagged.

A 0.3-ha open-field cultivation located near the net houses served as the control in which fruit bagging (with kraft paper bags) was carried out after fruit setting. A trellis system with plants grown in a patch (row), which was cultivated along with a bed, was established in the control and each type of house (Fig. 1).

Microclimate monitoring and comparison

Daily global radiation ($\text{MJ}\cdot\text{m}^{-2}$ per day) during the experimental period (June to Sept. 2016) was obtained from the nearest weather station, namely the Wuqi, of Central Meteorological Bureau of Taiwan. In addition, at cloudless noon (11:00 AM to 2:00 PM) on 4 and 7 Aug. 2016, the amount of solar radiation ($\text{W}\cdot\text{m}^{-2}$) and light intensity (PPFD , $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) at about 2 m above the ground was measured (in three replicates) using a light meter and data logger (LI-1400 data logger; LI-COR Biosciences, Lincoln, NE) in combination with a solar radiation sensor (LI-200SA; LI-COR Biosciences) and quantum sensor (LI-190SA;

LI-COR Biosciences) in the net houses and open field, respectively. These data were used to calculate the noon radiation transmittance under the screens. Radiation transmittance (%) = $[(\text{net house average value}) / (\text{open field average value})] \times 100\%$.

Temperature and RH

The temperature and humidity logger (HOBO® U23-001 Pro v2 data logger; Onset Computer Corp., Bourne, MA) was set at the height of the canopy and shielded from direct sunlight. Data were recorded at 15-min intervals from 12 June to 25 Sept. 2016 (total 122 d) and averaged daily to monitor in-field temperature and RH fluctuations. The means of data were further used to compare the daily maximum, average, and minimum air temperatures as well as the RH between settings.

Flowering phenology and flowering percentage

Eight separate plant patches (rows) were randomly selected in the open field and each of two net houses, respectively. One section (4- to 5-m long for avoiding additional shade on plants caused by fixed structures of net house) containing ≈ 10 plants with totally 20 to 68 current-year cladodes and 69 to 82 noncurrent-year cladodes from each patch was marked for study. Each section was regarded as one replicate, i.e., eight replicates were used. Flowering phenology and flowering (floral bud emergence) percentage were studied for both types of cladodes from 12 June to 25 Sept. 2016. Weekly flowering rate were examined to evaluate total amount of flower and accumulative flowering rate during natural reproductive period (June to Sept. 2016).

Flowering rate per week = (number of flowering cladodes per week / total number of cladodes) $\times 100\%$. A cladode with one or more areoles in each wave that sprouted flower buds was regarded as a flowering cladode.

Notably, pitaya may sometimes—but not always—flower two times (waves) on a cladode during the natural reproductive period (Chen, 2017; Jiang et al., 2012); therefore, those accumulative flowering percentage values exceeding 100% indicate that there were two

flowering waves on a cladode during the experimental period.

Fruit quality analysis and market acceptability

The fruit setting was almost 100% after flowering because of complete self-compatibility in white-fleshed pitaya cultivar VN White; therefore, fruit yield has never been a problem during the natural reproductive period in Taiwan (Chen, 2017; Jiang et al., 2012). To ensure fruit quality, flower/fruit thinning was made by hand and only one flower/fruit was left on each cladode in each wave in accordance with standard cultivation practices in Taiwan (Chen, 2017). Thus, the number of fruits and total yield were not calculated in this study, although they could be estimated through the following formulas, respectively: 1) accumulative flowering percentage per cladode $\times$ cladode number, and 2) accumulative flowering percentage per cladode $\times$ cladode number $\times$ average fruit weight. There were 10 flowering/fruiting waves in total during experimental period. Fruits were harvested at the peak of fruit production (11 Sept. 2016; a representative wave with flowering on 24 July 2016) and brought back to the laboratory for analysis. On average, four (ranged from two to nine) and 4.5 (ranged from four to five) fruits were sampled for each section of the open field (seven replicate) and each of two net houses (eight replicates), respectively; thus, in total, 32 (for open field) to 36 (for 16 and 24 mesh net houses) fruits were analyzed.

The analyzed parameters reported in the sections that follow.

Fruit weight. The fresh weight of each fruit was measured using an electronic balance (XS 3250C-SCS; Precisa Gravimetrics AG, Dietikon, Switzerland).

Longitudinal and transverse diameter. Each fruit was cut longitudinally, and the longitudinal and transverse diameters were measured using digital liquid crystal calipers (500-196-20; Mitutoyo Corp., Kawasaki, Japan).

Peel color on the exposed and shaded sides. The colors of the exposed and shaded sides were measured using a pen-type colorimeter (Spectro-pen; Dr. Lange, Düsseldorf, Germany) at the equator of

Fig. 1. The ‘VN White’ white-fleshed pitaya grown in an open field (A), 16 mesh net house (B), and 24 mesh net house (C) and fruit production during the natural reproductive season.

each fruit. Data were recorded as L* (brightness), a* (red/green), and b* (yellow/blue) values in the CIE color system. The a* and b* values were then converted to a chroma (C*) value and hue angle (h°) (McGuire, 1992).

Average and center of TSS content. Each fruit was cut longitudinally, and juice was extracted from the style end, center, and stem end of the pulp. A pocket-type digital refractometer (PAL-1; ATAGO, Tokyo, Japan) was zeroed using distilled water and then used to measure TSS of the juice from the different parts. The results are presented as °Brix. The average TSS of each fruit was the average of the TSS values of the aforementioned parts.

Titrate acid. One milliliter of fruit juice was mixed with 25 mL of distilled water and a drop (0.02–0.04 mL) of phenolphthalein. The solution was titrated with 0.1 N NaOH until the color turned pink. The amount of 0.1 N NaOH (mL) used was converted into malic acid content. The results are presented as percentages.

Titrate acid (%) = $0.1 \text{ N NaOH titration amount (mL)} \times \text{NaOH factor} \times 0.0067 / \text{sample amount (mL)} \times 100\%$

The fruits were entrusted to fruit farmers for sale at the Taipei Agricultural Products Marketing Company market, Taipei, Taiwan, during experimental period. The auction price was recorded as market acceptability.

Sunburn

The cladode sunburn scale was adopted from Chen and Lin (2016) with modifications. In the month when sunburn was most severe (August in central Taiwan), four plant patches were selected from each treatment group, and one section (4–5 m long) was selected from each patch (each section was considered one replicate) (Fig. 2). The sun-

burn severity (average = 94–132) was rates for cladodes from each section were. The number of cladodes with browning (levels 1 + 2), bleaching (levels 3 + 4), and necrosis (level 5), as well as the total number of cladodes with sunburn (levels 1 + 2 + 3 + 4 + 5), were recorded and calculated as percentages.

Pests and diseases

The types and severity of diseases {including stem canker [*Neoscytalidium dimidiatum* (Penz.) Crous & Slippers], anthracnose [*Colletotrichum* spp.], and sooty mold [*Phaeosaccardinula javanica*]} and pests {including snails [*Bradybaena similaris* (Ferussac)], scarab beetles [*Protaetia orientalis*], melon flies [*Bactrocera cucurbitae*], stink bugs [*Nezara viridula*], noctuid moths [*Spodoptera litura*], and thrips [*Scirtothrips dorsalis*]} in each group were assessed monthly. The descriptive rating scale by Bock et al. (2010) was adopted and modified to a scale with levels from 0 to 5: none (level 0), slight (level 1), light-to-moderate (level 2), moderate (level 3), moderate-to-severe (level 4), and severe (level 5). This scale was used to evaluate the effects of screens on pests and diseases control compared with the open field.

Statistical analysis

The experiments on microclimate, fruit quality, and sunburn status followed a completely randomized design. The accumulative flowering percentages of cladodes at different ages between treatments were studied using a split-plot completely randomized design with net house type as the main plot factor and cladode age as the sub-plot factor.

Flowering phenology was plotted using SigmaPlot 12.0 (Systat Software, Inc., San Jose,

CA). To compare the means of more than two groups, the Bartlett's test in Costat 6.1 statistics (CoHort Software, <http://www.cohort.com>) was first used to analyze the homogeneity of the variance. If the variance was homogeneous, data were further analyzed with analysis of variance and Fisher's protected least significant difference tests. If the variance was heterogeneous and could not be improved by data transformation, the Kruskal–Wallis test was used and the significance of the difference was determined by Dunn's test.

Results

Microclimate. The transmittance of solar radiation at noon in the 16 mesh and 24 mesh net houses were 78.12% and 75.03% of that in the open field (control), respectively (shading rates were 21.88% and 24.97%), and the light intensity was 76.03% and 73.00% (shading rates were 23.97% and 27.00%) (Table 1). From June to Sept. 2016, the average global radiation was 15.73 to 23.85 MJ·m⁻² per day (Fig. 3). The average maximum air temperature was 36.2 °C in the 16 mesh and 35.8 °C in the 24 mesh net houses, respectively; both were significantly greater than that in the field (34.7 °C). By contrast, there were no significant differences between the two net houses. There were also no significant differences in the averaged air temperature, minimum air temperature, or RH among the three treatments (Table 2). The period showing the greater intergroup difference in maximum temperature was from late June to early August, during which the maximum temperature in the 16 and 24 mesh houses was 1 to 7 °C greater than that in the open field (Fig. 3).

The average temperature in the net houses and in open field began to rise at 6:00 AM. The average temperatures inside the net houses

Fig. 2. Visual assessment of sunburn damage to 'VN White' white-fleshed pitaya cladodes. Ranked from 0 to 5: level 0: normal (no damage) (A); level 1: small-scale browning (B); level 2: large-scale browning (C); level 3: small-scale bleaching (D); level 4: large-scale bleaching (E); and necrosis (F).

Table 1. Comparison of midday solar radiation and light intensity (*PPFD*) transmittances in the open field, 16 mesh, and 24 mesh net houses.

Net house type	Transmittance (%)	
	Solar radiation	<i>PPFD</i>
Open field	100 a	100 a
16 mesh net house	78.12 ± 0.13 b ²	76.03 ± 0.04 b
24 mesh net house	75.03 ± 0.63 c	73.00 ± 0.12 c

²Mean ± SE (n = 3). Means within each column followed by the same letters are not significantly different by Fisher's protected least significant difference test at 5% level.

PPFD = photosynthetic photon flux density.

Fig. 3. The daily maximum, average, and minimum air temperature and global radiation changes in the net houses during the natural flowering and fruiting periods of 'VN White' white-fleshed pitaya. Because there were no significant differences in the average or minimum air temperature among treatments, data were combined and are presented as means. 24 mesh = 24 mesh net house; 16 mesh = 16 mesh net house; OF = open field.

were greater than those in the open field from 10:00 AM until sunset. Especially from 1:00 to 2:00 PM, the temperatures in the net houses (34.2 to 34.6 °C) were significantly greater than those in the open field (32.7 to 33.1 °C) at 95% confidence intervals (Fig. 4A); the difference average RH between different types of net houses was insignificant in the daytime (Fig. 4B). From 9:00 PM to 6:00 AM, the temperature and RH inside the houses were not significantly different from the outside. The average night time temperature in the net houses ranged from 24.9 to 27.5 °C, which was slightly lower than that in the open field (25.3 to 27.1 °C) on most days (Fig. 4A). The RH was 84.3% to 92.8% in the net houses and 86.3% to 90.5% in the open field (Fig. 4B).

Flowering phenology and flowering percentage. Regardless of cultivation location, the first natural flowering wave started on 12 June 2016. New floral buds formed every week in July, the flowering rate declined late August onward, and the last flowering wave ended on 11 Sept. 2016. There were about 10 flowering waves during the natural flowering period (Fig. 5). In the early flowering period (June), noncurrent-year cladodes had a greater flowering rate and were the major flowering cladodes, whereas current-year cladodes were physiologically mature enough for reproduction. The flowering percentage of current-year cladodes increased gradually in July 2016 and reached

the level of noncurrent-year cladodes. In August and September, the flowering rate of current-year cladodes exceeded that of noncurrent-year cladodes (Fig. 5).

The accumulative flowering percentages in the open field group and net house groups were >80%, and the net house type and cladode age showed an interaction effect (Table 3). In the open-field environment, the accumulative flowering percentage of noncurrent-year cladodes was greater than that of the current-year cladodes; for cladodes in the 16 mesh and 24 mesh net houses, there were no significant difference between age treatments (Table 3). For noncurrent-year cladodes, the accumulative flowering rate in the open field was significantly greater than that in net houses; for current-year cladodes, the accumulative flowering rates of 24-mesh net houses were greater significantly than open-field control, but there was no difference significantly between two net house conditions (Table 3).

Fruit quality and market acceptability. The open field showed the greatest L* value of fruit peel color, followed by the 24 mesh net group; the 16 mesh net group had the lowest L* value. Among the fruits bagged in kraft bags (in the open field), the L* values at the exposed side were significantly greater than those at the shaded side; for unbagged fruits, the differences between sides were not significant (Table 4). The C* (chroma) values at the exposed and shaded sides of the fruits from the open field were both greater than those from the net facilities. Further, the C* values at the shaded side were significantly greater than those at the exposed side (Table 4). The average h° values at the exposed and shaded sides of the fruits ranged from 20.2 to 39.3 and 3.2 to 5.1, respectively, across treatments. These findings indicate that peel color turned red or reddish purple, and that the h° values of shaded sides were significantly lower than those of the exposed side (Table 4).

The average fruit weight was greater in the 16 mesh net house than in the open field; there were no significant differences in fruit weight between the two net houses (Table 5). The longitudinal diameter of the fruits among treatments did not differ significantly. Regarding the transverse diameters, net house fruits had greater values than open-field fruits (Table 5). Regarding inner quality, fruits from the 24 mesh net house had lower average TSS content than fruits from control or 16 mesh treatment. Further, there were no significant differences in center TSS content and titratable acidity between the three treatments (Table 5). Fruits from net houses treatments were acceptable to the market and their price (2.3 USD/kg) was slightly greater than that of open field (2.0 USD/kg) (Table 5).

Sunburn, pests, and diseases. Browning, bleaching, and necrosis occurred in all groups; however, the rates of these did not differ significantly between groups (Table 6). Both the 16 and 24 mesh screens blocked invasion by scarab beetles, stink bugs, and melon flies and reduced damage caused by these pests. However, small pests like thrips

were not effectively excluded. The screens provided limited control against the noctuid moth larva and snails (Table 7). There were no significant differences in the occurrence of diseases such as stem canker and anthracnose between the open-field and net house groups. At the end of the season (September), fruit sooty mold was more severe in the open-field than in the net house treatments (Table 8).

Discussion

Insect-proof screens had different porosities (30% to 69%) for pests of various sizes. Screens typically were made of Italian weaving of single transparent plastic threads (Castellano et al., 2006). With decreasing porosity, the radiation transmittance [including ultraviolet radiation, photosynthetically active radiation (*PAR*), visible light, and near-infrared light] tends to decrease (Castellano et al., 2006). In this study, the porosity of 16 mesh insect-proof screen was greater than that of the 24 mesh screen, and so was the transmittance of solar radiation and *PAR* (Table 1), which was consistent with the aforementioned study. *PAR* can be estimated from solar radiation; the conversion variability of these two parameters is 2.01 mol·MJ in summer (Wang et al., 2014). According to data recorded at the Wuqi Station of the Central Meteorological Bureau of Taiwan, the average global radiation from June to Sept. 2016 was 20.4 MJ·m⁻² per day (Fig. 3), which converted to an average daily light integral of ≈41.0 mol·m⁻² per day. Such a high light intensity exceeds the amount required for maximum net CO₂ assimilation by the white-fleshed pitaya (20 mol·m⁻² per day) and, in this case may cause photoinhibition (Nobel and De la Barrera, 2004). For this reason, the white-fleshed pitaya should be cultivated in shaded facilities in Taiwan. The 16 mesh and 24 mesh insect-proof screens reduced the amount of *PAR* by about 24% to 27% (Table 1), which helps the plants in the net houses maintain better photosynthesis.

In the daytime, as the sun's elevation angle increases, more solar radiation reaches the surface of the earth. In solar radiation spectrum, the *PAR* provides the energy essential for photosynthesis, whereas the long-wave radiation is thermal (Tanny, 2013). The amount of solar radiation was greater at noon than in the morning or evening. Although the insect-proof screens provided partial shade and reduced the amount of radiant heat entering the houses (Table 1), they also may decrease air flow and lower the warm air removal rate, leading to significant greenhouse effect (Mupambi et al., 2018; Shen, 2004; Tanny et al., 2003).

Pitaya is a crassulacean acid metabolism plant that closes its stomata during the day (Nobel and De la Barrera, 2004); thus, it cannot effectively reduce its temperature of the plant and must undergo transpiration (Chen and Lin, 2016). Because of the aforementioned factors, during the study period of June to Sept. 2016, the average maximum temperature in both net house groups was

Table 2. Comparison of air temperature and relative humidity in the open field, 16 mesh, and 24 mesh net houses during the natural reproductive period.

Net house type	Maximum air temp (°C)	Avg air temp (°C)	Minimum air temp (°C)	Relative humidity (%)
Open field	34.7 ± 0.2 b ^c	28.5 ± 0.1 a	24.6 ± 0.1 a ^y	80.6 ± 0.6 a
16 mesh net house	36.2 ± 0.3 a	28.9 ± 0.2 a	24.4 ± 0.1 a	80.1 ± 0.6 a
24 mesh net house	35.8 ± 0.3 a	28.8 ± 0.2 a	24.4 ± 0.1 a	80.3 ± 0.6 a

^aMean ± SE (n = 122). Means within each column (except minimum air temperature) followed by different letters are significantly different by Fisher's protected least significant difference test at the 5% level.

^yMeans within the column of minimum air temperature followed by the same letters are not significantly different at the 5% level by the Kruskal–Wallis test.

Fig. 4. The average diurnal change of air temperature (A) and relative humidity (B) in the net houses during the natural growing season of 'VN White' white-fleshed pitaya. The values represent the mean ± 95% confidence intervals (n = 122). The black and white bars of top side indicate the average night and day time, respectively.

significantly greater than that in the open field (Table 2; Fig. 4A). Interestingly, there was no significant difference between the two net house treatments (Table 2). However, the maximum and average temperature of both net houses was lower than those previously reported for the 32 mesh net house (Lai, 2017). Since 16 mesh and 24 mesh insect-proof screens have greater porosity than 32 mesh screens, the use of

nets with greater porosity may help improve ventilation (Mupambi et al., 2018; Tanny, 2013). However, efforts should be made to reduce the potential adverse effects of high temperature. Cultivating white-fleshed pitaya in a high temperature (day/night temperature 35/25 °C) environment will result in net CO₂ assimilation lower than that at 30/20 °C, and the dry weights gain of cladodes and roots

(Nobel and De la Barrera, 2002) and yield (Nerd et al., 2002) will decrease.

Environmental humidity change may be due to temperature change (Tanny et al., 2008), atmospheric exchange, or transpiration by crops (Tanny et al., 2003). Because the insect-proof screen also hampered air flow, the wind speed inside the facility decreased (Tanny, 2013), which may result in slower moisture removal and thus increased humidity (Gruda and Tanny, 2015; Haijun et al., 2015). In net house cultivation of sweet peppers, plant transpiration mainly occurred during the day, and the open-field environment was found to have better ventilation than the net house; thus, daytime absolute humidity near the canopy was usually greater in the net house than in the open field (Tanny et al., 2003). The stomata of white-fleshed pitaya mainly open at night (Nobel and De la Barrera, 2004) and plant has strong transpiration; as a result, white-fleshed pitaya in the net houses tend to have greater average night time RH than the open field (Fig. 4B). However, the net house is a moderately isolated facility, and its internal microclimate was still affected by external climate (Gruda and Tanny, 2015; Tanny, 2013); therefore, the difference in average daily RH between treatments is insignificant (Table 2). The pitaya in the net houses had less sooty mold because it was not bagged.

Independent of net house use, the first natural flowering wave of the white-fleshed pitaya started on 12 June 2016. The average temperature before flowering was about 25 to 30 °C, which is close to the temperature suitable for floral bud outgrowth reported by Khaimov-Armoza et al. (2012). New floral buds emerged every week in July, but the flowering percentage greatly decreased in August and September (Fig. 5). In September, the critical daylength was shorter than the 12-h period required for floral bud differentiation (Jiang et al., 2012). The decrease in August may be due to the period of heavy flowering and fruit bearing. Water and nutrient competition, combined with hormonal regulation, inhibit later flowering (Khaimov and Mizrahi, 2006). Flower thinning could be used to slightly prolong the flowering season; however, the later the flower thinning (when flower differentiation and development are closer to completion), the lower the subsequent flowering rate (Khaimov and Mizrahi, 2006).

Khaimov and Mizrahi (2006) suggested that the flowering performance of the white-fleshed pitaya varies under different degrees of shade. In Israel, 40% shading has been found to lead to maximal natural flowering (on average, every 3 m of trellis had 68 flowers). For the current-year cladodes with good sunlight exposure, the net house had no adverse effects on flowering; on the contrary, for noncurrent-year cladodes, flowering performance in the open-field environment was significantly better than that in the net houses (Table 3). This is probably due to the more central distribution of these cladodes and the lower light intensity under 16 or 24 mesh

Fig. 5. Effect of net house cultivations and cladode ages on flowering percentage of 'VN White' white-fleshed pitaya from 12 June 2016 to 25 Sept. 2016. Values are mean $\pm$ SE of seven to eight replication analyses for the current-year (A) and noncurrent-year (B) cladodes.

Table 3. Effects of net house, cladode age, and their interaction on accumulative flowering percentage.

Cladode age	Net house type	Accumulative flowering percentage (%) ^a
Noncurrent-year cladode	Open field	124.1 $\pm$ 7.4 a ^y
	16 mesh net house	82.1 $\pm$ 10.6 bc
	24 mesh net house	82.2 $\pm$ 4.7 bc
Current-year cladode	Open field	79.8 $\pm$ 8.9 c
	16 mesh net house	90.6 $\pm$ 12.2 bc
	24 mesh net house	105.9 $\pm$ 6.4 ab
Source	F test ^x	
Cladode age	NS	
Net house type	NS	
Cladode age $\times$ net house type	**	

^aValues are means $\pm$ SE of eight replication analyses obtained from 12 June 2016 to 25 Sept. 2016 through 10 waves of flowering according to calculation of Fig. 5. Values exceed 100% indicated that there were two flowering waves on a cladode during experimental period.

^yMeans within each column followed by the same letters are not significantly different by Fisher's protected least significant difference test at 5% level.

^xF test of analysis of variance. NS = nonsignificant; ** = significant at 1% level.

screens (Table 1). Nerd et al. (2002) noted that summer weather with an average maximum temperature of 34 to 38 °C is unfavorable for the flowering of white-fleshed pitaya. However, in the present study, the maximum temperatures in the 16 and 24 mesh net houses were greater than those in the open field. Even though the average maximum temperature exceeded 34 °C (Table 2), the natural flowering waves did not significantly decrease (Fig. 5). This may be due to differences in plant varieties or insignificant differences related to the temperature in the net houses (Table 2). Consequently, the overall accumulative flowering percentage exceeded 80% (Table 3).

At early developmental stages, white-fleshed pitaya peels have an a^* value between -15 and -20 and a b^* value between 25 and 30 (Ortiz and Takahashi, 2015). Around 21 to 29 d after pollination (DAP) in summer, the

starch in the fruit rapidly degrades. TSS rapidly accumulated during 25 to 30 DAP, accompanied by peel color change. At 25 DAP, the titratable acidity rises briefly and then decreases sharply before plateauing at 27 DAP (Huang and Lin, 2008; Nerd et al., 1999). The peels color change was completed at 30 to 32 DAP, with a^* and b^* values reaching at least >20 and <20 , respectively (Nomura et al., 2005). The fruits reached mature status several days later (about 30–35 DAP) (Chang and Yen, 1997; Huang and Lin, 2008; Nerd et al., 1999), which is considered to be the optimal harvesting period (Nerd et al., 1999; Nomura et al., 2005). The ratio of soluble sugar to acidity was about 40 at this time point (Nerd et al., 1999).

During the development of white-fleshed pitaya fruit, the peel coloration is affected by the synthesis of betacyanin and the degradation of chlorophyll (Jamaludin et al., 2010; Phebe

et al., 2009). Factors such as temperature and light also synergistically affected color change (Huang and Lin, 2008; Khandaker et al., 2009; Nomura et al., 2005). Huang and Lin (2008) noted that the dark environment created by kraft paper bag may help promote chlorophyll degradation; thus, the L^* values of the bagged fruits were significantly greater than those of fruits without bagging. This may explain the lower L^* values of fruits (without bagging) in the 16 mesh net house relative to the open field control group. The L^* values of the 24 mesh net house treatment were greater than those in the 16 mesh net house (Table 4), probably because the 24 mesh insect-proof screen has a greater shading rate (Table 1).

The betacyanin contents of *Amaranthus tricolor* L. tend to be high in high temperature (24–29 °C) and high light intensity environments (1240–1257 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) (Khandaker et al., 2009). For white-fleshed pitaya from Ishigaki Island, Japan, the a^* value of the peel increases with accumulated temperature, and the a^* values of the exposed side were greater than those of the shaded side (Nomura et al., 2005). Based on the results of these two studies, the a^* values at the exposed side of white-fleshed pitaya fruits were better, perhaps due to the greater daily radiation (temperature and light exposure were also higher), which promotes the accumulation of betacyanin. However, the light environment may also make chlorophyll degradation difficult (Fang et al., 2016; Huang and Lin, 2008). The balance between the two pigments determines the fruit color (Jamaludin et al., 2010; Phebe et al., 2009).

In recent years, C^* (chroma) and h° have been used as indicators of pitaya fruit color (Chang et al., 2016; Ortiz and Takahashi, 2015; Tran et al., 2015a), with C^* representing saturation and h° indicating visual color (McGuire, 1992). The h° of white pitaya at early development is yellow-green (118–120°) (Nerd et al., 1999; Ortiz and Takahashi, 2015). While turning red (64–80°), C^* drops to 28–30. At maturity, the hue is red or reddish purple (0–15°) (Nerd et al., 1999; Nomura et al., 2005; Ortiz and Takahashi, 2015; Tran et al., 2015a) and C^* can become 40. The main source of red coloration is betanin (Suh et al., 2014). Compared with the open field, the plastic screens increased scattered light (Shahak et al., 2004) and the fruits were not bagged. These factors may result in lower color saturation (Table 4). Chang et al. (2016) reported that the degree of shading did not significantly affect fruit color in the red-fleshed species *H. polyrhizus*, indicating that different species/cultivars may respond differently to shade. Although the white-fleshed pitaya fruits from the net houses had inferior performance in terms of L^* and C^* values (Table 4), they were still acceptable at the market and attracted a greater price (Table 5).

The production of white-fleshed pitaya was affected by light and cladode status. Insufficient or heavy shading (Chang et al., 2016) and sunburn (Chen and Lin, 2016)

Table 4. Peel color analysis of pitaya fruits produced in the open field, 16 mesh, and 24 mesh net houses.

Position	Net house type	L* ^z	C*	h°
Exposed side	Open field	47.2 ± 0.4 a ^y	26.7 ± 0.6 c	21.0 ± 1.2 a ^x
	16 mesh	42.9 ± 0.2 d	24.1 ± 0.9 d	20.2 ± 1.4 ab
	24 mesh	45.0 ± 0.5 bc	21.9 ± 0.9 e	39.3 ± 4.9 a
Shaded side	Open field	45.2 ± 0.3 b	32.4 ± 0.4 a	5.1 ± 1.2 bc
	16 mesh	44.0 ± 0.4 cd	29.9 ± 0.8 b	3.2 ± 1.7 cd
	24 mesh	45.5 ± 0.7 b	29.4 ± 0.8 b	4.7 ± 1.1 bc

^zMean ± SE, n = 32–36 (averagely 4–4.5 fruits per replicate were sampled, and seven and eight replicates for the open field and each type of house were used, respectively).

^yMeans within L* and C* column followed by the same letters are not significantly different by Fisher's protected least significant difference test at the 5% level.

^xData within h° column followed by the same letters are not significantly different by Dunn's test at the 5% level.

Table 5. Quality analysis and market acceptability of pitaya fruits produced in the open field, 16 mesh, and 24 mesh net houses.

Net house type	Fresh wt	Longitudinal diam	Transverse diam	Total soluble solid content (°Brix)		Titratable acidity	Market acceptability/price
	(g/fruit)	(mm)	(mm)	Avg	Center	(%)	
Open field	336.8 b ^z	108.9 a ^y	71.0 b	16.5 a	17.8 a	0.28 a	Y / 2.0 (USD/kg)
16 mesh net house	409.6 a	115.7 a	76.6 a	16.3 a	17.2 a	0.30 a	Y / 2.3 (USD/kg)
24 mesh net house	369.1 ab	110.5 a	75.2 a	15.1 b	16.4 a	0.28 a	

^zMeans within each column, except longitudinal diameter, followed by the same letters are not significantly different by Fisher's protected least significant difference test at 5%, n = 32–36 (averagely 4–4.5 fruits per replicate were sampled, and seven and eight replicates for the open field and each type of house were used, respectively).

^yMeans within the longitudinal diameter column followed by the same letters are not significantly different at 5% level by the Kruskal–Wallis test.

Table 6. Comparison of cladode sunburn among three net house cultivations in Aug. 2016.

Net house type	Total cladode no.	Normal percentage (%)	Sunburn (%)			
			Browning	Bleaching	Necrosis	Total sunburn
Open field	132.0	29.5 a ^z	59.3 a	8.8 a	2.4 a	70.5 a
16 mesh net house	94.5	27.9 a	66.8 a	5.0 a	0.3 a	72.1 a
24 mesh net house	115.8	24.7 a	64.3 a	10.1 a	0.9 a	75.3 a

^zMeans (n = 4) within each column followed by the same letters are not significantly different by Fisher's protected least significant difference test at 5% level.

Table 7. Types incidences of pests in the open field, 16 mesh, and 24 mesh net house.

Net house type	Pest ^z	June	July	August	September
Open field	Snail	2	1	0	2
	Melon fly	1	0	0	4
	Scarab beetles	0	0	0	1
	Stink bugs	0	1	3	1
	Noctuid moths	1	3	3	0
	Thrips	0	1	2	2
16 mesh net house	Snail	2	3	3	5
	Noctuid moths	1	4	4	4
	Thrips	0	2	3	2
24 mesh net house	Snail	2	3	3	4
	Noctuid moths	1	4	3	4
	Thrips	0	2	2	2

^zRank from 0 to 5 level: 0 = none; 1 = slight; 2 = slight to moderate; 3 = moderate; 4 = moderate to severe; 5 = severe.

Table 8. Types and severities of diseases in the open field, 16 mesh, and 24 mesh net houses.

Disease ^z	Net house type	June	July	August	September
Stem canker	Open field	1	1	1	1
	16 mesh net house	1	1	1	1
	24 mesh net house	1	1	1	1
Anthracnose	Open field	2	1	1	1
	16 mesh net house	2	1	1	1
	24 mesh net house	2	1	1	1
Sooty mold	Open field	0	1	0	3
	16 mesh net house	0	1	1	1
	24 mesh net house	0	1	1	2

^zRank from 0 to 5: 0 = none; 1 = slight; 2 = slight to moderate; 3 = moderate; 4 = moderate to severe; 5 = severe.

will decrease fruit weight and TSS content. The use of plastic nets increased the amount of scattered light penetration into the canopy and therefore increased the photosynthesis rate (Shahak et al., 2004; Tanny, 2013). In this regard, the 16 mesh net house may

provide better light than the open field (Fig. 1). In addition, the transient high temperature condition in the net facility at noon did not exacerbate sunburn (Table 6). Overall, the 16 mesh net house facilitated accumulation of photosynthetic assimilates in

cladodes, which in turn resulted in a greater sink–fruit weight (Table 5). The 24 mesh house had greater shading than the open field and 16 mesh net houses (Table 1), and the total sunburn percentage was also greater than that in the 16 mesh net house (Table 6); this could lead to inadequate accumulation of photosynthetic products in the plants, adversely affecting the average TSS content of pulp (Table 5).

The cladodes of white-fleshed pitaya showed sunburn symptoms, including browning, bleaching, and necrosis, in the summer (Fig. 2). Pitaya cannot dissipate heat through transpiration during the day; thus, the surface temperature of cladodes in the summer may be 10 °C greater than the ambient air temperature. The high daytime accumulated temperature and radiant solar heat inflicted sunburn in pitaya cladodes (Chen and Lin, 2016). When the porosity of the screen was low, ventilation was usually poorer than that for screens with greater porosity, leading to weaker heat dissipation (Arthurs et al., 2013). The heat accumulation of the cladodes in the 16 mesh net house should be less than that of the 24 mesh net house, and the insect-proof screen can reduce radiation in the facility (Tanny, 2013) (Table 1). However, as a protected cultivation facility, the 16 mesh net house may slow internal air circulation (Mupambi et al., 2018; Shen, 2004; Tanny et al., 2003) and result in greater daytime temperature (Fig. 4; Table 2), resulting a limiting control against sunburn (Table 6). If the aim is simply to reduce sunburn without net house

cultivation, 50% black overhead shading screen had been suggested (Chu et al., 2015).

Both the 16 and 24 mesh screens could partially block the invasion of pests like scarab beetles, stink bugs, and melon flies. However, small pests were not effectively excluded (Table 7), possibly because the crevice of the screen allows noctuid moth larva and snails, which could move from open field into net house and, thus, attack plant and fruits, and finally reproduce within the houses. Noctuid moth larvae and snails could still be found inside the net houses (Table 7), which suggests that effective sealing of net houses is important for regular maintenance and good practice by personnel. During the natural growing season, under traditional disease management, the rates of stem canker and anthracnose did not differ significantly between the treatments. Sooty mold was less severe in the net houses (Table 8), likely because fruits in the open field were bagged and so the nectars were not washed off by rainwater (Fig. 1).

Conclusions

We demonstrated that cultivating white-fleshed pitaya in 16 or 24 mesh net houses could replace fruit bagging, allowing the accumulative flowering percentage to exceed 80% and meeting the light intensity required for photosynthesis. Although the peel coloration of net house fruits was not as good as that of bagged fruits in the open field, the fruit weight of the 16 mesh net house was excellent, and internal qualities like TSS and acidity were unaffected. The 16 mesh net house fruits were well accepted by the market. The 16 mesh net house also blocked major pests, such as melon flies, beetles and bugs, without exacerbating sunburn. Therefore, the use of 16 mesh net house has considerable potential for commercial production of white-fleshed pitaya. In the future, net houses could be combined with environmental light intensity monitoring with shade control to alleviate sunburn while ensuring sufficient light intensity for photosynthesis.

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