Growth and Physiological Responses of *Dendrocalamus asper* as Influenced by Different Water Application

Zainol Haida,[a] Ruzana Sanusi,[a,b,]* Hafidz Khairul Hisham,[b] Sheriza Mohd Razali,[a] and Hazandy Abdul Hamid [a,b]

Bamboo plantations are in high demand in the global market due to bamboo's versatility and fast-growing nature. *Dendrocalamus asper* is one of the important species and is utilized in various industries, making it an economically valuable crop. Increasing yields while maintaining effective cost management is essential for planters. However, water stress possesses a significant challenge which can potentially disrupt bamboo growth and its physiological responses and thus the plant productivity. The objective of this study was to evaluate the growth and physiological responses of *D. asper* under different water treatments. A total of 45 seedlings were placed in a greenhouse and subjected to three different watering regimes at field capacity. The growth and physiological parameters including culm diameter, plant height, transpiration rate, photosynthesis rate, intercellular carbon dioxide concentration, and stomatal conductance were measured. The study showed that 100% of water capacity produced the best results for all the growth and physiological parameters measured. The reduction of water significantly reduced the growth of the seedlings, and the increment of water application beyond that point did not contribute to the increment of the plant growth. This indicates that excessive watering of bamboo did not improve growth performance, emphasizing the importance in optimizing water usage and conserving resources for economic sustainability.

DOI: 10.15376/biores.20.3.6069-6081

Keywords: Water use efficiency; Plant height; Diameter breast height; Transpiration rate; Net photosynthesis rate; Intercellular carbon dioxide concentration; Stomatal conductance

Contact information: a: Institute of Tropical Forestry and Forest Products, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia; b: Department of Forestry Science and Biodiversity, Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia;
** Corresponding author: ruzanasanusi@upm.edu.my*

INTRODUCTION

Forest plantations play a vital role in supporting the sustainable management of Malaysia's natural resources, contributing significantly to both the economy and environmental conservation. Malaysia is one of the world's largest exporters of timber and timber-based products alongside other countries including Canada, China, Indonesia, Brazil, Thailand, and the United States (Huang *et al*. 2024). The importance of establishing forest plantations has been recognized in Malaysia to meet the growing demand for timber while reducing pressure on natural forests. The forest plantations provide a sustainable source of wood and non-wood products, which also contribute to biodiversity conservation and carbon sequestration (McEwan *et al*. 2020; Betts *et al*. 2021). In Malaysia, the establishment of forest plantations mainly involves fast-growing native or non-native tree species to enhance the production of pulp and wood. Fast-growing trees are characterized by a mean annual increment of at least 10 to in excess 40 cubic meters per hectare (m^3/ha/year), though this can vary depending on species traits, soil conditions, climate, and management practices (IUFRO 2024). According to Malaysian Timber Industry Board (MTIB) (2021), a total of 11 plant species including *Hevea brasiliensis*, *Acacia mangium*, *Tectona grandis*, *Khaya ivorensis* and *Khaya senegalensis*, *Azadirachta excelsa*, *Neolamarckia cadamba*, *Paraserianthes falcataria*, *Octomeles sumatrana*, *Paulownia* species, *Eucalyptus* species, and bamboo species are listed under the Forest Plantation Development Programme.

Bamboo plantation has become a key focus for sustainable development in Malaysia, offering economic and environmental benefits. Malaysia's tropical climate with warm temperatures and abundant rainfall provides an ideal environment for bamboo growth (Thuy *et al*. 2021). In Malaysia, over 60 species of bamboo have been identified, with both exotic and native varieties thriving all over the country (MTIB 2021). The most commonly planted bamboos in Malaysia include *Dendrocalamus asper*, *Gigantochloa albociliata*, *Gigantochloa scortechinii*, *Bambusa vulgaris*, and *Bambusa nutans* (Goh *et al*. 2020). These species are mostly planted because of high yield, fast growth, and the fact that they can be utilized for various purposes such as furniture, paper production, and construction materials as well as for mitigation of soil erosion (Ekhuemelo *et al*. 2018; Isukuru *et al*. 2023). The demand for bamboo and bamboo-based products keeps growing and is expected to further increase in the future. However, the current bamboo plantations in Malaysia could not meet the market demand due to shortage of bamboo raw materials (Hamid *et al*. 2018).

Dendrocalamus asper, which is known as giant bamboo or Buluh Betung, is one of the most planted bamboos in Malaysia. It is one of the largest and most valuable bamboo species found in Malaysia and Southeast Asia (Hassan *et al*. 2022). *D. asper* can grow to 30 m tall with culms diameters of 12 to 15 cm (Hassan *et al*. 2022). This species has rapid growth with mature culms, often to be harvested within 5 to 7 years (Mustafa *et al*. 2021). The culms of *D. asper* are thick and solid, which makes the material suitable for various purposes such as eco-friendly timber-based products, construction materials, and paper (Azadeh *et al*. 2022; Khair and Masrol 2022), besides, the usage for flooring, scaffolding, textiles, and handicrafts (Felisberto *et al*. 2019; Umar *et al*. 2020; Aduldejcharas 2024). *D. asper* plays an important role in sustainable agricultural practices by promoting reforestation, soil conservation, and as an alternative to timber (Singh *et al*. 2020; Pan *et al*. 2023). In addition, a bamboo plantation can absorb 5.1 tons of carbon dioxide per hectare per year, depending on its size; thus, this huge amount can maintain the dynamic equilibrium in the atmosphere (Aparecido *et al*. 2018).

The health and stability of ecosystems are substantially at risk due to the rising frequency of extreme weather phenomena, such as flash floods and drought. Drought is characterized by extremely low soil moisture and high evapotranspiration, resulting from a combination of high temperatures and minimal precipitation (Yao *et al*. 2020). Research has shown that water shortages can disrupt bamboo production and quality (Wu *et al*. 2019). Conversely, other studies indicate that some bamboo species struggle to survive during flooding seasons (Sungkaew and Teerawatananon 2017). The species *D. asper*, which is widely planted globally, is not exempt from growth deterioration due to water scarcity and excess watering. Furthermore, improper watering and fertilizer application leads to resource wastage and negatively impacts plant growth and survival. Therefore, it is crucial to determine optimal watering regimes for *D. asper* to ensure effective silviculture management and maximize yield production. This present study aimed to evaluate *D. asper* growth and physiological responses to water stress. Specifically, the objectives were to:

1. Determine the effect of different watering regimes on the growth rate of *D. asper*.
2. Determine the effect of different watering regimes on leaf gas exchange of *D. asper*.

The study will provide a better knowledge of morphological and physiological responses of *D. asper* under different water regimes. Additionally, this study will identify the most effective silvicultural treatments, particularly in terms of irrigation practice for *D. asper*. The findings will benefit the bamboo plantations planters by providing information on suitable watering regime in developing effective nursery water management plans for bamboo cultivation. Ultimately, this study will contribute to producing high-quality yield, while minimizing water waste and associated costs through efficient resource management.

EXPERIMENTAL

Experimental Site

The experiment was carried out in a greenhouse at the Plant Nursery, Institute of Tropical Forestry and Forest Products, Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia (coordinates: 101°42’14.9832” E, 3°0’10.9116” N). In the greenhouse, the average temperature ranged from 27 °C to 40 °C and relative humidity ranged from 75% to 80%.

Planting Materials and Maintenance

A total of 45 healthy *D. asper* seedlings were used for this experiment. The seedlings were raised in the polybag (16 cm width × 19 cm height) and acclimatized for 10 months. The soil medium used was sandy loam topsoil. The plants were maintained in the greenhouse and watered regularly in the morning and evening. The weeding activity was done manually every week to avoid any competition to the *D. asper* plants.

Water Field Capacity Analysis

The water field capacity was conducted prior to the experiment to determine the water holding capacity of the soil medium. Briefly, 1.0 kg of soil sample was oven dried for 24 h and sieved with a 2.0 mm sieve. The soil was placed in a pot and saturated with water. The pot was covered with a black plastic sheet. After 24 h, the water content in the soil medium was measured using Tome Domain Reflectometer (Trime-Pico 64). The water field capacity of the soil medium was presented in Table 1. Based on the water field capacity analysis, the soil medium used in this study was favorable for an optimal plant growth.

Table 1. Mean Value of Temperature, Electrical Conductivity and Field Capacity

Soil Properties	Temperature (°C)	Electrical Conductivity (dS m^{-1})	Field Capacity (%)
Value	29	0.16	18.22

Experimental Design

In this study, the experiment was laid out in completely randomized design (CRD) with three replications and five plants for each replication (n=15). The plants were subjected to three levels of water field capacity (50%, 100%, and 150%). The experiment was conducted from September until December 2023. The growth and leaf gas exchange parameters were measured the weeks of 1, 3, 5, 7, 9, 11 and 13.

Measurement of Growth Parameter

The plant diameter was measured at the basal of the culm by using the vernier caliper and height was measured from the basal to the top by using the meter tape. The diameter and plant height were expressed in millimeter (mm) and centimeter (cm), respectively.

Measurement of Leaf Gas Exchange

The leaf gas exchange parameters including transpiration rate, net photosynthesis rate, intercellular carbon dioxide (CO_2) concentration, and stomatal conductance were measured using the Portable Photosynthesis System (LI-6800, Li-COR Inc., Lincoln, NE, USA). Three fully expanded leaves of each clump were chosen and measurements were made in the morning (09:00 am to 12:00). Measurements were used with the following settings: photosynthetically active radiation (PAR) at 1000 μmol m^{-2} s^{-1}, 400 μmol mol^{-1} for CO_2 in the chamber, 30 °C of cuvette temperature and 60% of relative humidity with the airflow was set at 500 μmol s^{-1}.

Statistical Analysis

All the data for growth and leaf gas exchange parameters were analyzed with two-way analysis of variance (ANOVA) between the factorials water field capacity and number of weeks The analysis was performed using Statistical Analysis System (SAS ver. 9.4, Cary, NC, USA). The mean separation between the treatments was conducted using Tukey's Honestly Significant Difference (HSD) test at $p<0.05$.

RESULTS AND DISCUSSION

The water stress treatments applied to *D. asper* directly influenced its growth. The analysis of variance (Table 2) showed that the water field capacity significantly ($p < 0.05$) affected the culm diameter of the *D. asper*. The plants watered with 100% of field capacity significantly produced the biggest culm diameter with 6.04 mm, followed by treatment of 150% and 50% with the of 5.56 and 4.85 mm, respectively. Based on the analysis by week, the culm diameter recorded at week 1, 3, 5 and 9 were not significantly influenced by the application of water at 100% and 150% of field capacity. However, the culm diameter of plants watered with 100% was significantly increased at week 11 and 13 with the value recorded 7.08 and 8.07 mm, respectively.

The effect of water stress was observed on the plant growth of *D. asper*. The treatment of 100% of water at field capacity significantly exhibited the highest plant height with 75.4 cm, followed by the treatment of 150% of water at field capacity with 72.3 cm (Table 2). Meanwhile, treatment of 50% at field capacity exhibited the shortest plant height with 67.8 cm.

Table 2. The Effect of Water Field Capacity Application on Growth Parameters of *D. asper*

Parameter	Treatment	Week							
		1	3	5	7	9	11	13	Mean
Diameter breast height (mm)	50	3.81 b	4.00 b	4.33 b	4.32 c	5.00 b	6.01 b	6.49 c	4.85 C
	100	4.54 a	4.64 a	4.96 a	6.25 a	6.72 a	7.08 a	8.07 a	6.04 A
	150	4.42 a	4.51 a	4.81 a	5.74 b	6.38 a	6.28 b	6.81 b	5.56 B
	Mean	4.25 F	4.38 F	4.70 E	5.44 D	6.03 C	6.46 B	7.13 A	
	F value								
	Water field capacity	523.18***							
	Week	765.85***							
	Water field capacity x Week	25.30***							
		1	3	5	7	9	11	13	Mean
Plant height (cm)	50	56.40 a	60.70 b	61.50 b	65.93 b	69.43 c	77.13 b	83.27 b	67.77 C
	100	53.37 a	65.53 a	68.77 a	69.67 ab	72.67 b	85.47 a	112.20 a	75.38 A
	150	55.87 a	61.60 b	69.40 a	71.87 a	77.30 a	81.83 ab	89.00 b	72.34 B
	Mean	55.21 G	62.61 F	66.56 E	68.99 D	73.13 C	81.48 B	94.82 A	
	F value								
	Water field capacity	132.98***							
	Week	659.89***							
	Water field capacity x Week	43.37***							

The values expressed in mean (n=45) followed by the same letter within the columns were not significantly different at $p<0.05$ using HSD test. The upper-case letters indicated the overall means by treatments and weeks. Meanwhile, the lower-case letters indicated the means between the treatments by weeks.

The ANOVA results show that the plant height was significantly affected as the number of weeks increased (Table 2). For the plants that received 50% of water at field capacity, the plant height increased from 56.4 cm (week 1) to 83.3 cm (week 13), showing a total increment of 26.9 cm over 13 weeks. As for the treatment 100% of water at field capacity, the plant height increased from 53.4 cm in week 1 to 112.2 cm in week 13 with a total increment of 58.8 cm. Meanwhile, the plants that received an excessive water treatment showed an increment of plant height from 55.9 cm to 89 cm over 13 weeks with a total increment of 33.1 cm, respectively. In this study, it was observed that treatment of 150% water at field capacity produced higher plant height from week 5 to week 11 as compared to treatment 100% water at field capacity. This might be due to the physiological and environmental factors. For bamboo plants, some species need high amounts of water at the early stage, which results in greater plant height. However, after the plant adapts in a new environment, the growth of the plant including plant height will accelerate under optimal water treatment.

The treatment of water stress significantly impacted the leaf gas exchange parameters. The results in Table 3 show that the application of 50%, 100%, and 150% at field capacity significantly affected the transpiration rate of *D. asper*. The treatment 100%

of water capacity significantly produced the highest transpiration rate with 3.78 mmol H_2O $m^{-2}s^{-1}$. Meanwhile, treatments at 50% and 100% of field capacity did not significantly affect the transpiration rate of *D. asper*.

The highest transpiration rate was recorded in week 13 after planting. Based on the weekly analysis, the transpiration rate showed an increment trend for all the water capacity treatments. The transpiration rate ranged between 2.8 and 3.6 mmol H_2O $m^{-2}s^{-1}$ from week 1 to week 9 for all the water capacity treatments. At week 11 and week 13, the transpiration rate of the 100% water capacity was drastically increased to 4.05 and 5.34 mmol H_2O $m^{-2}s^{-1}$, respectively. In contrast, the highest transpiration rate recorded for the treatment 50% and 150% at field capacity were 3.94 and 3.70 mmol H_2O $m^{-2}s^{-1}$ on week 13. The transpiration rate for the treatment 100% of water at field capacity was more intense from week 9 to week 13 as compared to treatment of 50% and 150% water at field capacity. This might be due to the fact that plants with 100% water at field capacity received optimal soil moisture for stomatal conductance, by which the plants were able to maximize transpiration. In contrast, excess water (150% water at field capacity) might have led to mild root hypoxia, reducing root function and limiting water uptake and transpiration.

For the net photosynthesis rate, the statistical analysis showed that different water capacity application on the *D. asper* significantly affected the net photosynthesis rate from week 1 to week 13 (Fig. 4). The highest net photosynthesis rate was recorded from the treatment 100% of water capacity, followed by the treatments with 50% and 150% of water capacity with 9.02, 8.33 and 8.19 µmol CO_2 $m^{-2}s^{-1}$, respectively. Based on the weekly analysis, a stable increment of net photosynthesis rate was observed from all the water capacity treatments from week 1 to week 7. Starting from the week 9, the net photosynthesis rate recorded from the treatment 100% water capacity was drastically increased and reached the peak at week 13 with 11.30 µmol CO_2 $m^{-2}s^{-1}$. Meanwhile, treatment of 50% and 150% of water at field capacity did not significantly affect the net photosynthesis rate at week 11 and week 13. The more intense increment in photosynthesis rate at 100% water at field capacity from the week 9 to week 13 was because at 100% water at field capacity, soil moisture was ideal for maintaining high stomatal conductance and efficient CO_2 diffusion into the leaves and resulted with high photosynthesis rate. At lower water levels, plants might have partially closed the stomata to reduce water loss, limiting CO_2 uptake and reducing photosynthesis. Meanwhile, excess water caused root hypoxia, reducing nutrient and water uptake, leading to lower photosynthetic efficiency.

Next, it was found that water capacity significantly affected the intercellular CO_2 concentration in *D. asper* (Table 3). Application of 100% of water capacity significantly showed the highest intercellular CO_2 concentration with 317.82 µmol mol^{-1}. Meanwhile, the lowest intercellular CO_2 concentration was exhibited from the treatment 150% of water capacity with 308.52 µmol mol^{-1}. From Table 3, the 100% treatment at field capacity exhibited the highest intercellular CO_2 concentration from week 1 (304 µmol mol^{-1}) to week 13 (335 µmol mol^{-1}). The lowest intercellular CO_2 concentration in *D. asper* was observed from the treatment 150% at field capacity with 296 µmol mol^{-1} (week 1) to 320 µmol mol^{-1} (week 13).

Table 3. Effect of Water Field Capacity Application on Physiological Parameters of *D. asper*

Parameter	Treatment	Week							
		1	3	5	7	9	11	13	Mean
Transpiration Rate (mmol H_2O $m^{-2}s^{-1}$)	50	2.82 c	2.97 c	3.13 a	3.33 ab	3.37 ab	3.56 b	3.94 b	3.30 B
	100	3.28 a	3.31 a	3.43 a	3.47 a	3.58 a	4.05 a	5.34 a	3.78 A
	150	3.06 b	3.15 b	3.24 a	3.28 b	3.31 b	3.43 b	3.70 b	3.31 B
	Mean	3.02 E	3.14 DE	3.27 CD	3.37 C	3.42 C	3.68 B	4.33 A	
	F value								
	Water field capacity	138.23***							
	Week	146.49***							
	Water cap.x Week	22.02***							
		1	3	5	7	9	11	13	Mean
Photosynthesis Rate (μmol CO_2 $m^{-2}s^{-1}$)	50	7.81 ab	8.00 a	8.17 a	8.40 ab	8.27 b	8.54 b	9.15 b	8.33 B
	100	8.05 a	8.14 a	8.30 a	8.69 a	9.01 a	9.65 a	11.30 a	9.02 A
	150	7.62 b	7.83 a	7.73 b	8.23 b	8.66 ab	8.37 b	8.89 b	8.19 C
	Mean	7.82 F	7.99 EF	8.07 E	8.44 D	8.65 C	8.86 B	9.78 A	
	F value								
	Water field capac.	231.40***							
	Week	227.39***							
	Water cap.x Week	33.78***							
		1	3	5	7	9	11	13	Mean
Intercellular CO_2 Concentration (μmol mol^{-1})	50	298.54 b	303.73 a	307.19 a	314.35 b	315.19 ab	322.97 a	326.78 b	312.68 B
	100	303.48 a	308.38 a	313.56 a	317.63 a	320.37 a	326.23 a	335.11 a	317.82 A
	150	296.25 b	303.19 a	306.25 a	309.63 c	310.55 b	313.71 a	320.02 b	308.52 C
	Mean	299.43 F	305.10 E	309.00 DE	313.87 CD	315.37 C	320.97 B	327.32 A	
	F value								
	Water field capac.	34.18***							
	Week	60.51***							
	Water cap.x Week	0.93***							
		1	3	5	7	9	11	13	Mean
Stomatal Conductance (mmol $m^{-2}s^{-1}$)	50	0.26 b	0.26 b	0.26 b	0.27 b	0.28 b	0.30 b	0.32 b	0.27 B
	100	0.30 a	0.31 a	0.32 a	0.35 a	0.34 a	0.42 a	0.45 a	0.36 A
	150	0.25 b	0.26 b	0.27 b	0.26 b	0.27 b	0.29 b	0.31 b	0.28 B
	Mean	0.27 E	0.28 DE	0.28 CDE	0.29 CD	0.30 C	0.34 B	0.36 A	
	F value								
	Water field capac.	276.22***							
	Week	60.62***							
	Water cap.x Week	8.45***							

Values expressed in mean (n=45) followed by the same letter within the columns were not significantly different at $p<0.05$ using HSD test. The upper-case letters indicated the overall means by treatments and weeks. Meanwhile, the lower-case letters indicated the means between the treatments by weeks.

As for the stomatal conductance, treatment at 100% of water capacity resulted in significantly the highest value with 0.36 mmol $m^{-2}s^{-1}$ (Table 3). Meanwhile, the treatment 50% and 150% at field capacity did not significantly influence the stomatal conductance of *D. asper*, with 0.27 and 0.28 mmol $m^{-2}s^{-1}$, respectively. At the beginning of the planting duration, the stomatal conductance ranged from 0.27 to 0.30 mmol $m^{-2}s^{-1}$ from week 1 to week 9. At week 11 and week 13, the stomatal conductance was significantly increased. The values recorded were 0.34 and 0.36 mmol $m^{-2}s^{-1}$, respectively. The individual trend of the field capacity treatment is presented in Table 3. The stomatal conductance value recorded for all the water capacity treatment ranged between 0.25 and 0.32 mmol $m^{-2}s^{-1}$.

Water availability is a critical factor affecting plant growth and physiological processes. The results of this study indicate that water field capacity significantly influenced the growth and leaf gas exchange performances, with optimal water availability contributing to better growth of *D. asper*. Field capacity refers to the measurement of water application on the plant, making it possible to determine an optimal amount of water needed by plant without excessive leaching (van Lier 2017). The results in this study found that 100% of watering at field capacity was the optimal field capacity for promoting growth of *D. asper* with greatest height at 75.4 cm compared to 50% and 150% water at field capacity with 67.8 and 72.3 cm, respectively. As 100% watering at field capacity produced the highest plant height, this treatment also recorded the highest culm diameter with 6.04 cm. In a study conducted by Vaconcelos *et al*. (2022), the growth and physiological responses of *D. asper* were affected by the application of water at 0.25%, 50%, and 100% of field capacity. The results found that different water field capacity did not significantly affect the shoot length and diameter of culm of *D. asper* at days 7 and 30. The results on physiological responses indicated that watering at 100% of field capacity resulted in the highest transpiration rate and stomatal conductance of *D. asper*. Similarly, 100% watering at field capacity resulted in the highest transpiration rate and stomatal conductance with 3.78 mmol H_2O $m^{-2}s^{-1}$ and 0.36 mmol $m^{-2}s^{-1}$. A study by Souza *et al*. (2019) indicated that *Bambusa vulgaris* is more sensitive to water stress and reducing the volume of water resulted in the death of *B. vulgaris* seedlings. Bamboo species including *D. asper* are known for their rapid growth and high water requirements, making bamboo species highly sensitive to water availability (Kaur *et al*. 2019). The superior performance of *D. asper* under 100% water at field capacity is due to optimal water received by plants to support physiological and biochemical processes such as nutrient uptake, cell expansion, and photosynthesis (Wahab *et al*. 2022). Adequate water supply ensures optimal turgor pressure which contributes to cell elongation (Nieves-Cordones *et al*. 2019). Hence, the increment of plant height and diameter breast height of the culm were observed.

Conversely, excessive application of water (150% at field capacity) negatively impacted the bamboo morphological and physiological responses. Excessive water creates hypoxic conditions in the root zone, thus reducing oxygen availability for root respiration. This anaerobic environment inhibits nutrient update and transport, leading to lower stomatal conductance and photosynthesis rates (Habibi *et al*. 2023). The stomatal conductance and net photosynthesis rate exhibited from *D. asper* under the treatment of 150% water at field capacity were 0.28 mmol $m^{-2}s^{-1}$ and 8.19 μmol CO_2 $m^{-2}s^{-1}$ which was significantly lower than *D. asper* under the treatment of 100% water at field capacity. Furthermore, excessive water conditions promote the production of ethylene, a hormone that inhibits cell division and elongation and decreases the growth rate of the plants (Dubois *et al*. 2018). The plant height of *D. asper* was reduced by 4.03% as the water at field capacity was increased from 100% to 150%. Meanwhile, the culm diameter also was reduced by 7.95% when the plants received 150% water at field capacity. In this study, the decrement of intercellular CO_2 concentration from 318 µmol mol^{-1} under 100% watering at field capacity to 309 µmol mol^{-1} under 150% watering at field capacity was observed. The decrease of intercellular CO_2 concentration under excessive water conditions indicated a disruption in the balance between CO_2 uptake and assimilation. Under excessive water conditions, impaired root function limits overall physiological capacity of the plant (Pais *et al*. 2022; Zhu *et al*. 2024). These mechanisms in physiological processes collectively explain the lower growth performance of 150% of water at field capacity compared to the optimal conditions at 100% of water at field capacity.

In this present study, water stress particularly at 50% of water at field capacity significantly affected physiological responses including intercellular CO_2 concentration, transpiration rate, net photosynthesis rate, and stomatal conductance. The transpiration rate and stomatal conductance of *D. asper* under 50% of watering at field capacity was significantly lower than 100% watering at field capacity, however not significantly different with 150% watering at field capacity. Meanwhile, the net photosynthesis rate and intercellular CO_2 concentration were significantly affected at 50% water at field capacity, which was significantly higher than 150% water at field capacity. Under water deficit conditions, the stomata are closed to reduce water loss through transpiration. However, this stomatal closure limits the diffusion of CO_2 into the leaf, resulting in a decline in net photosynthesis (Devi and Reddy 2018). The reduction in photosynthesis translates to lower carbohydrate production, which directly affects energy availability for cell expansion, elongation, and biomass accumulation (Shah *et al*. 2024). For bamboo species, physiological impairments result in shorter internodes and small culm diameter, which causes low plant height and diameter breast height. Prolongation of water stress also triggers oxidative stress by accumulating reactive oxygen species that can damage cellular structures including chloroplast where the photosynthesis process occurs (Sachdev *et al*. 2021). In addition, water stress causes an increment of abscisic acid concentration. Abscisic acid is a hormone that inhibits cell division and elongation and promotes stomatal closure (Muhammad *et al*. 2022). This is in line with the current findings, where a decrease of watering to 50% at field capacity resulted in lower culm diameter and plant height compared to the *D. asper* under the 100% and 150% water at field capacity. The reduction of plant growth and productivity are essential for plants to adapt and survive under water stress conditions.

For bamboo growers, maintaining water at 100% field capacity is essential for achieving optimal growth and productivity in *D. asper*. An optimal water irrigation is very important to support critical physiological processes, including efficient photosynthesis, transpiration, and stomatal conductance, which directly influence plant growth and development. Practical implementation includes precise irrigation techniques such as soil moisture sensors to monitor water supply in order to ensure that the plants have optimal growth and development. Additionally, mulching can be applied to conserve soil moisture and minimize water evaporation. By optimizing water use efficiently, growers can enhance the production of biomass with low water waste and irrigation costs, making 100% of water at field capacity a sustainable and economically viable strategy for large-scale bamboo cultivation. This approach ensures long-term environmental and economic benefits, aligning with sustainable agricultural practices.

CONCLUSIONS

The present study demonstrated that water stress was significantly impacted on the growth and leaf gas exchange parameters of *Dendrocalamus asper*.

1. The treatment at 100% of water capacity was found to be an optimal amount of water needed for the *D. asper*, as it produced the best results in terms of size of culm diameter, plant height, transpiration rate, net photosynthesis rate, intercellular carbon dioxide concentration, and stomatal conductance.
2. The plants watered at 50% and 150% of field capacity showed an increment in the parameters recorded; however, the increment was not as high as the treatment with 100% of water capacity.
3. The results showed that although *D. asper* is a fast-growing plant with high water intake, excessive watering is not needed to produce an optimal growth.
4. This study also found that *D. asper* can grow under low water supply without majorly affecting the growth and leaf gas exchange activity.

ACKNOWLEDGMENTS

The authors are grateful for the financial support given by the Ministry of Higher Education Malaysia (MOHE) under the Higher Institution Centre of Excellence (800-3/8/HICoEF2/2023/5210001) at the Institute of Tropical Forestry and Forest Products, Universiti Putra Malaysia.

REFERENCES CITED

Aduldejcharas, R. (2024). "Bamboo (*Dendrocalamus asper*) as an eco-friendly sustainable material: Optimising mechanical properties and enhancing load-bearing capacity for environmental architectural design," *Nakhara: Journal of Environmental Design and Planning* 23(2), 414-414. DOI: 10.54028/NJ202423414

Aparecido, L. E. D. O., Moraes, J. R. D. S. C. D., Rolim, G. D. S., Martorano, L. G., Soares, S. D. S., de Meneses, K. C., Costa, C. T. S., Mesquita, D. Z., Barbosa, A. M. D. S., do Amaral, E. F., and Bardales, N. G. (2018). "Neural networks in spatialization of meteorological elements and their application in the climatic agricultural zoning of bamboo," *International Journal of Biometeorology* 62, 1955-1962. DOI: 10.56083/RCV3N10-064

Azadeh, A., De Sá, A. D., Kadivar, M., Gauss, C., and Junior, H. S. (2022). "The effect of densification on physical and mechanical properties of bamboo *Dendrocalamus asper*," *European Journal of Wood and Wood Products* 80(4), 877-888. DOI: 10.1007/s00107-022-01823-5

Betts, M. G., Phalan, B. T., Wolf, C., Baker, S. C., Messier, C., Puettmann, K. J., Green, R., Harris, S. H., Edwards, D. P., Lindenmayer, D. B., and Balmford, A. (2021). "Producing wood at least cost to biodiversity: Integrating T riad and sharing–sparing approaches to inform forest landscape management," *Biological Reviews* 96(4), 1301-1317. DOI: 10.1111/brv.12703

Devi, M. J., and Reddy, V. R. (2018). "Transpiration response of cotton to vapor pressure deficit and its relationship with stomatal traits," *Frontiers in Plant Science* 9, article 1572.

Dubois, M., Van den Broeck, L., and Inzé, D. (2018). "The pivotal role of ethylene in plant growth," *Trends in Plant Science* 23(4), 311-323. DOI: 10.3389/fpls.2018.01572

Ekhuemelo, D. O., Tembe, E. T., and Ugwueze, F. A. (2018). "Bamboo: A potential alternative to wood and wood products," *South Asian Journal of Biological Research* 1(1), 9-24. DOI: 10.5539/jmsr.v2n2p90

Felisberto, M. H. F., Beraldo, A. L., Costa, M. S., Boas, F. V., Franco, C. M. L., and Clerici, M. T. P. S. (2019). "Characterization of young bamboo culm starch from *Dendrocalamus asper*," *Food Research International* 124, 222-229. DOI: 10.1016/j.foodres.2018.03.074

Goh, Y., Yap, S. P., and Tong, T. Y. (2020). "Bamboo: The emerging renewable material for sustainable construction," *Encyclopedia of Renewable and Sustainable Materials* 2, 365-376. DOI: 10.1016/B978-0-12-803581-8.10748-9

Habibi, F., Liu, T., Shahid, M. A., Schaffer, B., and Sarkhosh, A. (2023). "Physiological, biochemical, and molecular responses of fruit trees to root zone hypoxia," *Environmental and Experimental Botany* 206, article 105179. DOI: 10.1016/j.envexpbot.2022.105179

Hamid, A. G. A., Rahman, K. A. A. A., and Ismail, S. (2018). "The factor of industrial development problems on bamboo furniture designs in Malaysia: A concept paper," *Global Business and Management Research* 10(3), article 881.

Hassan, N. H. M., Abdullah, N., Kelana, D. N. A., and Perumal, M. (2022). "Early field growth performance of ten selected bamboo taxa: The case study of Sabal bamboo pilot project in Sarawak, Malaysia," *Biodiversitas Journal of Biological Diversity* 23(6), 2882-2892. DOI: 10.13057/biodiv/d230614

Huang, H., Su, S., and Li, L. (2024). "Advancing timber construction: historical growth, research frontiers, and time series forecasting," *Journal of Asian Architecture and Building Engineering* 1-30. DOI: 10.1080/13467581.2024.2373829

Isukuru, E. J., Ogunkeyede, A. O., Adebayo, A. A., and Uruejoma, M. F. (2023). "Potentials of bamboo and its ecological benefits in Nigeria," *Advances in Bamboo Science* 4, article 100032. DOI: 10.1016/j.bamboo.2023.100032

IUFRO. (2024). "Fast-growing trees to advance wood in the bioeconomy in Africa," *International Union of Forest Research Organization* Accessed from https://www.iufro.org/divisions/40000-forest-assessment-modeling-and-management/40400-forest-management-planning/40402-planning-and-economics-of-fast-growing-plantation-forests (Accessed on 12th March 2025).

Kaur, P. J., Pant, K. K., and Kaushik, G. (2019). "Properties and importance of various bamboo species for multi-utility applications," *Sustainable Agriculture, Forest and Environmental Management* 251-283. DOI: 10.1007/978-981-13-6830-1_8

Khair, F. N. M., and Masrol, S. R. (2022). "The characteristics of pulp and paper made from top section of Betong (*Dendrocalamus Asper*) bamboo by soda pulping method," *Progress in Engineering Application and Technology* 3(1), 849-857. DOI: 10.30880/peat.2022.03.01.084

Malaysia Timber Industry Board. (2021). *Development of Forest Plantation Programme. Malaysia Timber Industry Board,* Accessed on 8th December 2023.

McEwan, A., Marchi, E., Spinelli, R., and Brink, M. (2020). "Past, present and future of industrial plantation forestry and implication on future timber harvesting technology," *Journal of Forestry Research* 31, 339-351. DOI: 10.1007/s11676-019-01019-3

Muhammad, A. M., Waseem, M., Jakada, B. H., Okal, E. J., Lei, Z., Saqib, H. S. A., Yuan, W., Xu, W., and Zhang, Q. (2022). "Mechanisms of abscisic acid-mediated drought stress responses in plants," *International Journal of Molecular Sciences* 23(3), article 1084. DOI: 10.3390/ijms23031084

Mustafa, A. A., Derise, M. R., Yong, W. T. L., and Rodrigues, K. F. (2021). "A concise review of *Dendrocalamus asper* and related bamboos: Germplasm conservation, propagation and molecular biology," *Plants* 10(9), article 1897. DOI: 10.3390/plants10091897

Nieves-Cordones, M., García-Sánchez, F., Pérez-Pérez, J. G., Colmenero-Flores, J. M., Rubio, F., and Rosales, M. A. (2019). "Coping with water shortage: An update on the role of K^+, Cl^-, and water membrane transport mechanisms on drought resistance," *Frontiers in Plant Science* 10, article 1619. DOI: 10.3389/fpls.2019.01619

Pais, I. P., Moreira, R., Semedo, J. N., Ramalho, J. C., Lidon, F. C., Coutinho, J., Maçãs, B., and Scotti-Campos, P. (2022). "Wheat crop under waterlogging: Potential soil and plant effects," *Plants* 12(1), article 149. DOI: 10.3390/plants12010149

Pan, C., Zhou, G., Shrestha, A. K., Chen, J., Kozak, R., Li, N., Li, J., He, Y., Sheng, C., and Wang, G. (2023). "Bamboo as a nature-based solution (NbS) for climate change mitigation: biomass, products, and carbon credits," *Climate* 11(9), article 175. DOI: 10.3390/cli11090175

Sachdev, S., Ansari, S. A., Ansari, M. I., Fujita, M., and Hasanuzzaman, M. (2021). "Abiotic stress and reactive oxygen species: Generation, signaling, and defense mechanisms," *Antioxidants* 10(2), article 277. DOI: 10.3390/antiox10020277

Shah, I. H., Jinhui, W., Li, X., Hameed, M. K., Manzoor, M. A., Li, P., Zhang, Y., Niu, Q., and Chang, L. (2024). "Exploring the role of nitrogen and potassium in photosynthesis implications for sugar: Accumulation and translocation in horticultural crops," *Scientia Horticulturae* 327, article 112832. DOI: 10.1016/j.scienta.2023.112832

Singh, L., Sridharan, S., Thul, S. T., Kokate, P., Kumar, P., Kumar, S., and Kumar, R. (2020). "Eco-rejuvenation of degraded land by microbe assisted bamboo plantation," *Industrial Crops and Products* 155, article 112795. DOI: 10.1016/j.indcrop.2020.112795

Souza, C. S., Oliveira, V. N. S., da Silva, E. C. A., Ferreira, L. M. M., Silva, M. J. N., and Araújo, P. C. D. (2019). "Comportamento de mudas de Bambusa vulgaris Schrad. EX JC Wendl submetidas ao estresse hídrico e salino, utilizando água residuária da pisciculture (Behavior of *Bambusa vulgaris* Schrad seedlings. EX JC Wendl subjected to water and saline stress, using wastewater from fish farming)," *Revista Ciência Agrícola* 17(2), 7-16. DOI: 10.28998/rca.v17i2.7055

Sungkaew, S., and Teerawatananon, A. (2017). "Survey of flood-tolerant bamboos in 2011 flooding in Thailand," *Agriculture and Natural Resources* 51(6), 499-503. DOI: 10.1016/j.anres.2018.03.001

Thuy, V. T., Huyen, N. T., and Loi, N. K. (2021). "Status of bamboos in Binh Duong province, Vietnam: Distribution, species diversity, conservation and utilization," *Trees, Forests and People* 6, article 100137. DOI: 10.1016/j.tfp.2021.100137

Umar, M. Z., Arsyad, M., Santi, S., and Faslih, A. (2020). "Principles of sustainable architecture in the production of bamboo woven wall materials (*Dendrocalamus asper*)," *Sinergi* 24(1), 57-64. DOI: 10.22441/sinergi.2020.1.008

van Lier, Q. D. J. (2017). "Field capacity, a valid upper limit of crop available water?," *Agricultural Water Management* 193, 214-220. DOI: 10.1016/j.agwat.2017.08.017

Vasconcelos, J. M., da Silva Lopes, H., da Silva Costa, F. H., de Oliveira Martins, M., and Scherwinski-Pereira, J. E. (2022). "Growth and physiological responses of young plants of *Dendrocalamus asper* (Poaceae: Bambusoideae) under water stress," *Brazilian Journal of Development* 8(6), 42694-42712. DOI: 10.34117/bjdv8n6-013

Wahab, A., Abdi, G., Saleem, M. H., Ali, B., Ullah, S., Shah, W., Mumtaz, S., Yasin, G., Muresan, C. C., and Marc, R. A. (2022). "Plants' physio-biochemical and phyto-hormonal responses to alleviate the adverse effects of drought stress: A comprehensive review," *Plants* 11(13), article 1620. DOI: 10.3390/plants11131620

Wu, X. P., Liu, S., Luan, J., Wang, Y., and Cai, C. (2019). "Responses of water use in Moso bamboo (*Phyllostachys heterocycla*) culms of different developmental stages to manipulative drought," *Forest Ecosystems* 6, 1-14. DOI: 10.1186/s40663-019-0189-8

Yao, N., Li, L., Feng, P., Feng, H., Li Liu, D., Liu, Y., Jiang, K., Hu, X., and Li, Y. (2020). "Projections of drought characteristics in China based on a standardized precipitation and evapotranspiration index and multiple GCMS," *Science of the Total Environment* 704, article 135245. DOI: 10.1016/j.scitotenv.2019.135245

Zhu, K., Zuo, Q., Liu, F., Qin, J., Wang, A., Zhang, J., and Flexas, J. (2024). "Divergences in leaf CO_2 diffusion conductance and water use efficiency of soybean coping with water stress and its interaction with N addition," *Environmental and Experimental Botany* 217, article 105572. DOI: 10.1016/j.envexpbot.2023.105572

Article submitted: February 8, 2025; Peer review completed: March 9, 2025; Revised version received: March 15, 2025; Accepted: June 1, 2025; Published: June 9, 2025.
DOI: 10.15376/biores.20.3.6069-6081