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Responses to Water Deficit of Mung Bean Cultivars at the Vegetative and Flowering Stages under Greenhouse Conditions

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Abstract

Mung bean (*Vigna radiata* L. Wilczek) is grown mainly under rainfed conditions, facing water deficits in different growth stages. This study was conducted to evaluate the responses of a local cultivar, Dau tam Thanh Hoa, and three introduced mung bean cultivars (DX14, Mongo Labo, and TV06425) to water stress at the different growth stages. The experiment was carried out in a greenhouse following a completely randomized arrangement with two replications. Drought was induced by withholding water at either the vegetative or flowering growth stages for 20 consecutive days. The control consisted of well-watered plants. After 8, 12, 15, and 20 days of drought, plant available water, growth characteristics, and the weights of fresh stems and roots were measured. After 20 days of drought, plants were watered to assess their recovery after 7 days and the growth characteristics, weights of fresh stems and roots, and yield components at the harvest stage were evaluated. The results showed that drought affected the growth, resilience, and yield-related factors more severely at the vegetative stage than at the flowering stage. The longer drought was imposed, the greater decline in plant growth was observed. Despite the recovery, fresh root mass and root length were still 40-50% and 10-30% worse than the control, respectively. Based on the growth responses and individual yields, Dau tam Thanh Hoa and DX14 were more tolerant to water deficit and can be used as materials for improving the drought tolerance of mung bean.

Keywords

Drought tolerance index, flowering stage, mung bean, vegetative stage, water deficit

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Introduction

Mung bean (*Vigna radiata* L. Wilczek) is an important, short-growth-duration crop grown in many countries in tropic and subtropic regions (Nair *et al*., 2020). Drought is one of the adverse conditions for the growth and yield of many crops including mung bean (Sivaji *et al*., 2021). Screening for drought-tolerant genotypes has always been one of the strategies for water stress adaptation. Mung bean yield is dependent on an adequate water supply regardless of other environmental factors during critical growth periods. Different growth stages also exhibit various vulnerabilities to water deficit. For example, the vegetative stage is more vulnerable than the flowering and pod formation stages (Bangar *et al*., 2019; Vu *et al*., 2021), or vice versa (Naresh *et al*., 2013; Uddin *et al*., 2013). However, drought occurring at any stage adversely affects plant growth and yield components, leading to reductions in yield from 20-100% (Singh *et al*., 2015; Bangar *et al*., 2019; Nadeem *et al*., 2019; Vu *et al*., 2021; Haeften *et al*., 2023). Exploring growth and physiological traits related to plant water use, particularly water requirements during growth, in mung bean are needed to determine these trait values in different environments.

In Vietnam, mung bean is usually grown under rainfed conditions, and in intercropping and crop rotation systems, so it often faces drought at different growth stages. For example, the summer-autumn season in Thanh Hoa and Nghe An is often harsh and dry with prolonged heat, which is the most important constraint for mung bean production (Nguyen The Anh *et al*., 2017). Thus, water shortages affect yield and the expansion of mung bean in the production area. Due to the increasing scarcity of water resources for agriculture, screening for drought-resistant varieties is always an urgent need. Therefore, to design an effective phenotypic screening strategy for crop improvement, understanding the responses of mung bean agronomic traits under different drought conditions is required. Further evaluation of variable parameters and their correlations under drought conditions will be helpful in selecting valuable and useful varieties for drought-tolerance breeding programs (Singh *et al*., 2021; Haeften *et al*., 2023). In recent years, research and breeding of mung bean varieties have focused on selecting varieties with wide adaptability, tolerance to adverse environmental conditions, a short growth duration, synchronized ripening, high seed quality, and a high and stable yield (Singh *et al*., 2021; Haeften *et al*., 2023).

However, in Vietnam, mung bean production often faces unfavorable water conditions during critical periods. Mung bean yield is highly variable due to unpredictable rainfall. This study therefore evaluated the effects of water deficit on mung bean cultivars at the vegetative and flowering stages based on growth characteristics, recovery, and yield components to find their relationship with drought tolerance, which will serve as a basis for screening drought-tolerant genotypes.

Materials and Methods

Plant materials and experimental design

This study used four mung bean cultivars, namely DX14 (Korea), Mongo Labo (Philippines), TV06425 (World Vegetable Research and Development Center), and the local cultivar Dau tam Thanh Hoa - a drought tolerant cultivar (Nguyen The Anh *et al*., 2017). The experiment was conducted in a greenhouse from May to August 2019.

Plants were planted in plastic pots 40cm in height x 30cm in width with two plants/pot. Pots were filled with 6.5kg of alluvial soil mixed with fine sand (1:1, v/v), 0.5kg of Song Gianh microbial-organic fertilizer, and 0.45g of phosphorus. Pots were saturated with water and left overnight before sowing seeds. Pots were watered every day before water was withheld in the drought treatment.

The experiment was arranged in a completely randomized design, with two replications, two pots per replication, and two factors, namely the four cultivars and three levels of treatments (control - no drought, drought stress during the vegetative growth stage, and drought stress during the flowering stage). The control plants were well-watered. In the drought experiment, two pots (four plants) per replication were set up to measure the traits and collect plant and root samples after 8, 12, 15, and 20 days of drought. Specifically, the drought experiment was set up with two sets, namely (1) drought imposed at the vegetative stage and (2) drought imposed at the reproductive stage. Each set included 32 pots (64 plants) (2 treatments, control vs drought × 4 cultivars × 2 replications × 2 pots/replication) and plants were destroyed during sampling. Plants were fully watered until 20 days after emergence (two-leaf stage) or 33 days after emergence (first flower bud appearance) for drought imposed at the vegetative and flowering stages, respectively.

The recovery experiment was a separate set with 48 pots (96 plants) (3 treatments, control vs drought at vegetative and reproductive stages × 4 cultivars × 2 replications × 2 pots/replication). After 20 days of drought imposition, pots were regularly watered to evaluate the 7-day recovery rate, yield components, and yield.

Trait measurement

Before sowing, pots were saturated with water and weighed (kg). At each evaluation time (8, 12, 15, and 20 days of drought), pots were weighed to calculate the plant available water (PAW) - the amount of water available in the pot.

The measured growth characteristics were plant height, number of leaves, number of nodes, length of internodes, fresh weights of above-ground mass and roots, and root length. Plants were collected and weighted for above-ground mass (stem and leaves). Roots were collected, washed, and weighted. Root length was measured for the longest taproot.

The recovery measurements after 7 days were plant height and number of leaves. Recovery was scored using a 1-4 scale: (1) plant death; (2) less than 30% of wilted leaves recovered; (3) more than 60% of wilted leaves recovered; and (4) complete recovery with more than > 90% of wilted leaves recovered.

The yield components were the number of pod clusters per plant, number of pods per plant, pod weight per plant, and individual yield.

Data analysis

Plant available water (PAW)

PAW indicates the level of water that plant uses (Likoswe, 1997; Likoswe & Lawn, 2008) and is calculated as follows:

$$\text{PAW (\%)} = \frac{W_t - W_c}{W_{bh} - W_c} \times 100$$

where W_t is the pot weight at 8, 12, 15 and 20 days of drought; W_{bh} is the weight of the pot saturated with water; and W_c is the initial weight of the pot filled with substrate.

The average reduction of PAW per day (%/day) was calculated as follows:

$$= \left(\frac{100 - PAW_8}{8} + \frac{PAW_8 - PAW_{12}}{4} + \frac{PAW_{12} - PAW_{15}}{3} + \frac{PAW_{20} - PAW_{15}}{5} \right) \Big/ 4$$

where PAW_8, PAW_{12}, PAW_{15}, and PAW_{20} are PAW at 8, 12, 15, and 20 days of drought, respectively.

Relative changes (%) of the evaluated traits under the drought treatment compared to the control was calculated as follows:

$$\text{Relative changes (\%)} = \frac{T_t - T_{dc}}{T_{dc}} \times 100$$

where T_t and T_{dc}, respectively, are traits under the drought and control treatments. Yield components and individual yield were the averages of measured plants in each replication.

Drought resistance index (DRI) was determined according to Fischer and Maurer (1978):

$$\text{DRI} = \frac{Y_t/Y_c}{\bar{Y}_t/\bar{Y}_c}$$

where Y_t and Y_c are grain yields in the drought and control treatments, respectively, and $\bar{Y}_t$ and $\bar{Y}_c$ are the average values of all the examined genotypes of grain yield in the drought and control treatments, respectively.

ANOVA was used to evaluate differences in the measured traits between cultivars exposed to drought at different stages and different times (8, 12, 15, and 20 days of drought) by Minitab ver. 20.0. Means were calculated from replicates and compared by using Tukey's test with a 0.05 level of significance. Tukey's test was conducted for interaction of variety × drought stage × day or interaction of variety × drought stage.

Results

Plant available water under drought stress at the vegetative and flowering stages

Plant available water (PAW) indicates the relative amount of water left in a pot for plants to use. Generally, cultivars using less water have a higher PAW and a slower rate of water loss, thus extending their drought tolerance period.

PAW was significantly different among the cultivars, drought stages, and the four points of drought days (**Table 1**). After 8 days of drought, PAW decreased to 55.0-70.0% at the vegetative stage and decreased faster in the flowering stage from 23.7-43.3%. PAW decreased rapidly at the flowering stage, possibly due to the larger sizes of the plants and leaves, and higher transpiration levels compared to the vegetative stage.

PAW decreased rapidly over the time drought was imposed, especially from days 12 to 20. After 20 days of drought in both stages, the cultivars used almost all their available water with remaining PAW of 0.2-2.0%. PAW after 20 days of drought at the vegetative stage of DX14 (2%) was higher than that of other cultivars.

Average rates of PAW decline fluctuated around 4-5%. Average PAW reduction rates under drought conditions were low for Dau tam Thanh Hoa (5.06%) and DX14 (5.23%) at the vegetative stage, and for Dau tam Thanh Hoa (4.15%) and TV06425 (4.02%) at the flowering stage.

Effects of drought on mung bean growth

Under drought conditions, the plant height, number of nodes, and internode length were reduced in comparison with the control, especially from days 12-15 of drought (**Table 2**). Twenty days of drought was the threshold at which the mung bean cultivars could maintain tolerance, with decreases in plant height and node characteristics > 45%.

In the vegetative stage, the longer the duration of drought was, the higher the decrease of plant height was. After 8 days of drought, plants retarded their height, with heights 4.58-12.41% shorter compared to the control. After 12 and 15 days of drought, plant heights decreased significantly compared to the control from 22.71-40.41%, and reached decreases of 31.92-52.75% after 20 days. Dau tam Thanh Hoa and Mongo Labo declined at lower rates than the other cultivars. Similarly, the number of nodes decreased sharply. Internode length decreased at lower rates than plant height and the number of nodes.

When drought occurred in the flowering stage, plant height after 8 days had decreased less than that in the vegetative stage (1.45-7.65%). The plant height of Dau tam Thanh Hoa increased slightly but not significantly (0.58%), which was possibly due to its drought tolerance allowing the plants to still grow in the early stages of drought. Plant height continued to decrease and plants were 36.56-45.77% shorter

Table 1. Plant available water (PAW, %) of mung bean cultivars under drought at the vegetative and flowering stages and at 8, 12, 15 and 20 days of drought

Drought stages	Cultivars	PAW (%) post drought exposure				Average reduction of PAW (% per day)
		8 days	12 days	15 days	20 days	
Vegetative stage	Dau tam Thanh Hoa	55.0^{a-c}	38.8^{b-f}	17.1^{d-h}	0.5^{h}	5.06
	DX14	56.7^{a-c}	41.7^{b-e}	13.2^{f-h}	2.0^{h}	5.23
	Mongo Labo	70.0^{a}	54.2^{a-c}	30.0^{c-g}	0.6^{h}	5.41
	TV06425	65.4^{ab}	40.5^{b-f}	18.8^{d-h}	0.5^{h}	5.36
Flowering stage	Dau tam Thanh Hoa	31.5^{c-g}	8.3^{gh}	3.6^{gh}	0.3^{h}	4.15
	DX14	38.8^{b-f}	18.1^{d-h}	10.0^{gh}	0.2^{h}	4.37
	Mongo Labo	43.3^{a-d}	25.4^{d-h}	14.9^{e-h}	0.2^{h}	4.50
	TV06425	23.7^{d-h}	15.4^{d-h}	4.7^{gh}	0.2^{h}	4.02

Note: Values with the same superscript letter are not significantly different (P ≥0.05). Dash (-) is used for differences of more than two letters (e.g., a-c = abc; d-h = defgh).

Table 2. Relative changes (%) of plant height, number of nodes, and internode length in mung bean cultivars under drought at the vegetative and flowering stages and at 8, 12, 15 and 20 days of drought compared to the control

Traits	Cultivars	Duration of drought exposure at vegetative stage				Duration of drought exposure at flowering stage			
		8 days	12 days	15 days	20 days	8 days	12 days	15 days	20 days
Plant height	Dau tam Thanh Hoa	-4.58^{ab}	-24.37^{e-g}	-33.06^{f-k}	-45.15^{j-l}	$+0.58^{a}$	-9.39^{a-c}	-26.02^{e-h}	-36.56^{f-l}
	DX14	-12.41^{b-d}	-28.64^{e-i}	-36.33^{g-l}	-45.90^{kl}	-1.45^{a}	-19.55^{c-e}	-33.34^{f-k}	-43.90^{i-l}
	Mongo Labo	-7.71^{ab}	-22.71^{d-f}	-30.36^{e-k}	-31.92^{e-k}	-7.65^{ab}	-20.68^{de}	-29.10^{e-j}	-45.77^{kl}
	TV06425	-6.64^{ab}	-29.52^{e-i}	-40.41^{i-l}	-52.75^{l}	-7.34^{ab}	-27.03^{e-h}	-34.31^{f-k}	-41.05^{h-l}
Number of nodes	Dau tam Thanh Hoa	-0.54^{ab}	-10.42^{b-e}	-13.39^{c-f}	-30.0^{g-k}	$+1.56^{a}$	-10.37^{b-e}	-17.78^{c-g}	-25.0^{e-i}
	DX14	-7.34^{a-c}	-20.50^{e-g}	-27.98^{g-i}	-38.18^{h-k}	$+0.88^{a}$	-13.52^{c-e}	-19.19^{d-g}	-31.11^{g-k}
	Mongo Labo	-1.79^{ab}	-19.64^{e-g}	-25.89^{f-h}	-44.44^{jk}	-11.39^{c-e}	-28.64^{g-i}	-36.52^{h-k}	-42.73^{i-k}
	TV06425	-8.63^{b-d}	-20.83^{e-g}	-27.98^{g-i}	-47.22^{k}	-8.72^{b-d}	-20.37^{e-g}	-28.64^{g-j}	-40.0^{h-k}
Internode length	Dau tam Thanh Hoa	$+1.31^{bc}$	-8.05^{d-h}	-12.70^{f-i}	-28.83^{k-q}	$+12.54^{a}$	-5.02^{b-g}	-27.40^{l-p}	-32.65^{l-q}
	DX14	$+3.51^{ab}$	-5.67^{b-h}	-14.96^{g-k}	-28.81^{k-q}	-6.20^{c-h}	-21.35^{i-n}	-26.70^{k-p}	-35.46^{o-q}
	Mongo Labo	$+1.08^{b-d}$	-14.10^{g-i}	-21.67^{i-o}	-31.47^{m-q}	$+2.28^{bc}$	-8.46^{e-h}	-16.18^{h-l}	-29.62^{l-q}
	TV06425	-4.63^{b-f}	-19.94^{i-m}	-31.03^{n-q}	-40.33^{pq}	-0.92^{b-e}	-14.93^{h-j}	-25.0^{j-o}	-28.40^{j-q}

Note: Values (+) and (-), respectively, represent relative increases (%) and relative decreases (%) in evaluated traits under drought conditions compared to the control. Values with the same superscript letter are not significantly different (P ≥0.05). Dash (-) is used for differences of more than two letters (e.g., a-c = abc; d-h = defgh).

compared to the control on day 20 of drought. Dau tam Thanh Hoa showed the lowest decrease in plant height.

Responses of the number of nodes to drought were variable compared with plant height. In the vegetative stage, all the cultivars had the same responses, except for Dau tam Thanh Hoa. In the flowering stage, Dau tam Than Hoa had the lowest decrease in the number of nodes, followed by DX14.

A few days after the imposed drought, plants exhibited growth and development processes, especially at the vegetative stage since PAW was still accessible for the plants (**Table 1**). Therefore, compared to the control, a few plants had non-significant increases in the number of nodes (0.88-1.56 nodes) and node lengths (1.08-12.54cm). However, after 8 days of drought, the node characteristics decreased significantly.

Generally, in the vegetative stage, Dau tam Thanh Hoa and DX14 showed the least effects of drought on their growth, plant height, number of nodes, and length of internodes; while in the flowering stage, Dau tam Thanh Hoa and the other cultivars responded differently for different traits.

Effects of drought on leaf number and leaf size in mung bean cultivars

Leaves are responsible for photosynthesis, providing nutrients for plants, and creating conditions for the plant to grow. Under unfavorable conditions, leaves often react and manifest symptoms such as wilting, dry edges, yellowing, or falling. Cultivars that can maintain leaves on plants under adverse conditions would have better recovery (Vu *et al*., 2021).

Drought significantly affected leaf formation and leaf sizes of the mung bean cultivars. Under drought conditions in the vegetative stage, the number of leaves during days 8-20 of drought decreased from 1.99 to 50.0% (**Table 3**). During days 8-12 of drought, Dau tam Thanh Hoa and DX14 had low relative reductions in the number of leaves and leaf sizes, followed by TV06425. Leaf length and width had relative reductions from 0.46 to 30.92% and from 1.14 to 44.07% during days 8-20, respectively.

Table 3. Relative reductions (%) of the number of leaves and leaf size in mung bean cultivars under drought at the vegetative and flowering stages and at 8, 12, 15 and 20 days of drought compared with the control

Traits	Cultivars	Duration of drought exposure at vegetative stage				Duration of drought exposure at flowering stage			
		8 days	12 days	15 days	20 days	8 days	12 days	15 days	20 days
Leaf number	Dau tam Thanh Hoa	-1.99^{a-d}	-16.67^{f-h}	-19.17^{g-j}	-28.57^{h-m}	-0.58^{ab}	-1.25^{bc}	-14.29^{d-h}	-15.48^{b-i}
	DX14	-2.08^{a-d}	-18.33^{g-i}	-27.62^{h-l}	-33.33^{i-n}	-0.39^{ab}	-9.52^{b-g}	-13.52^{d-h}	-16.67^{c-j}
	Mongo Labo	-2.07^{a-d}	-23.65^{h-k}	-38.10^{l-n}	-46.43^{mn}	-5.95^{b-f}	-21.46^{h-j}	-33.54^{j-n}	-38.75^{k-n}
	TV06425	-3.96^{a-e}	-26.67^{h-l}	-42.14^{mn}	-50.0^{n}	-5.65^{b-f}	-8.40^{b-g}	-14.88^{e-h}	-19.44^{e-k}
Leaf length	Dau tam Thanh Hoa	-4.50^{a-e}	-10.40^{ef}	-13.85^{e-k}	-25.18^{g-l}	-4.95^{a-e}	-8.10^{de}	-15.60^{e-l}	-24.12^{f-l}
	DX14	-3.92^{a-c}	-10.52^{e-h}	-22.96^{i-l}	-30.92^{l}	-2.29^{a-c}	-4.60^{a-e}	-12.42^{e-j}	-17.54^{e-l}
	Mongo Labo	-2.94^{a-c}	-19.82^{f-l}	-24.99^{j-l}	-28.46^{kl}	-2.22^{a-c}	-6.15^{c-e}	-11.46^{e-i}	-16.24^{e-l}
	TV06425	-0.46^{a}	-14.54^{e-k}	-22.85^{g-l}	-24.23^{f-l}	-3.44^{a-c}	-5.14^{b-e}	-10.15^{d-h}	-15.0^{e-l}
Leaf width	Dau tam Thanh Hoa	-1.14^{a-c}	-19.57^{hi}	-30.51^{k-o}	-42.08^{no}	-6.83^{b-f}	-13.21^{f-h}	-25.84^{i-m}	-39.36^{m-o}
	DX14	-3.19^{b-d}	-18.37^{g-i}	-30.26^{j-o}	-42.44^{no}	-3.92^{b-e}	-12.14^{e-h}	-18.28^{g-i}	-27.51^{i-n}
	Mongo Labo	-5.91^{b-f}	-22.73^{i-l}	-31.09^{l-o}	-34.56^{l-o}	-2.26^{a-c}	-9.22^{d-g}	-19.02^{g-j}	-28.51^{i-o}
	TV06425	-4.25^{b-e}	-20.24^{h-k}	-31.03^{l-o}	-44.07^{o}	-1.93^{a-c}	-7.20^{c-f}	-14.79^{f-i}	-21.42^{g-l}

Note: Value (-) represents relative decrease (%) in evaluated traits under drought condition compared with the control. Values with the same superscript letter are not significantly different (P ≥0.05). Dash (-) is used for differences of more than two letters (e.g., a-c = abc; d-h = defgh).

However, the number of leaves, leaf length, and leaf width decreased significantly more in the vegetative stage than in the flowering stage, indicating that mung bean is more sensitive to water deficit at the vegetative stage. In the flowering stage, the number of leaves decreased from 0.39 to 38.75%, leaf length decreased from 2.22 to 24.12%, and leaf width decreased from 1.93 to 39.36%. In both stages, the order of drought tolerance for the leaf traits was Dau tam Thanh Hoa, DX14, and TV06425.

Effects of drought on stem and root weights of mung bean cultivars

The fresh weights of stems from plants in the drought treatment were much lower compared to the control at the vegetative stage than at the flowering stage (**Table 4**). In the vegetative stage, the weight of fresh stems was reduced by 5-50% at 8 and 12 days of drought, and by 60-80% at 15 and 20 days of drought. The weight of fresh roots had a higher decrease than that of fresh stems, a decreased of 30-60% after 8 and 12 days of drought, and by 60-90% after 15 and 20 days of drought. For dry stem weight, reduction levels were obvious, ranging from 15-80% during the 8-20-day drought period.

In the flowering stage, the fresh stem weights of Mongo Labo and TV06425 decreased the least at day 8 of drought, ranging from 5.01-5.65%. Although the reduction level of fresh stem weight of DX14 was highest at day 8 of drought (20.36%), this level of DX14 was lower than Mongo Labo at day 20 of drought (69.91%). The same observation was made for the fresh root weights of Mongo Labo and TV06425, where reduction levels were 16.82-75.08% and 15.28-75.98%, respectively, from day 8 to day 20 of drought. Mongo Labo and TV06425 also had high reductions in dry stem weight, 64.66% and 52.33%, respectively. Mongo Labo and TV06425 did not extend drought tolerance up to 20 days, however, like Dau tam Thanh Hoa and DX14.

Effects of drought on recovery of mung bean cultivars

Cultivars and drought stages had significant effects on plant height, number of leaves, and recovery after 7 days of re-watering. Generally, cultivars had 2-4 leaves that were wilted or had

Table 4. Relative reductions (%) of fresh and dry plant and root weights in mung bean cultivars under drought at the vegetative and flowering stages and at 8, 12, 15 and 20 days of drought compared to the control

Traits	Cultivars	Duration of drought exposure at vegetative stage				Duration of drought exposure at flowering stage			
		8 days	12 days	15 days	20 days	8 days	12 days	15 days	20 days
Fresh plant weight	Dau tam Thanh Hoa	-5.72^{a}	-46.17^{a-c}	-54.45^{a-c}	-80.10^{c}	-10.25^{ab}	-26.71^{a-c}	-63.79^{a-c}	-46.40^{a-c}
	DX14	-4.98^{a}	-47.77^{a-c}	-70.44^{bc}	-81.38^{c}	-20.36^{a-c}	-56.15^{a-c}	-63.82^{a-c}	-69.91^{bc}
	Mongo Labo	-18.06^{a-c}	-59.07^{a-c}	-68.03^{a-c}	-79.74^{c}	-5.01^{a}	-51.39^{a-c}	-63.98^{a-c}	-70.25^{bc}
	TV06425	-45.68^{a-c}	-48.63^{a-c}	-52.18^{a-c}	-81.19^{c}	-5.65^{a}	-44.90^{a-c}	-51.70^{a-c}	-54.54^{a-c}
Fresh root weight	Dau tam Thanh Hoa	-45.0^{a-c}	-62.14^{a-c}	-69.20^{a-c}	-80.45^{a-c}	-7.83^{a}	-31.09^{a-c}	-55.13^{a-c}	-72.62^{a-c}
	DX14	-58.33^{a-c}	-78.82^{a-c}	-79.26^{a-c}	-83.28^{bc}	-25.16^{a-c}	-34.2^{a-c}	-52.02^{a-c}	-61.67^{a-c}
	Mongo Labo	-33.33^{a-c}	-59.30^{a-c}	-88.75^{bc}	-92.83^{c}	-16.82^{ab}	-48.76^{a-c}	-74.18^{a-c}	-75.08^{a-c}
	TV06425	-30.0^{a-c}	-58.33^{a-c}	-65.71^{a-c}	-83.84^{bc}	-15.28^{ab}	-23.05^{a-c}	-44.62^{a-c}	-75.98^{a-c}
Dry plant weight	Dau tam Thanh Hoa	-21.83^{a-c}	-38.41^{a-d}	-44.91^{a-d}	-77.21^{d}	-27.20^{a-d}	-28.17^{a-d}	-47.51^{a-d}	-51.55^{a-d}
	DX14	-16.16^{a-c}	-47.14^{a-d}	-63.07^{cd}	-75.45^{d}	-36.53^{a-d}	-43.67^{a-d}	-44.39^{a-d}	-57.31^{cd}
	Mongo Labo	-32.69^{a-d}	-57.20^{b-d}	-60.70^{cd}	-74.10^{d}	-28.36^{a-d}	-34.98^{a-d}	-63.94^{cd}	-64.66^{cd}
	TV06425	-15.62^{a-c}	-43.98^{a-d}	-53.21^{a-d}	-79.79^{d}	-23.72^{a-c}	-29.33^{a-d}	-48.51^{a-d}	-52.33^{a-d}

Note: Value (-) represents decrease (%) in evaluated traits under drought condition compared to control. Values with the same superscript letter are not significantly different (P ≥0.05). Dash (-) is used for differences of more than two letters (e.g., a-c = abc; d-h = defgh).

2-4 leaves that were wilted or had dry leaf edges after 20 days of drought. When re-watering, leaves that remained on the plants and did not lose their turgor recovered and the plants recovered their growth (**Table 5**).

In the vegetative stage, within 7 days after re-watering, plants recovered their growth, although compared to the control, the growth characteristics were lower. For example, plant height and number of leaves were 32.7-46.9% and 7.6-41.6% lower than the control, respectively. Average recovery scores were 2.5-2.8.

In the flowering stage, reduction levels for plant height and number of leaves were 24.5-34.7% and 10.5-40.1%, respectively. The reduction level in plant height was lower than that in the vegetative stage, possibly because at the time drought was imposed, plants had already reached their relatively full height. However, the number of dead plants (about 1-2 plants per variety) was higher than that at the vegetative stage (about 0-1 plants per variety). Average recovery scores were 1.6-2.4 and lower than the vegetative stage. Thus, plants that encountered drought at the flowering stage had a lower recovery ability than at the vegetative stage.

Effects of drought at the vegetative and flowering stages on growth and yield components of mung bean cultivars after recovery

After recovery, plants were watered and cared for until harvest. Many Mongo Labo plants died when exposed to drought at the flowering stage, so this cultivar's characteristics at harvest could not be evaluated (**Tables 6 and 7)**. Dau tam Thanh Hoa exhibited better recovery after 7 days and most characteristics at harvest were generally higher than other cultivars.

At harvest, the heights of the mung bean cultivars varied from 39.3-48.5cm and the internode lengths varied from 6.2-8.3cm. The weights of fresh stems and fresh roots varied from 8.2-15.4g and 0.34-1.23g, respectively. Root lengths reached 8.4-12.2cm (**Table 6**). Some traits, namely fresh stem weight, fresh root weight, and root length, were significantly different among cultivars.

After 7 days of recovery, although the growing traits of plant height, number of leaves, and the weights of stems and roots increased, they were at lower levels than the control. The reduction level in plant height under drought in the vegetative stage tended to be higher than that in the flowering stage (**Table 7**). The relative reductions of plant height, number of leaves, internode length, and root length were, respectively, 17.1-37.7%, 2.0-31.0%, 10.1-28.8%, and 9.5-32.9%.

Water deficit affected yield components such as the number of pod clusters, number of pods/plant, pod weight, and individual yield. The relative reductions for the yield components were not significantly different but all were high, mostly from 40-60% (**Table 8**).

In the vegetative stage, the number of pod clusters, number of pods/plant, and pod weight/plant were, respectively, 31.3-50.3%, 22.0-53.8%, and 48.8-62.5% lower than the control. Individual yields had relative reductions

Table 5. Relative changes of plant height and number of leaves (%) in comparison to the control, means of plant height, number of leaves, and recovery score 7 days after re-watering in mung bean cultivars

Drought stages	Cultivars	Relative reduction (%) compared to the control		Plant height (cm)	Number of leaves	Recovery (score)
		Plant height	Number of leaves			
Vegetative stage	Dau tam Thanh Hoa	-36.5^{b}	-17.0^{ab}	32.0^{ab}	5.4^{a}	2.8^{a}
	DX14	-32.7^{ab}	-7.6^{a}	33.3^{ab}	5.6^{a}	2.5^{a}
	Mongo Labo	-45.4^{b}	-41.6^{b}	27.9^{b}	5.4^{a}	2.5^{a}
	TV06425	-46.9^{b}	-34.4^{ab}	26.8^{b}	5.3^{a}	2.5^{a}
Flowering stage	Dau tam Thanh Hoa	-24.5^{ab}	-10.5^{ab}	38.5^{ab}	4.5^{a}	2.4^{a}
	DX14	-26.4^{a}	-13.1^{ab}	46.0^{a}	5.8^{a}	1.8^{a}
	Mongo Labo	-34.7^{ab}	-40.1^{b}	41.0^{ab}	6.0^{a}	1.6^{a}
	TV06425	-25.4^{ab}	-30.2^{ab}	39.4^{ab}	5.8^{a}	1.8^{a}

Note: Value (-) represents corresponding decrease (%) in the evaluated trait after recovery compared to the control; Values in a column with the same superscript letter are not significantly different (P ≥0.05).

Table 6. Growth characteristics of mung bean cultivars at the harvest stage after recovery

Drought stages	Cultivars	Plant height (cm)	Number of leaves	Number of nodes	Internode length (cm)	Fresh plant weight (g)	Fresh root weight (g)	Root length (cm)
Vegetative stage	Dau tam Thanh Hoa	39.3^{a}	5.8^{a}	11.1^{a}	6.6^{a}	13.7^{ab}	0.70^{bc}	12.2^{ab}
	DX14	38.6^{a}	5.4^{a}	10.6^{a}	7.0^{a}	15.4^{a}	0.63^{bc}	10.2^{bc}
	Mongo Labo	42.0^{a}	7.9^{a}	10.4^{a}	7.3^{a}	11.9^{b}	0.34^{c}	8.4^{c}
	TV06425	36.7^{a}	6.9^{a}	10.3^{a}	6.2^{a}	8.2^{b}	0.38^{c}	11.6^{ab}
Flowering stage	Dau tam Thanh Hoa	44.5^{a}	6.5^{a}	9.5^{a}	8.2^{a}	9.1^{b}	1.23^{a}	12.0^{ab}
	DX14	48.5^{a}	7.3^{a}	11.3^{a}	8.3^{a}	10.5^{ab}	0.63^{bc}	10.7^{bc}
	Mongo Labo	-	-	-	-	-	-	-
	TV06425	44.7^{a}	8.4^{a}	11.5^{a}	7.3^{a}	12.1^{ab}	0.40^{c}	9.7^{bc}

Note: Tukey's comparison was for variety × drought stage. Values in a column with the same superscript letter are not significantly different (P ≥0.05).

Table 7. Relative reductions (%) of growth characters in comparison to the control in mung bean cultivars under drought at the vegetative and flowering stages at harvest

Drought stages	Cultivars	Relative reduction (%) compared to control						
		Plant height	Leaf number	Node number	Internode length	Fresh plant weight	Fresh root weight	Root length
Vegetative stage	Dau tam Thanh Hoa	-27.8[a]	-8.0[ab]	-6.6[a]	-27.3[a]	-42.5[a]	-41.7[a]	-9.5[a]
	DX14	-24.7[a]	-2.0[a]	-6.3[a]	-22.3[a]	-44.0[a]	-44.9[a]	-20.4[ab]
	Mongo Labo	-37.7[a]	-6.8[ab]	-26.3[a]	-27.0[a]	-52.5[a]	-52.9[a]	-32.9[b]
	TV06425	-32.0[a]	-15.0[ab]	-12.9[a]	-28.8[a]	-48.9[a]	-50.1[a]	-22.3[ab]
Flowering stage	Dau tam Thanh Hoa	-18.4[a]	-12.2[ab]	-16.5[a]	-10.1[a]	-23.7[a]	-41.0[a]	-17.0[a]
	DX14	-19.8[a]	-11.7[ab]	-20.1[a]	-12.0[a]	-36.8[a]	-21.4[a]	-23.7[ab]
	Mongo Labo	-	-	-	-	-	-	-
	TV06425	-17.1[a]	-31.0[b]	-11.4[a]	-16.5[a]	-52.1[a]	-49.1[a]	-22.7[ab]

Note: Value (-) represents corresponding decrease (%) in evaluated traits under drought conditions compared to the control. Values in a column with the same superscript letter are not significantly different (P ≥0.05).

Table 8. Relative reductions (%) of yield components in comparison to the control in mung bean cultivars under drought at the vegetative and flowering stages, individual yields, and drought tolerance index (DRI) at harvest

Drought stages	Cultivars	Relative reduction (%) compared to control*				Number of pod clusters/ plant	Individual yield (g/plant)	DRI
		Number of pod clusters/ plant	Number of pods/plant	Pod weight/ plant	Individual yield			
Vegetative stage	Dau tam Thanh Hoa	-31.3	-22.0	-48.8	-47.1	4.00ab	1.80	1.125
	DX14	-49.0	-27.3	-53.5	-60.1	3.38abc	1.60	1.078
	Mongo Labo	-46.4	-30.5	-62.5	-63.3	3.00bc	1.10	0.800
	TV06425	-50.3	-53.8	-57.0	-68.6	2.17c	1.20	1.040
Flowering stage	Dau tam Thanh Hoa	-11.3	-39.0	-39.3	-49.6	4.00ab	2.35	1.228
	DX14	-23.4	-31.6	-40.6	-50.2	4.75a	2.00	0.875
	Mongo Labo	-	-	-	-			-
	TV06425	-28.6	-45.3	-54.1	-49.7	3.89ab	1.62	0.918

Note: Value (-) represents relative decrease (%) in the evaluated trait compared to the control at harvest stage; Values in a column with the same superscrpt letter are not significantly different (P ≥0.05).

varying from 47.1-68.6%. Dau tam Thanh Hoa had the lowest individual yield reduction (47.1%) and highest yield of 1.80 g/plant, followed by DX14.

When drought was applied in the flowering stage, reduction levels were lower than those when drought occurred at the earlier stage. The relative reduction in the number of pod clusters per plant was from 11.3-28.6% and lower than that in the vegetative stage (31.3-50.3%). Dau tam Thanh Hoa and TV06425 had the lowest individual yield reductions (49.6% and 49.7%) and achieved higher individual yields than the other cultivars, respectively, 2.35 g/plant and 1.62 g/plant.

The number of pod clusters per plant was significantly different with higher values at the flowering stage, ranging from 3.89-4.75.

The drought tolerance index (DRI) varied from 0.80-1.125 in the vegetative stage and from

0.875-1.228 in the flowering stage, with the highest DRI being in Dau tam Thanh Hoa. Dau tam Thanh Hoa showed the best drought tolerance at both stages. Combined with the growth and yield traits under water stress, DRI can be useful for screening drought-tolerant genotypes.

Discussion

Drought is one of the major disadvantages affecting mung bean production because mung bean is often grown in rainfed conditions (Sivaji *et al*., 2021). Water deficit reduces mung bean yield regardless of whether it occurs in the vegetative or reproductive stages (Raza *et al*., 2012). However, water stress occurring at the reproductive stage, especially during flowering and pod formation, affects yield more severely than at other stages (Sadeghipour, 2009; Raza *et al*., 2012). For example, drought can reduce yield by 20-45% in the vegetative stage compared to 30-100% in the reproductive stage (Hamid *et al*., 1990; De Costa *et al*., 1999). However, Bangar *et al*. (2019) suggested that the vegetative stage was more sensitive to drought because the biomasses of leaves and stems do not accumulate enough before flowering. Drought reduces leaf growth at any growth stage through the reduction of leaf area (Baroowa & Gogoi, 2015; El-Nakhlawy *et al*., 2018). This reinforces the importance of leaf development for yield in mung bean (Geetika *et al*., 2022b). The results of this study are similar to those of Bangar *et al*. (2019), who showed that when subjected to drought in the vegetative stage, the growth characteristics such as plant height, number of leaves, and length of internodes all decreased more strongly than in the flowering stage.

Leaf canopy reduction is an important mechanism for regulating water use and reducing cell damage. A smaller leaf canopy results in reduced radiation reception needed to support yield growth (De Costa & Shanmugathasan, 1999; Geetika *et al*., 2022a) and maintaining leaf area under drought conditions is an interesting trait in mung bean (Hamid *et al*., 1990). In this study, the recovery rates of the mung bean cultivars were different and depended on remnant leaves on plants after 20 days. It was observed that the leaves that had undergone drought had curled edges and were dried out. If leaves are completely dry or dehydrated, the leaves and plants will not be able to recover. Therefore, mung bean cultivars that can maintain a higher number of leaves have better recovery, such as Dau tam Thanh Hoa and DX14.

In this study, although individual yields were not significantly different among the cultivars and growth stages, higher individual yields can be an indicator for selection of drought tolerance cultivars. Additionally, based on the growth responses, cultivars that had lower relative reductions in growth compared with the control but higher yields than other cultivars should have potential for drought tolerance. Thus, together with lower relative reductions for growth traits and individual yield, Dau tam Thanh Hoa and DX14 are suggested for better drought tolerance in this study.

Drought is one of the main constraints affecting mung bean production in Vietnam. Selecting mung bean cultivars tolerant to abiotic stresses in general and drought in particular requires precise identification of appropriate plant materials that exhibit tolerance at certain growth stages. Growth and yield components determine yield potential. However, growth and yield are strongly reduced due to water stress. The results of this study also show that water stress significantly affects growth and yield at both the vegetative and flowering stages, but the effects are more severe when drought occurs in the vegetative stage. Among the studied cultivars, Dau tam Thanh Hoa exhibited consistent drought tolerance in both growth stages. For more accurate drought tolerance assessments, detailed studies of above and below-ground traits with several cultivars are needed to design an effective drought-tolerant mung bean breeding program.

Conclusions

Mung beans are sensitive to drought, especially in the vegetative stage. Water deficit reduces plant height and leaf area, thereby reducing yield. To ensure the yield of mung bean, it is necessary to water and ensure soil moisture from planting until flowering. Based on the general results of the assessment of drought tolerance at the vegetative and flowering stages, Dau tam Thanh Hoa and DX14 are drought-tolerant cultivars can be used as materials to develop drought-tolerant mung bean.

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