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Effect of canopytecture design and plant density on the vegetative, physiological, reproductive and yield of cucumber (*Cucumis sativus* L.) under rainshelter

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Abstract

Urban agriculture plays a crucial role in promoting sustainable food production within densely populated regions, where limited space and environmental constraints challenge optimal plant growth and yield. To address this, an experiment was conducted at the Horticultural Research Centre, MARDI. The study aimed to investigate the effect of canopytecture design (square and circular) and plant density (4, 5 and 6 plants per pot) on the vegetative, physiological, reproductive, and yield aspects of cucumber (*Cucumis sativus* L.) under a rainshelter. The experiment, conducted from March 20 to May 25, 2023, used a split-plot randomised complete block design with three replications. Results revealed that the circular×6 treatment resulted in the highest plant height, while circular×4 had the maximum stem diameter, chlorophyll content, and chlorophyll fluorescence. The square×6 treatment led to the shortest time to first flowering, earliest fruiting and first harvesting and recorded the highest number of male and female flowers. Plant density was the sole factor influencing yield, with 6 plant per pot producing fruits comparable in weight, length and diameter to those from 4 and 5 plants. However, 6 plants resulted in the highest number of fruits and the heaviest fruit weight per plant and per pot. In summary, the combination of 6 plant per pot and a square canopy architecture design had the most significant positive impact on the growth, physiology, reproduction and yield of cucumber.

Keywords: *canopy architecture, canopytecture, cucumber (Cucumis sativus* L.*), plant density, rainshelter*

Introduction

In 2020, the Department of Statistics Malaysia reported that the country's population had reached 32.4 million, with a substantial 70% of individuals falling within the active age group of 15 to 64 years. The report revealed that 75.5% of the population resided in urban areas, underscoring the increasing trend of urbanisation, while 24.5% lived in rural areas. In response to this urban shift, the government launched the Urban Community Garden Policy in 2021, recognising the imperative to maximize land use and environmental spaces through community gardening (Intan Maisarah et al. 2021). This initiative not only addresses the competition for limited resources due to urban expansion and land conversion, as highlighted by Bernama in 2018, but also strives to empower urban communities by promoting sustainable, local food production.

The Malaysian Agricultural Research and Development Institute (MARDI), a pivotal player in agricultural research introduced 'canopytecture,' a groundbreaking fusion of 'canopy' and 'architecture.' Standing at 180 cm tall, this innovative structure provides a unique support system for the vertical growth of climbing fruits and vegetables. Its specialised architecture enables plants to twist, cling, and grow vertically on support poles (Hamdan et al. 2015). Canopytecture emerges as a solution for urban areas where farming space is a premium due to intense land competition. Notably, it goes beyond its functional role by contributing to the aesthetic appeal of garden spaces, serving as a therapeutic element.

The meticulously planned canopytecture is vital for managing growth patterns and ensuring high-quality fruit production. Properly shaped canopies enhance aeration, optimise exposure to foliage and fruits, and improve biochemical and photosynthetic efficiency. This approach leads to better fruit bud differentiation, ripening, and overall fruit quality while also mitigating microclimate conditions conducive to pests and diseases (Singh et al. 2023).

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Cucumber (*Cucumis sativus* L.) is a crucial vegetable crop widely cultivated in Malaysia due to its high demand and adaptability to various growing conditions (Din et al. 2020). As an important crop in the Malaysian vegetable sector (Goundar et al. 2022), cucumber contributes significantly to the country's agricultural economy and is a staple in the local diet, valued for its nutritional benefits and versatility in culinary applications (Wan Shafiin et al. 2020). The cultivation of cucumber also supports the livelihoods of many farmers, making it an essential crop for both food security and economic sustainability (Okwuokenye 2020).

Considering plant density's impact on photosynthetic yield optimisation, enhanced plant density can improve light penetration to lower leaves and optimise crop water productivity, ultimately benefiting overall yield and fruit quality (Qiu et al. 2013; Hao et al. 2015). However, an increase in planting density may also pose challenges, such as mutual shading, resource competition, heightened leaf senescence, and reduced photosynthesis (Antonietta et al. 2014; Li et al. 2019; Liu et al. 2020). Despite various studies exploring density changes and yield impacts, research specifically addressing cucumber quality concerning plant density is scarce (Russo 2008; Calori et al. 2017).

Acknowledging the economic importance of determining the optimal cucumber density, this study aimed to assess yield optimisation through canopytecture design and plant density. The evaluation encompasses vegetative, physiological, reproductive aspects, and overall yield of cucumber (*Cucumis sativus* L.) under rainshelter conditions, contributing valuable insights for sustainable urban agriculture practices.

Materials and method

Location of experiment and experimental design

The experiment was carried out within a rainshelter at the Horticultural Research Centre of the Malaysian Agricultural Research and Development Institute (MARDI) in Serdang, Selangor. It was carried out from March 20 to May 25, 2023, following a split plot design. The experiment had three replications, each consisting of four canopytecture, amounting to a total of 72 pots used. The two factors used in the experiment were canopytecture design as the first factor, which formed the main plot, with treatments as square shaded shape (1.21 m^2) and circular shaded shape (1.50 m^2). Plant density was the second factor formed as the subplots, and the treatments were four, five and six plant/pot.

Management practices

The study used the TC311 cucumber variety. Initially, seeds were placed in trays with peat moss and covered with black plastic for four days to enhance germination rates. After sprouting, seedlings were transferred to a planter box filled with plain water at a depth of 2.0 cm for the first two weeks without fertiliser. Later, they were transplanted into canopytecture pots filled with a 2:1:1 media mixture of peat moss, perlite, and topsoil, including composted chicken dung. NPK Green (15:15:15) was applied one week after transplanting, and NPK Blue (12:12:17:2+TE) was used at the onset of flowering. Additional foliar fertiliser was given weekly. Stems were trained by tying them to a canopy structure with string, allowing only the portions extending above the canopy to retained. Irrigation was provided four times daily through a drip tape system connected to a water tank, ensuring consistent moisture. Effective pest and disease management further supported smooth experimentation under a rain shelter. Fruit harvesting began seven weeks after seed sowing and was conducted twice weekly.

Determination of media components

The physical and chemical properties of the growing media samples were analysed in the study. Moisture content was calculated using the gravimetric method. To determine pH, 100 g of substrate was mixed with distilled water until saturated, shaken for 15 minutes, left to settle for 60 minutes, and then filtered for measurement using a pH meter. Organic matter was assessed through the 'Kjeldahl N' method, while total organic carbon was measured using a carbonaceous analyser. Mineral nitrogen concentration was evaluated through potassium chloride extraction. Phosphorus was extracted using the Bray Method, and potassium was extracted using ammonium acetate (Hartz 2007). Calcium and magnesium levels in the filtered extract were analysed using an inductively coupled plasma atomic emission spectrometer (ICP-AES).

Data collection

To explore the dynamics of plant growth and development, quantitative data were collected for vegetative and physiological growth across all treatments. These measurements were recorded weekly from the first to the fourth week after transplanting (WAT). Plant height was measured from the base to the tips of the plants using a measuring tape, while stem diameter was measured at the first node of the stem with a vernier caliper. A portable PAM-2500 Chlorophyll Fluorometer (WALZ, Effeltrich, Germany) was utilised to measure the chlorophyll fluorescence parameters. In contrast, a SPAD502 meter (Konica Minolta Optic Inc., Tokyo, Japan) was applied to measure the relative chlorophyll content. To obtain reproductive data, the time taken for plants to flower was recorded as the number of days to flowering. For each plant, the number of days taken to produce the first fruit buds was recorded as the number of days to fruiting. The count of male and female flowers produced by each plant for every treatment was also recorded. In relation to yield data, the time taken for yield to fully mature was recorded as the number of days to harvesting. For yield per fruit, the weight of yield was recorded in kilograms (kg) using an electronic balance. The length of fruit (cm) was measured between the base and apex. The diameter (cm) was measured on top of the fruit using a pair of vernier calipers. In terms of yield per plant, the total number and weight of the fruit per plant for each treatment were calculated to determine the overall yield. Similarly, for yield per canopy structure, the total number and weight of the fruit per plant for each treatment were computed to obtain the total yield.

Statistical analysis

Data analyses were conducted using SAS software (Version 9.4, SAS Institute Inc., Cary, North Carolina, USA) through Analysis of Variance (ANOVA). To assess differences among treatments, the Least Significant Difference (LSD) was employed at a significance level of $P \leq 0.05$.

Results and discussion

Physico-chemical properties of experimental media

The general physical and chemical properties of the media used in the experiment are presented in *Table 1*. The container capacity was measured at 42.15%, with wet mass recorded at 0.67 g/g. The bulk density was 0.50 g/cm^3. The total porosity was 51.95% suggesting that more than half of the soil volume was composed of pores or open spaces, with air space at 3.17%. The moisture content is 10.2%, and the electrical conductivity suggested a moderate level of electrical conductivity at 146 µS/cm. A soil pH of 6.95 indicated that the soil was slightly acidic. The cation exchange capacity of 21.6 meq/100g indicated a moderate capacity for exchanging cations, and the 32.0% organic matter content signified that the medium was rich in organic material. The levels of total organic carbon, nitrogen, phosphorus, and potassium were all below 0.1%. Calcium was present at 5090 mg/kg, while magnesium was at 7075 mg/kg.

Vegetative growth

An evaluation of the data presented in *Table 2* revealed that, during the first week after transplanting, there was no significant difference in plant height among the combination treatments. However, as subsequent weeks progressed, the combination treatment involving circular×6 consistently yielded the highest plant height, starting from the second (34.25 cm), third (105.76 cm), and fourth (190.1 cm) weeks after transplanting (WAT). Similarly, stem diameter did not show significant differences among treatments in the first week after transplanting. On the second week, however, circular×4 recorded the highest stem diameter (5.33 cm). On the third and fourth weeks, all treatments yielded high stem diameters, with the exception of square×6, which remained lower than the others. The increase in the number of plants/pot correlated with an elevation in plant height, indicating heightened competition for sunlight with an increased number of plants/unit area. This heightened competition resulted in thinner stems diameter possibility to factors such as competition for nutrients, water availability and space. This effect was further compounded by reduced competition from nearby plants in lower plant density scenarios compared to higher plant density (Lam et al. 2019; Choudhury and Sarangi, 2020; Mladenovic et al. 2020; Sebrina Shahniza et al. 2023). Moreover, the design shape of the canopytecture, particularly its greater surface area, provided ample space for plant growth. This design, particularly in comparison to the circular canopytecture design, accommodated more trailing branches, thereby fostering superior plant development. The increased surface area not only supported enhanced plant growth but also facilitated improved space and light penetration, creating optimal conditions for overall plant development (Zilio et al. 2013; Blanc et al. 2021).

Physiological growth

As shown in *Table 3*, the interaction between canopytecture design and planting density had a significant impact on the relative chlorophyll content (%) and chlorophyll fluorescence (Fv/Fm) of cucumber plants over the weeks after transplanting (WAT). Both physiological indicators of photosynthetic efficiency showed distinct variations in response to the combined effects of canopytecture design and plant density.

For relative chlorophyll content (%), the circular×4 treatment consistently exhibited the highest values, peaking in the first week (32.00%). In the second and third weeks, circular×4 and square×4 had the highest relative chlorophyll content, with circular×4 reaching 35.83% and 36.77%, while square×4 closely followed at 35.75% and 36.20%, respectively. By the fourth week, the highest relative chlorophyll content was observed in circular×4 (22.94%), square×4 (23.82%), and circular×5 (22.80%), reflecting optimal light interception and reduced competitive stress in these configurations. In contrast, higher density treatments like square×6 and circular×6 showed significantly lower relative chlorophyll content, especially at 4 WAT, suggesting that increased density limited light availability and intensified competition for resources, thereby reducing chlorophyll levels. As plant density increased, a cascade of environmental factors came into play, including heightened competition for sunlight, nutrient scarcity, reduced oxygen levels from increased respiration rates and constrained water availability. These combined factors further constrained photosynthetic capacity and chlorophyll production in higher density treatments.

A similar trend was observed for chlorophyll fluorescence (Fv/Fm). The circular×4 treatment had the highest Fv/Fm value in the first week (0.785). In the second week, circular×4 (0.825), square×4 (0.817), and circular×5 (0.816) recorded the highest fluorescence values. By the third week, circular×4 continued to maintain the highest fluorescence (0.804), reflecting sustained photosynthetic efficiency due to favorable light conditions within the canopy. In the fourth week, no significant differences were observed among the treatments, indicating an overall trend where lower density configurations, particularly circular×4, provided enhanced light distribution and reduced shading. As plant density increased, Fv/Fm values tended to decline, as observed in treatments like square×6, which consistently recorded lower fluorescence values. This trend highlights the impact of plant density on the photochemical efficiency of photosystem II, where high-density conditions intensify shading and inter-plant competition, reducing available energy for photosynthesis.

These findings align with previous studies indicating that both relative chlorophyll content and chlorophyll fluorescence are sensitive to canopy design and plant density. Increased plant density can intensify competition for sunlight, reducing chlorophyll production and lowering fluorescence, thereby limiting photosynthetic efficiency (Yanjun et al. 2018; Khan et al. 2019). Moreover, the canopytecture, particularly a circular form that extends into the interspace, plays a critical role in modulating light capture. The circular×4 design, in particular, enhanced radiation capture in the lower canopy, minimising shade effects and supporting continuous photosynthetic activity (Du et al. 2015; Chapepa et al. 2020; Sultana et al. 2023).

Table 1. Physico-chemical properties of experimental sites particle size distribution

Media rate	Peatmoss: Perlite: Topsoil (2:1:1)
Container capacity (%)	42.15
Mass wetness (g/g)	0.67
Bulk density (g/cm^3)	0.50
Total porosity (%)	51.95
Air space (%)	3.17
Moisture content	10.2
Electrical conductivity (µS/cm)	146
pH	6.95
Cation exchange capacity (meq/100g)	21.6
Organic matter (%)	32.0
Total organic carbon (%)	<0.1
Nitrogen (%)	<0.1
Phosphorus	<0.1
Potassium	<0.1
Calcium (mg/kg)	5090
Magnesium (mg/kg)	707

Table 2. Interaction effect of canopytecture design and density on plant height (cm) and stem diameter (mm) of cucumber (*Cucumis sativus* L.) WAT

Treatment	Plant height (cm)				Stem diameter (mm)			
	Weeks after transplanting (WAT)							
	1	2	3	4	1	2	3	4
Square×4	10.28a	25.59c	84.04c	160.42d	2.98a	5.21ab	5.69a	6.70a
Square×5	10.46a	26.66c	90.1c	163.75cd	2.98a	4.90abc	5.58a	6.45a
Square×6	11.48a	31.28ab	102.50ab	177.78b	2.97a	4.64c	5.17a	5.64b
Circular×4	10.54a	26.04c	88.56c	173.41bc	3.10a	5.33a	5.84a	6.82a
Circular×5	10.55a	28.81bc	93.45bc	176.91b	2.98a	5.08abc	5.66a	6.55a
Circular×6	10.97a	34.25a	105.76a	190.1a	2.97a	4.80bc	5.46a	6.39a
Mean	10.71	28.77	94.07	173.72	2.90	4.99	5.49	6.42
CV (%)	19.01	20.23	18.91	12.1	14.86	16.61	16.93	16.55

Means with different letters within each column is significantly different at $P \leq 0.05$ using LSD

Table 3. Interaction effect of canopytecture design and density on relative chlorophyll content (%) and chlorophyll fluorescence (Fv/Fm) of cucumber (*Cucumis sativus* L.) WAT

Treatment	Relative chlorophyll content (%)				Chlorophyll fluorescence (Fv/Fm)			
	Weeks after transplanting (WAT)							
	1	2	3	4	1	2	3	4
Square ×4	31.06ab	35.75a	36.20a	23.82a	0.781ab	0.817a	0.795ab	0.754a
Square ×5	29.50bc	35.03ab	35.85ab	22.90a	0.771abc	0.811ab	0.790b	0.750a
Square ×6	27.43c	34.20ab	35.75ab	20.36b	0.748d	0.800b	0.788b	0.749a
Circular ×4	32.00a	35.83a	36.77a	22.94a	0.785a	0.825a	0.804a	0.754a
Circular ×5	29.73ab	34.74ab	35.81ab	22.80a	0.769bc	0.816a	0.793b	0.750a
Circular ×6	28.16c	33.62b	34.12b	22.53ab	0.762cd	0.810ab	0.788b	0.750a
Mean	29.64	34.86	35.74	22.56	0.77	0.81	0.79	0.75
CV (%)	13.73	8.69	10.1	17.1	3.52	3.29	1.98	2.01

Means with different letters within each column is significantly different at $P \leq 0.05$ using LSD

Reproductive stage

The data in *Table 4* revealed that the combined treatment with square ×6 achieved the shortest duration for first flowering (31.00 days), remaining comparable to circular ×6, square ×5 and circular ×5 treatments. This specific combination treatment also led to the quickest days to fruiting (44.33 days) and a significant reduction in the time to initial harvesting (52.17 days). Phenological processes in cucumber plants exhibited a delay with decreased plant density and an accelerated pace with increased plant density. Plants with lower density displayed prolonged maturity, possibly due to improved resource utilisation efficiency at higher plant population densities. The uptake and conversion of resources into biomass were density dependent, with competition initiated as soon as plants reached sufficient size (Weiner and Freckleton 2010; Tana et al. 2017). Moreover, the square ×6 combination treatment recorded the highest counts of male flowers (107.75) and female flowers (13.58). Higher plant density often led to increased flower production due to heightened competition for resources such as sunlight, nutrients and water. In densely populated plant settings, elevated competition prompted plants to allocate more energy to reproductive processes, resulting in a greater number of flowers as part of their reproductive strategy (Novoplansky 2009; Bonser 2013). Additionally, the design of the square shaded canopy architecture featured an expanded surface area, enabling a greater number of leaves to serve as a canopy. This increased leaf counts intensified competition for light, potentially leading to early maturity for plants. In environments where plants had to compete for available light resources, those proficient in capturing and utilising light tended to experience accelerated growth. This competition for light compelled plants to allocate more energy to growth and development, expediting the maturation process (Cho et al. 2017; Liu et al. 2022).

Yield

The data presented in *Table 5* revealed that there was no significant difference in the interaction between canopytecture design and plant density concerning yield per fruit, yield/plant/pot. Notably, the sole factor influencing crop yield was the canopy's capacity to capture essential resources such as light, water and nutrients, even in high plant density. Additionally, the efficiency in converting these resources into biomass and the extent to which biomass was allocated played a significant role in determining crop yield (Wu et al. 2016). For yield/fruit, 6 plant/pot demonstrated comparable results to 4 and 5 plant/pot in terms of weight (0.35 kg), length (22.43 cm), and diameter (5.23 cm). This finding underscored that an increase in plant density did not negatively impact crop yield. The designated canopytecture continued to effectively accommodate the growth of 6 plants without compromising the overall yield. In the context of yield/plant, the maximum number of fruits (7.33) and the heaviest fruit weight (1.77 kg) were observed with 6 plant/pot. This pattern was similarly reflected in yield/pot, where 6 plant/pot yielded the highest number of fruits (42.50) and the greatest fruit weight (10.73 kg). This consistency across different parameters highlighted the robustness of the chosen canopytecture, affirming its ability to support the growth of 6 plants while maximising the overall yield.

Table 4. Interaction effect of canopytecture design and density on number of days to flowering, number of days to fruiting, number of days to first harvesting, number of male flowers and number of female flowers of cucumber (*Cucumis sativus* L.)

Treatment	Number of days to flowering	Number of days to fruiting	Number of days to first harvesting	Number of male flowers	Number of female flowers
Square×4	31.25a	47.21a	53.67ab	91.38b	8.79d
Square×5	31.00b	45.54ab	52.88bc	99.71ab	10.92bc
Square×6	31.00b	44.33b	52.17c	107.75a	13.58a
Circular×4	32.17a	47.25a	54.25a	92.63b	9.46cd
Circular×5	31.25b	46.50a	53.50abc	93.71b	10.17bcd
Circular×6	31.00b	44.67b	52.33bc	100.88ab	11.58b
Mean	31.27	45.92	53.13	97.67	10.75
CV (%)	1.81	6.69	4.44	18.54	27.14

Means with different letters within each column is significantly different at $P \leq 0.05$ using LSD.

Table 5. Effect of canopytecture design and density on yield/fruit, yield/plant/pot of cucumber (*Cucumis sativus* L.)

Treatment	Yield/fruit			Yield/plant		Yield/pot	
	Weight (kg)	Length (cm)	Diameter (cm)	Number of fruits	Weight of fruits (kg)	Number of fruits	Weight of fruits (kg)
Design							
Square	0.32a	21.79a	50.65a	6.44a	1.53a	34.22a	8.94a
Circular	0.34a	22.09a	52.44a	6.72a	1.68a	32.56a	8.20a
Density							
4	0.31a	21.67a	5.03a	5.42b	1.33b	22.33b	5.65b
5	0.33a	21.72a	5.21a	7.00a	1.72a	35.33a	9.33a
6	0.35a	22.43a	5.23a	7.33a	1.77a	42.50a	10.73a
Design×density							
Square×4	0.34a	22.37a	52.64a	9.86a	1.39a	21.67a	5.57a
Square×5	0.32a	21.70a	50.77a	8.80a	1.59a	32.33a	8.80a
Square×6	0.31a	21.35a	49.79a	5.57a	2.08a	38.33a	9.86a
Circular×4	0.38a	22.50a	53.91a	12.45a	1.27a	23.00a	5.73a
Circular×5	0.33a	22.09a	51.49a	9.02a	1.46a	36.33a	9.02a
Circular×6	0.31a	21.65a	50.69a	5.73a	1.86a	48.67a	12.48a
Mean	0.33	21.94	5.15	6.58	1.61	33.38	8.57
CV (%)	20.24	7.97	11.04	22.83	16.57	23.98	20.32

Means with different letters within each column is significantly different at $P \leq 0.05$ using LSD

Conclusion

Enhancing canopytecture design and adjusting plant density proved successful in improving the vegetative, physiological, reproductive, and yield aspects of cucumber (*Cucumis sativus* L.) under a rainshelter. A circular canopy structure with a density of 6 plant/pot maximised plant height, likely due to competition for light and nutrients, though it also resulted in reduced stem diameter. Lower readings of relative chlorophyll content and chlorophyll fluorescence for this density indicated higher stress levels in the plants, leading to shorter durations for flowering, fruiting and initial harvesting. This stress, consequently, led to shorter durations for flowering, fruiting and initial harvesting. The 6 plant/pot treatment notably impacted the number of female and male flowers, significantly enhancing overall yield. Interestingly, a plant density of 5 plant/pot provided comparable growth and yield outcomes to 6 plant/pot, suggesting that either option is effective for achieving similar results.

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Conflict of interest declaration

Each author played a role in conceiving and designing the study, writing the article, critically revising it for essential intellectual content and approving the final version. This paper has not been submitted to other journal or any other publishing outlet, and it is not currently under review elsewhere.

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