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Effect of Drought Stress on Chlorophyll Fluorescence and Yield Components of Common Beans (*Phaseolus vulgaris* L.)

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Abstract

The nutritional benefits of legumes to humans are surpassed only by those of the Gramineae family. The common bean (*Phaseolus voulgaris* L.) is one of the most widely cultivated legume crops and an important source of protein in South Korea. Among the major abiotic stresses affecting common bean production in South Korea, drought stress is the most significant. However, the most vulnerable stages of drought stress after planting are unknown. Therefore, this research has been conducted. The 'RWR2245' common bean variety was planted in a greenhouse after land preparation under a randomized complete block design (RCBD) with four replications. Three drought stress treatments were imposed during the growth period at 3, 6, and 9 weeks after planting (3 WAP, 6 WAP, and 9 WAP, respectively) by withholding water for 10 days, followed by a 1-week recovery period before data collection. The recorded data included plant height, leaf number, number of floral buds, shoot dry weight, lateral root number, primary root length, root nodule count, root dry weight, quantum photosynthetic yield, and maximum photochemical efficiency. These measurements were compared with those of the control treatment. The data were analyzed for variance ($p < 0.05$) using Minitab 2025 version 22 3.1 and Microsoft Excel. Except for the number of nodules, water stress significantly decreased for all measured parameters at 6 WAP, whereas at 9 WAP, only the number of leaves decreased significantly. Drought stress at 3 WAP resulted in significant decreases in all studied parameters except primary root length and leaf number. At 9 WAP, drought stress had no effect on the number of floral buds or pods; however, common bean plants were more tolerant to drought stress at 9 WAP. Further studies are needed to enhance common bean tolerance to drought stress across different growth stages to increase productivity, particularly at 6 WAP, which proved to be the most vulnerable stage.

Keywords: common bean, drought, variety, water stress

Introduction

Based on the United Nations Population Division's 2024 median projections, the global population is expected to rise from 8.2 billion in 2024 to a peak of 10.3 billion in 2084, then decline modestly to 10.2 billion by 2100 (United Nations, 2024). In Asia, food production grew sevenfold between 1961 and 2022, and the amount of food available per person was about two and a half times higher in 2022 than in 1961. Therefore, increasing agricultural production is essential to feeding the growing population (Mushtaq et al., 2024; Lam, 2025). The common bean, due to its availability and high nutritional value, has become one of the most widely consumed crops worldwide (Rathna & Manickavasagan, 2020). Common bean (*Phaseolus vulgaris* L.), adzuki bean (*Vigna angularis* L.), and soybean (*Glycine max L.*) are among the most widely cultivated

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legume crops and serve as major sources of protein in Korean diets (Chun et al., 2021). Among the *Phaseolus* species, the common bean is the most significant for direct human consumption, supplying roughly 30% of daily protein intake in both developed and developing nations (Márquez et al., 2024). However, agricultural productivity in food-insecure regions, particularly in Asia, is increasingly vulnerable to climate change. Climate-induced extremes including droughts, heat waves, irregular and intense rainfall, storms, floods, and the emergence of novel insect pests are undermining farmers' livelihoods (Habib et al., 2022).

In South Korea, recurring droughts linked to climate change have contributed to an ongoing water shortage crisis, frequently highlighted in recent reports (Lee et al., 2021). For the common bean (*Phaseolus vulgaris* L.), both the cultivation season and the crop's growth stages are strongly influenced by climatic conditions (Chun et al., 2016). In 2018, the yields of soybeans and common beans decreased by 6.1% and 21.7%, respectively, due to drought during both vegetative and reproductive stages, which was associated with changes in rainfall patterns in Korea (Lee et al., 2021). Drought stress has been shown to alter key physiological and biochemical processes, including photosynthesis, nitrogen assimilation, and metabolic pathways in several food crops (Kim & Lee, 2023; Pei et al., 2023; Razi & Muneer, 2023; Zahra et al., 2023). Few studies have examined the impact of drought on bean production, including mung bean (*Vigna radiata* L.) (Chun et al., 2021). Recently, due to climate change, rising atmospheric temperatures and decreasing rainfall during the bean cultivation period (June–August) have intensified, reducing productivity (Chun et al., 2020). Chlorophyll fluorescence (CF) is a very important tool in plant physiology. Maxwell and Johnson (2000) reported that chlorophyll fluorescence parameters (e.g., Fv/Fm, ΦPSII, and Y(II)) can detect physiological stress before visible symptoms such as wilting or chlorosis appear. In addition, CF is a rapid, non-destructive measurement technique that enables repeated (longitudinal) assessments of plant physiological status without causing damage (Liu et al., 2024). However, there is limited information on the specific growth stage after planting at which drought has the greatest effect on common bean (*Phaseolus vulgaris* L.) production. In addition, the effects of drought stress on chlorophyll fluorescence (CF) and yield components need to be assessed, as CF is closely linked to photosynthesis and can provide valuable information on plant growth at critical stages using a rapid, non-destructive method. Therefore, this experiment was conducted on common bean (*Phaseolus vulgaris* L.).

Materials and Methods

Experimental Location and Planting Material

This research was conducted at the experimental farm of the College of Agricultural Life Sciences, Chungnam National University (36.36° N, 127.35° E), from April to July 2025. Seeds of the common bean (*Phaseolus vulgaris* L.) variety 'RWR2245', originating from Rwanda, were sown on 5 April 2025 under greenhouse conditions.

Land Preparation and Experimental Design

A randomized complete block design (RCBD) was used in this study. Following land preparation, the recommended basal fertilizer (organic fertilizer at 2,000 kg/10 a) was applied. Each experimental plot measured 120 cm × 220 cm, with plants spaced at 40 cm × 20 cm. All plants were initially grown under normal conditions with regular irrigation based on soil moisture content, maintained at 50% of field capacity, until drought stress was imposed. Drought stress treatments were applied by withholding irrigation for 10 days at 3, 6, and 9 weeks after planting (3 WAP, 6 WAP, and 9 WAP), which reduced soil moisture content to approximately 15%. Control plots were consistently maintained under normal watering conditions at 50% soil moisture content. After each drought-stress period, plants were rewatered, and 10 plants were randomly selected from each plot for data collection.

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Data Collections

In addition to plant yield, which was recorded at harvest, the following parameters were evaluated one week after plant recovery from drought stress in each treatment: number of leaves, plant height, and chlorophyll fluorescence traits, including the quantum yield of photosystem II (Y(II)) and maximum photochemical efficiency (Fv/Fm). Chlorophyll fluorescence measurements were performed following the method described by Maxwell and Johnson (2000). Leaves were dark-adapted for 20–30 min using leaf clips prior to Fv/Fm measurement to ensure that PSII reaction centers were fully open and that non-photochemical quenching was minimized. Under stress-free conditions, Fv/Fm values typically ranged from 0.79 to 0.84. In addition, the number of floral buds, the number of lateral roots, the number of root nodules, and the root system dry weight were measured in both stressed and control plants. For root observations, plants from each experimental plot were carefully irrigated to facilitate uprooting without root damage, and then gently removed from the soil.

Data Analysis

Minitab Statistical Software (version 22.3.1, 2025) was used to compare treatment means, and analysis of variance (ANOVA) was performed at a significance level of $\alpha = 0.05$. Microsoft Excel was used to generate graphs and tables.

Results and Discussion

After three water-stress treatments imposed at 3, 6, and 9 weeks after planting (WAP), growth and yield parameters were recorded. Analysis of variance (ANOVA) was performed, and the results are presented in Table 1. At 9 WAP, only the number of leaves was significantly affected by 10 days of water stress, while no other parameters showed significant differences (Table 1). At 6 WAP, all measured parameters were significantly decreased, except for the number of nodules. At 3 WAP, the average primary root length, number of leaves, shoot dry weight, quantum photosynthetic yield (Y(II)), and maximum photochemical efficiency (Fv/Fm) were not significantly decreased by 10 days of drought stress (Table 1).

Leaves and Plant Height

The number of leaves increased with the duration of the stress period, as shown in Figure 1 (A & B). Plant morphological characteristics, including height, leaf size, leaf area, stem diameter, number of leaves per plant, and related traits, were affected by drought stress. The results showed that plant height, number of leaves, floral buds, and pods in stressed plants were significantly lower than in control plants. At 3 WAP, however, neither floral buds nor pods had yet developed in either control or stressed plants. Several studies have reported that under drought stress, mitosis is compromised, and reductions in plant height, leaf area, and overall growth are primarily caused by inhibited cell elongation and development (Kaya et al., 2006; Nonami, 1998). These findings are consistent with the significant differences observed between stressed and control plants in the present study.

Floral Buds and Pods

All plants were initially maintained under normal growing conditions before water stress was applied. The stress treatment consisted of withholding irrigation for 10 days at 3, 6, and 9 weeks after planting (3 WAP, 6 WAP, and 9 WAP) in separate experiments, while control plants were kept under normal conditions throughout. Significant differences were observed between stressed and control plants across all treatments, and the results are presented in Figure 2 (A & B). At 3 WAP, no floral buds or pods had formed, while higher reproductive development was observed at 9 WAP. Drought stress had little effect at 9 WAP, whereas 6 WAP was identified as the most vulnerable stage. As shown in Figure 3, water stress at 3 WAP and 6 WAP led to the formation of immature pods that

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eventually abscised before harvest. Although drought stress can induce early flowering, this response is disadvantageous due to poor pod development. Thomas et al. (2004) reported that bean plants subjected to water stress matured earlier than those grown under regular irrigation. Similarly, Javornik et al. (2025) noted that one of the primary constraints on this rainfed crop is reduced grain yield due to extended drought stress during the reproductive phase, commonly referred to as terminal drought.

Table 1

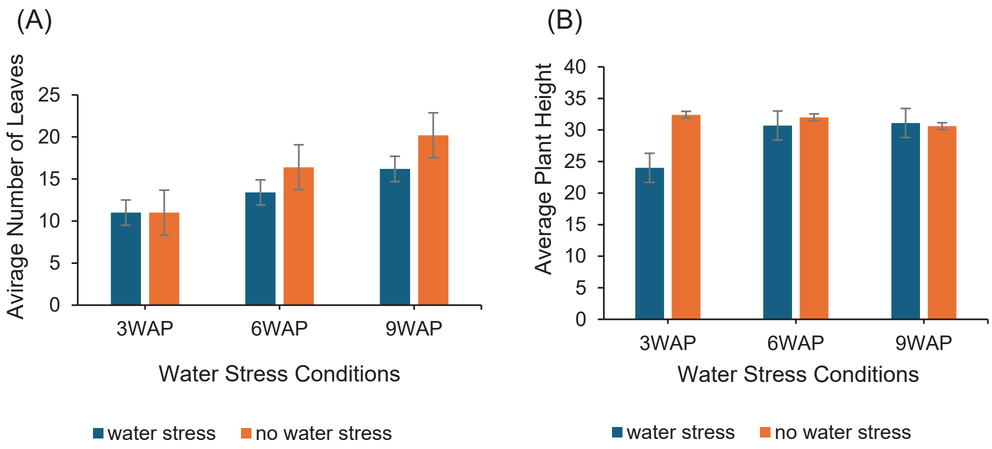
The Effects of Drought Stress Periods on Agronomic Yield Parameter at Different Growth Stages

Agronomic yield parameters	*P*value		
	3 WAP	6 WAP	9 WAP
Number of leaves	0.585*	0.016	0.011
Plant height(cm)	0.000	0.000	0.257*
Number of floral buds	-	0.000	0.079*
Number of pods	-	0.000	0.144*
Number of nodules	0.003	0.936*	0.062*
Yield per plant (g)	0.000	0.001	0.067*
Length of primary root (cm)	0.098*	0.005	0.061*
Number of lateral roots	0.009	0.006	0.213*
Shoot dry matter weight (g)	0.033	0.003	0.125*
Roots dry weight (g)	0.001	0.044	0.097*
Y(II)	0.489*	0.030	0.699*
Fv/Fm	0.329*	0.036	0.866*

Notes. The value indicated by * means that agronomic parameters were not significantly different according to analysis of variance (ANOVA) at α = 95%. WAP: weeks after planting. Water stress treatment was applied at 3, 6, and 9 WAP by withholding water for 10 days. Y(II): quantum photosynthetic yield; Fv/Fm: Maximal photochemical efficiency.

Figure 1

The Effect of Water Stress Conditions on the Number of Common Bean Leaves (A) and Plant Height (B)



Notes. (A) Number of leaves; (B) Plant height. Water stress condition by withholding watering for 10 days at 3, 6, and 9 weeks after planting.

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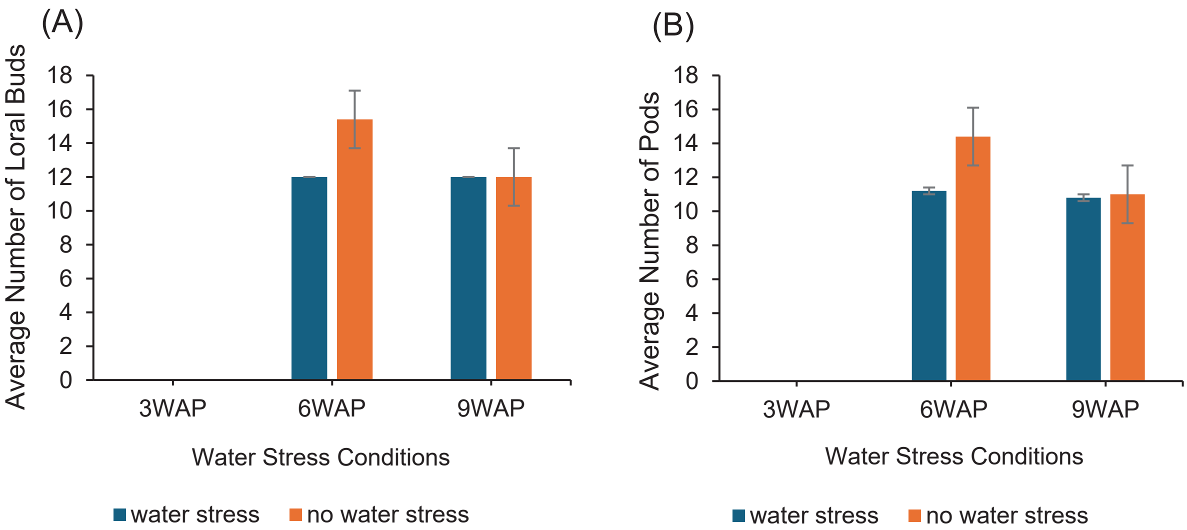
Figure 2

The Effects of Water Stress Conditions on the Number of (A) Floral Buds and (B) the Number of Pods



Notes. (A) The number of floral buds and (B) the number of pods. Water stress condition by with holding watering for 10 days at 3, 6, and 9 weeks after planting. No floral buds and pods were formed at 3 weeks after planting (B).

Figure 3

The Effect of Drought Stress on Common Bean Pods

Note. Water stress was applied by withholding watering for 10 days at 3, 6, and 9 weeks after planting (WAP).

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Yield per Plant and Plant Nodules

Drought stress affected crop performance depending on the plant growth stage. Based on the results, the average yield of the control common bean (RWR2245) treatment was 4.52 g per plant, while yields under drought stress were 1.75 g per plant at 3 WAP, 0.60 g per plant at 6 WAP, and 2.49 g per plant at 9 WAP (Figure 4B). This is indicated by the seeds per plant (Figure 5) These findings indicate that delaying the onset of stress until 9 WAP resulted in higher productivity in common beans compared with earlier stress treatments. The differences in yield were primarily due to drought stress during flowering and pod seed filling. Liu et al. (2003) reported that a higher rate of floral and pod abortion is the primary cause of yield loss when drought stress occurs during the reproductive stages. Similarly, Lu et al. (2021) noted that grain legume production is constrained by multiple environmental stresses, with water deficit being a leading cause of global yield reduction. Since most grain legumes are cultivated under rainfed conditions, they are particularly susceptible to drought stress. Kumar and Sharma (2009) also found that drought-stressed plants allocate a greater proportion of dry matter to roots and stems, whereas adequately irrigated plants allocate more resources to pods and grains, thereby increasing yield per plant.

Control and stressed plants showed significant differences for most evaluated parameters at 6 WAP, except for the number of nodules (Table 1). This is consistent with previous reports on nodule formation and development. Ashraf and Iram (2005) observed that drought stress does not prevent nodule formation or root colonization, but it does influence nodule growth and development. This is confirmed by the current findings (Figure 4A), where 6 WAP showed higher nodule formation but failed to sustain development. Singh and Singh (2006) proposed that restricted movement of carbohydrates from leaves to nodules under drought stress is the main cause of inhibited nodule development.

The Effects of Water Stress on the Common Bean Main Root Length, Lateral Root, Shoot Dry Matter, and Root Dry Matter Weight

Drought stress significantly decreases the shoot and root dry matter weights at both 3 WAP and 6 WAP (Figures 6C and 6D). In contrast, at 9 WAP, there was no significant decrease in the average length of the main root system (Figure 6A) or the number of lateral roots (Figure 6B) because the stress conditions were already applied while the shoot and root structure were established, although both traits were significantly reduced at 3 WAP and 6 WAP. Actually, at 9 WAP, the root system is already fully established before water stress is imposed; no significant difference was found. The differences on root and nodules formations are indicated by Figure 7 6WAP was the one most affected by drought stress, with increased root biomass in both the treatment and control, as this period corresponded to both the vegetative and reproductive stages. In addition, the roots were trying to help the plant adapt to drought stress at 6 WAP.

The timing of water stress influenced not only root system development but also overall productivity. Plant performance is strongly influenced by root system architecture (RSA), and different root types of primary, seminal, and nodal roots respond differently to water deficiencies (Kou et al., 2022). Camilo et al. (2021) highlighted that roots play a key role in adaptation to nutrient and water limitations, as drought stress promotes greater root growth relative to shoot growth, as evidenced by increases in root length, root hairs, and root number. Drought also alters nodule structure and weight once formed, and water stress can reduce both the number and morphology of root hairs (Ramos et al., 2003). This is confirmed by our research results, which show that 6 WAP has higher shoot and root dry weights than 3 WAP and 9 WAP.

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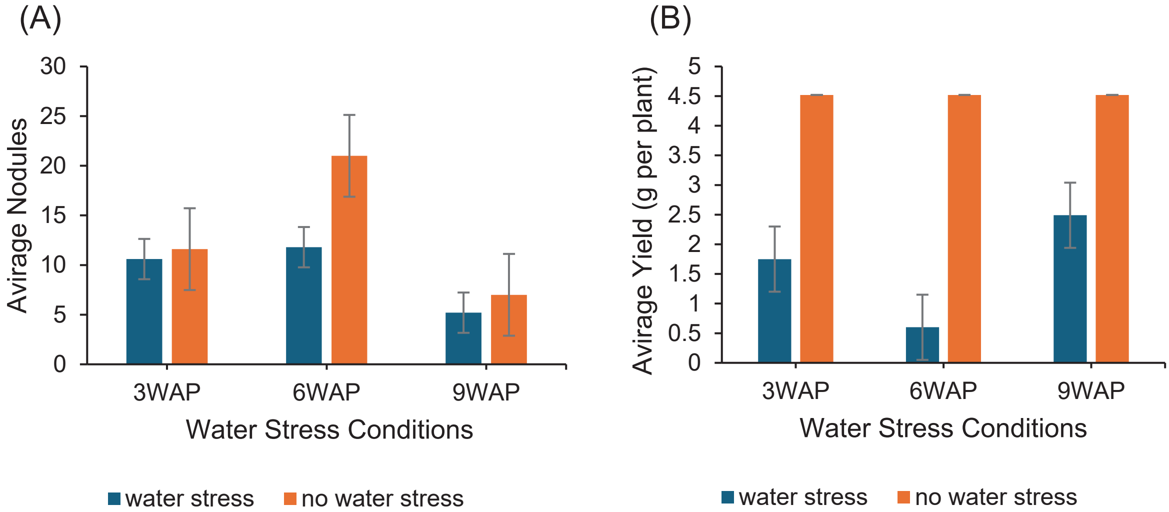
Figure 4

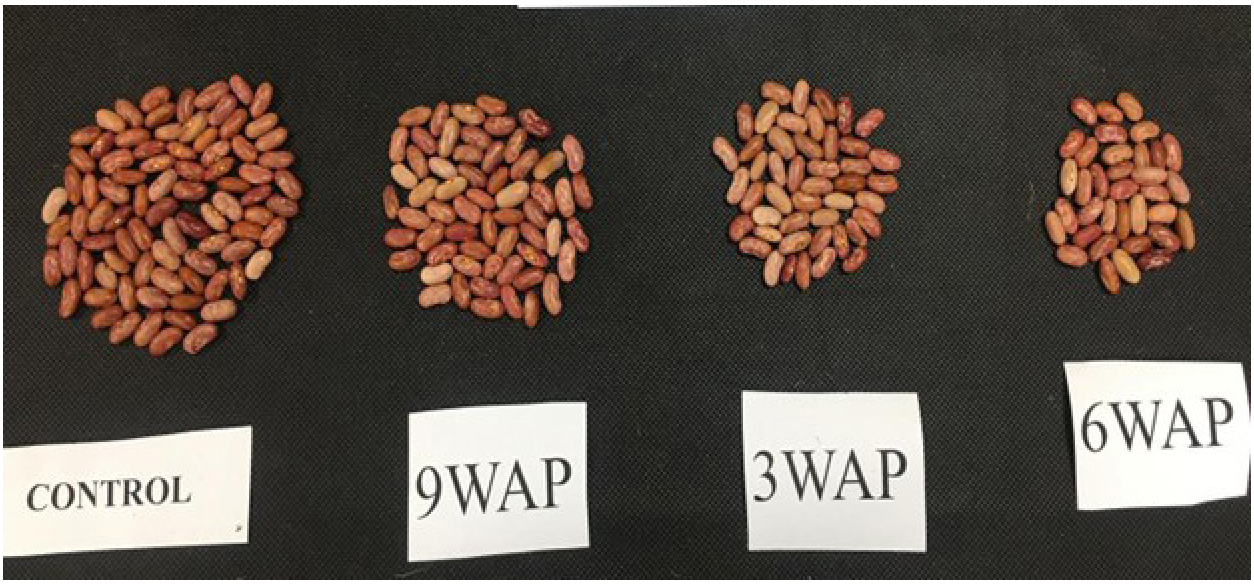
The Effects of Water Stress on Common Bean Nodulation and Plant Yield



*Notes.*Water stress was applied by withholding watering for 10 days at 3, 6, and 9 weeks after planting (WAP).

Figure 5

The effects of water stresses on the common bean plant yield



Notes. Common bean: control (regular irrigation at 50% of soil moisture content), water stress applied by withholding watering for 10 days at 9, 3, and 6 weeks after planting (WAP).

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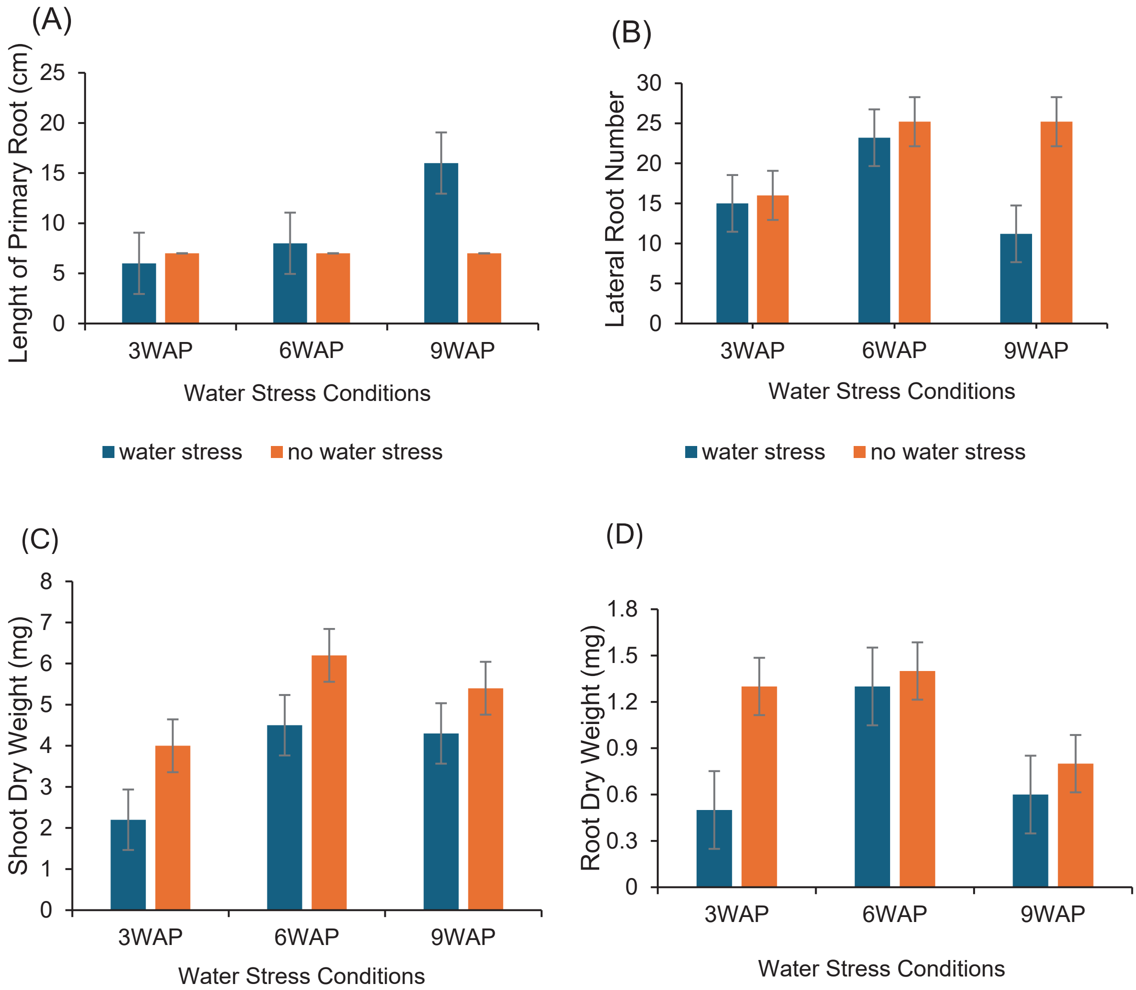
Quantum Photosynthetic Yield and Plant Maximum Photochemical Efficiency

This study showed that drought stress significantly reduces plant performance at 3 WAP and 6 WAP, with the average quantum photosynthetic yield and maximum photochemical efficiency falling below 0.75. In contrast, at 9 WAP, both quantum photosynthetic yield (Y(II)) and maximum photochemical efficiency (Fv/Fm) were not significantly different, with averages of 0.80-0.81, indicating a healthy plant with good production (Figure 8). According to Maxwell & Johnson (2000), healthy plants with good production had Fv/Fm values ranging from 0.78 to 0.84. Several studies have reported that Y(II) and Fv/Fm are highly sensitive indicators for detecting the effects of drought stress in C3 plants due to photorespiration (Burke, 2010). Chlorophyll fluorescence is a sensitive measure of the physiological state of leaves, allowing rapid evaluation of plant performance under both abiotic and biotic stress conditions (Baker et al., 2004). Guidi et al. (2008) reported that yield loss in stressed plants was significantly reduced, with a correlation of 0.65–0.75 with Fv/Fm, whereas high-yielding plants were in the 0.80–0.82 range of Fv/Fm.

Figure 6

The Effect of Water Stress (3, 6 and 9 Weeks After Planting) on Common Bean: Length Primary Root (A), Number of Lateral Roots (B), Shoot Dry Weight (C), and Root Dry Weight (D)



Note. Water stress treatment was applied by withholding watering for 10 days at 3, 6, and 9 weeks after planting (WAP).

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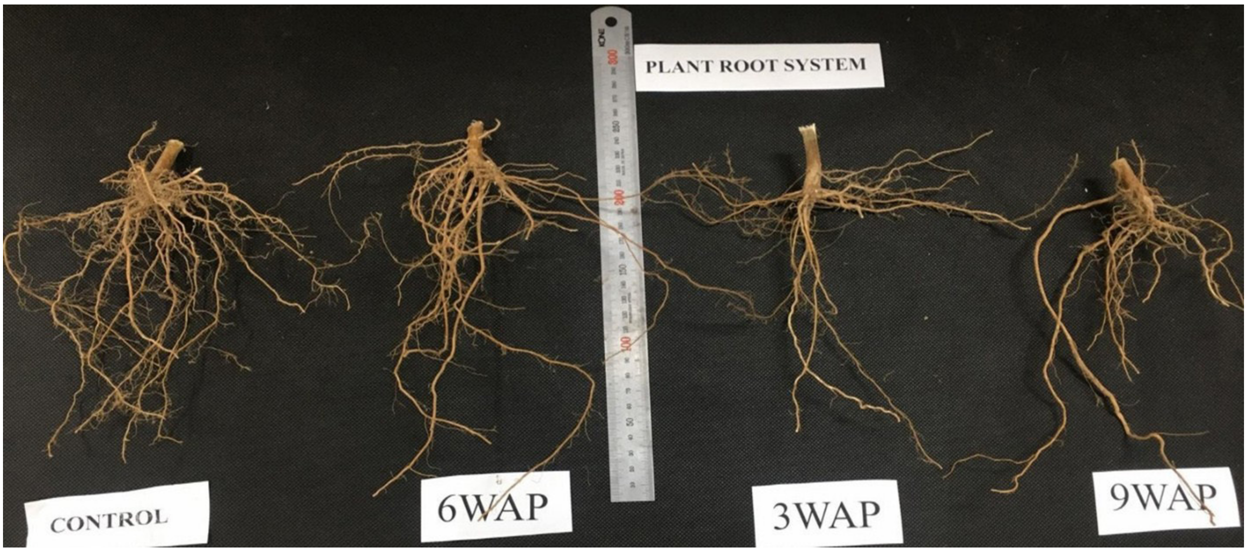
Figure 7

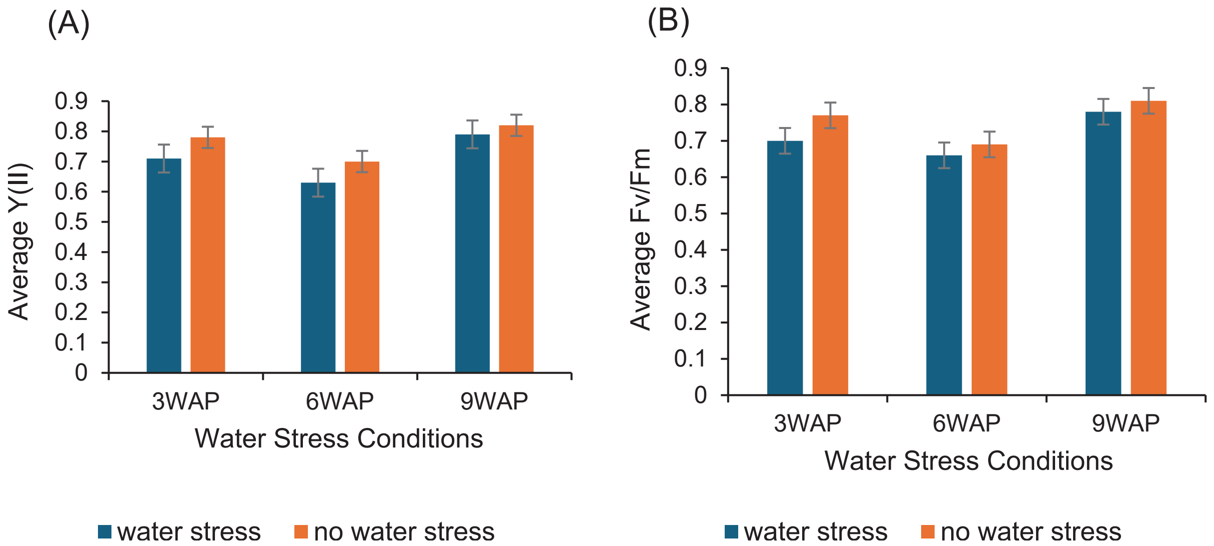
Effect of Water Stress on the Root System



Note. Water stress treatment was applied by withholding watering for 10 days at 3, 6, and 9 weeks after planting (WAP).

Figure 8

The Effects of Water Stress on Common Bean Quantum Photosynthetic Yield and Plant Maximum Photochemical Efficiency



Notes: Quantum photosynthetic yield (A), maximal photochemical efficiency (B). Water stress was applied by withholding watering for 10 days at 3, 6, and 9 weeks after planting (WAP). Y(II): quantum photosynthetic yield; Fv/Fm: maximal photochemical efficiency.

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Conclusions

The common bean (*Phaseolus vulgaris* L., cv. 'RWR2245') exhibits pronounced sensitivity to water deficit, which significantly impairs taproot elongation, leaf primordia development, and photosynthetic efficiency. At 3 weeks after planting (WAP), drought stress led to a marked reduction in the effective quantum yield of PSII and the maximum photochemical efficiency of PSII (Fv/Fm). By 6 WAP—a critical reproductive stage—all physiological parameters, except for nodulation, were significantly diminished under moisture stress. While water deficit inhibits canopy development throughout the life cycle, its impact on grain yield is most severe when stress coincides with these sensitive phenological phases. Consequently, to mitigate yield loss in drought-prone regions, planting schedules should be optimized to avoid drought exposure during the highly vulnerable 6 WAP period. Although the plants exhibited relative tolerance at 9 WAP compared to earlier stages, the yield penalties remained significant for stress occurring at 3 WAP and highly significant at 6 WAP. Chlorophyll fluorescence remains a robust, non-destructive tool for evaluating moisture-stress tolerance. Future breeding programs should prioritize developing genotypes resistant to water deficits during the 6 WAP window, complemented by management strategies such as organic mulching and targeted foliar fertilization to enhance resilience.

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