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ORIGINAL RESEARCH ARTICLE

Response of high-yielding soybean varieties to water-saturated and drought stress

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ABSTRACT

BACKGROUND AND OBJECTIVES: The cultivation of soybeans in Indonesia frequently encounters challenges related to water saturation and drought, which ultimately leads to reduced productivity. The objective of this study was to determine how various soybean varieties react to waterlogging and drought in order to identify soybean cultivars that exhibit tolerance to both types of stressors.

METHODS: The study was conducted at the greenhouse of the Indonesian Legumes and Tuber Crops Research Institute, spanning from June to August 2022. A factorial randomized block design was employed, utilizing pots as the experimental units, with three replicates. The first factor is the availability of groundwater, namely optimal water available (field capacity), 40 percent of field capacity (drought stress), and water-saturated soil (waterlogging stress). The soybean variety is the second factor to consider, which includes Dering 1 (known for its drought tolerance), Dering 2 (also drought tolerant), Deja 1 (tolerant to water saturation), Deja 2 (also tolerant to water saturation), Devon 1 (noted for its high isoflavone content), and Dega 1 (specifically adapted for irrigated lowland conditions).

FINDINGS: The results showed that Dering 2 and Deja 2 varieties grown in soil moisture levels at 40 percent field capacity were capable of achieving similar growth outcomes in terms of plant height, shoot/root ratio, number of pods per plant, seed yield, and 100 seed weight compared to those grown in optimal soil moisture conditions. The stress tolerance index of the two varieties in the soil moisture at 40 percent of field capacity reached 1.03 and 0.83, respectively. The yields of Dering 2 and Deja 2 varieties at the optimal soil moisture reached 4.53 gram per plant and 6.28 gram per plant, and in soil moisture of 40 percent field capacity were 4.68 gram per plant and 5.69 gram per plant respectively. In flooded soil, the Dering 2 and Deja 1 varieties can develop the weight of 100 seeds, number of branches, and plant height as same as in optimal soil moisture, with relatively lower yield reduction compared to other varieties, with stress tolerance index values of 0.66 and 0.54.

CONCLUSION: The Dering 2 and Deja 2 cultivars exhibit tolerance to drought stress levels of up to 40 percent of field capacity, whereas the Dering 2 and Deja 1 cultivars demonstrate tolerance to water-saturated soil. A noteworthy finding is the identification of soybean cultivars capable of thriving in both drought and waterlogged environments, exemplified by the Dering 2 variety. Originally bred to combat drought-related challenges, the Dering 2 cultivar has shown promising results in waterlogged soil conditions as well. Similarly, the Deja 2 variety, which was designed and released for water-saturated environments, was found in this study to be tolerant of drought conditions.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
43	3	7

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INTRODUCTION

Several soybean varieties in Indonesia have a potential yield of more than 3.5 ton per hectare (t/ha) (Harsono *et al.,* 2022), however, the national soybean productivity is relatively low namely 1.57 t/ha (CBS, 2020). The primary reason for this phenomenon is that over 60 percent (%) of soybeans in Indonesia are grown in lowland areas using a rice-rice-soybean or rice-soybean planting system. Soybean plants frequently encounter waterlogging at the onset of the vegetative growth stage, followed by drought stress during the reproductive phase. Both stresses can reduce the soybean yields significantly. Soybean yield is susceptible to a decline caused by flooding during the vegetative growth stage, with a range of 17% to 43%. However, the reproductive stage is even more adversely affected by flooding, resulting in a substantial reduction in seed yield by 50% to 56% (Ye *et al.*, 2018). The substandard germination and reduced viability of soybean seeds within the field can be ascribed to the rapid loss of viability in a hypoxic environment. This loss is primarily caused by the insufficient oxygen supply required for the activation of germination (Parolin, 2001). According to Reyna *et al.* (2003), the flood stress also caused chlorosis, necrosis, and defoliation of the leaves, shortening plant height, decreasing nitrogen (N) fixation, and the of death the soybean plants. The inundation of soybean plants for a period of three days during the second vegetative phase (V2) and third vegetative phase (V3) resulted in a 20% decline in yield (Sullivan *et al.*,2001). Smolenaars *et al.* (2021) reported that in Argentina the soybeans damage due to waterlogging during the rainy season reached 10%, and resulted in shortages reaching 0.25% of the national Gross Domestic Product (GDP). Approximately 40% of the soybean-growing land in China is situated within the Huanghua Hai Plan, a region that is susceptible to frequent occurrences of both flooding and drought. The seedling stage is the flooding-sensitive growth stage for dry matter mass and plant height of soybean, and the flowering-podding stage is the flooding-sensitive growth stage for seed yield, 100-grain weight, and the number of filled pods. According to Fletcher *et al.* (2023), flooding caused stress that had a major impact on yield at every stage of growth. Between 95 and 46% of the seeds germinated on average across the different treatments. The flood-tolerant genotypes exhibited a germination rate exceeding 80% following 8 hours of flooding, whereas the susceptible genotypes showed a notably lower range of 58 to 63%. Flood stress at the first vegetative phase of soybean (V1) and fourth vegetative phase of soybean (V4) growth stages for the highest tolerant genotype was constantly better than susceptible genotypes where tolerant genotype had 30% lower foliar damage and 10% higher the biomass than the susceptible genotype. Furthermore, the tolerant varieties exhibited a yield that was on average 25% greater than the susceptible genotypes. In Indonesia, soybean production faces a significant constraint due to the occurrence of drought, which is more prevalent during the reproductive phase of soybean plants. This is primarily because the majority of soybeans are cultivated during the dry season, when the risk of drought stress is highest. Consequently, the impact of drought on soybean production in Indonesia cannot be overlooked. Drought caused yield losses in soybeans ranging from 21 to 70%., depending on the variety (Adie and Krisnawati, 2019), duration of stress, and growth stadia (Ku *et al.,* 2013). Drought stress decreased soybean productivity and quality (Ginting *et al.*, 2022). According to Vogel *et al.* (2021), drought stress inhibits the growth of most plant organs, including lateral stem nodes and main stem nodes number. The development of pods heavily relies on these vital organs as they undergo growth in the vegetative phase. The soybean plant effectively accumulates nutrients to support its growth and blossoming throughout this vegetative stage. This phenomenon is exemplified by the elongation of the stem, the notable formation of nodes caused by branching that leads to the production of pods, the mechanism by which leaves are formed, and the improvement of water and nutrient absorption through the expansion of the root zone area. All of these factors collectively contribute to the process of photosynthesis (Kantolic and Slafer, 2005). As a result, when extreme moisture strikes during the plant's vegetative phase, it significantly reduces all other aspects of growth, including the development of plant organs (Xiong et al 2021). Pratiwi *et al.*, (2019) stated that during the vegetative phase, soybean plants may experience a reduction in root length and dry weight, node number, and plant height due to drought stress. In contrast to their vegetative growth stage, soybeans exhibit heightened susceptibility to water scarcity during the seed-filling phase. The seed weight, shoot biomass, and leaf photosynthetic rate of soybeans were reduced by 63.93%, 33.53%, and 41.65%, respectively, due to the impact of drought stress (Du *et al.,* 2020). The drought affected seed filling and seed development (Kreuzwieser *et al.*, 2014; Wang *et al.*, 2018). In Indonesia, water saturation stress in the begin of vegetative phase and drought in the generative phase are often the causes of not achieving optimal productivity of soybeans in the lowlands after rice. Hence, an effective measure to mitigate the consequences of these pressures is to cultivate soybean cultivars that exhibit resilience towards waterlogging or drought-induced stress. Harsono *et al.* (2022) reported that in Indonesia, Deja 1 and Deja 2 soybean varieties were tolerant to waterlogging stress. Meanwhile Dering 1, Dering 2, Dering 3, Detam 3 Prida, and Detam 4 Prida soybean varieties were tolerant to drought stress, especially in the period of generative growth. Riduan *et al.* (2022) also reported that soybean varieties such as Dena 1, Dena 2, Dering 1, Derap 1, Deja 2, Detam 1, Grobogan, and Argomulyo are categorized as drought-tolerant varieties. The mechanism of tolerance to drought stress is different for each variety, some of which are through increasing root length, and some are through an increasing in proline quantity using the mechanism of physiological tolerance. In order to address the aforementioned challenges of soybean stress in Indonesia, the current study was conducted to investigate the reaction of various high-yielding soybean cultivars to water saturation stress and drought stress. The objective was to identify soybean varieties that exhibit tolerance to both types of stress. The Deja1 and Deja2 varieties which are classified as tolerant to waterlogging stress, and the Dering 1 and Dering 2 varieties which are classified as tolerant to drought stress, are expected to provide higher yields than control on the water logging stress or drought stress condition, respectively. The primary aim of the study was to determine how various soybean varieties respond to water saturation and drought conditions in order to identify soybean varieties that exhibit tolerance to both of these stresses. This study has been carried out in Malang, East Java, Indonesia in 2022.

MATERIALS AND METHODS

Plant genetic material

A total of 6 soybean varieties that have been released by The Ministry of Agriculture of The Republic of Indonesia during 2012-2019 were used in this study. The six soybean varieties are: 1) Dering 1 and 2) Dering 2 which were specially developed to deal with drought problems, 3) Deja 1, 4) Deja 2 which were developed to deal with waterlogging problems, 5) Devon 1 which has high isoflavone content, and 6) Dega 1 which is adaptive to irrigated lowlands (Harsono *et al.*, 2022; Soehendi *et al.*, 2024).

Site description and planting

The research was conducted at the greenhouse facilities of the Indonesian Legumes and Tuber Crops Research Institute located in East Java, Indonesia, spanning from June to August 2022. Six different types of soybean were cultivated in pots and organized based on a randomized complete block design with two factors. Each treatment was replicated three times. The first factor is the availability of groundwater, namely: A) Optimal water available (field capacity), B) Soil moisture at 40% of field capacity, and C) Saturated soil. The second factor is six soybean variety (Dering 1, Dering 2, Deja 1, Deja 2, Devon 1, and Dega 1). Table 1 displays the treatment combination of the first and second factors.

Plastic pots were utilized to sow the soybean seeds, with an allocation of 8 kilograms (kg) of soil per pot. Initially, four soybean seeds were planted in each pot, but at the age of two weeks, the number of plants was reduced to two per pot, ensuring the presence of only robust and healthy soybean plants. During the planting process, water was added to the soil in all pots until it reached the field capacity water content. Fertilizer was added at the age of 2 weeks, namely after thinning with a dose equivalent to potassium chloride (KCL) 100 kilogram per hectare (kg/ha), Urea 50 kg/ha, and super phosphate (SP)-36 100 kg/ha. To ensure control, the water treatments that were available (optimal and at 40% of field capacity) were administered once the plants reached 2 weeks of age. This was done by measuring the weight of both the pots and plants every 2 days. Next, water was added to each pot in the volume needed so that the availability of soil moisture remains at around field capacity and 40% of field capacity, respectively. Subsequently, healthy soybean plants that were considered water-saturated from the age of 2 weeks onwards were positioned in a reservoir of water, with the water level maintained at 10 cm below the soil

Table 1: Combination of treatment of the first factor and the second factor in the study

Code	Firs factor (availability of groundwater)	Second factor (Soybean varieties)
A 1	Optimal water available (field capacity)	Dering 1 (drought tolerant)
A2	Optimal water available (field capacity)	Dering 2 (drought tolerant)
A3	Optimal water available (field capacity)	Deja 2 (tolerant to water saturation
A4	Optimal water available (field capacity)	Deja 2 (tolerant to water saturation stress)
A5	Optimal water available (field capacity)	Devon 1 (high isoflavone content)
A6	Optimal water available (field capacity)	Dega 1 (adaptive in irrigated lowland)
B1	Soil moisture at 40% of field capacity	Dering 1 (drought tolerant)
B2	Soil moisture at 40% of field capacity	Dering 2 (drought tolerant)
B3	Soil moisture at 40% of field capacity	Deja 2 (tolerant to water saturation stress)
B4	Soil moisture at 40% of field capacity	Deja 2 (tolerant to water saturation stress)
B5	Soil moisture at 40% of field capacity	Devon 1 (high isoflavone content)
B6	Soil moisture at 40% of field capacity	Dega 1 (adaptive in irrigated lowland)
C1	Saturated soil	Dering 1 (drought tolerant)
C2	Saturated soil	Dering 2 (drought tolerant)
C3	Saturated soil	Deja 2 (tolerant to water saturation stress)
C4	Saturated soil	Deja 2 (tolerant to water saturation stress)
C5	Saturated soil	Devon 1 (high isoflavone content)
C6	Saturated soil	Dega 1 (adaptive in irrigated lowland)

surface of the pots. Water saturation and drought stress treatments were given until two weeks before the plants were harvested. The content of soil water was maintained at 40% of field capacity, every two days the pot containing the plant is weighed, and an amount of water is added according to the amount of water that needs to be added to reach the water content of 40% of field capacity and field capacity. The adjustment of the water quantity added is also regulated based on the rise in plant weight resulting from growth. In the water saturation treatment, the water level in the water pool is maintained at around 10 cm below the soil surface of the pot by adding a specific volume of water every two days. Vigorous management practices are implemented to ensure optimal plant growth by effectively controlling weeds, pests, and diseases, with the exception of water stress impacts.

Data collection

The data that was gathered encompassed various parameters such as the height of the plants, the presence of root nodules, the leaf chlorophyll index, the rate at which the plants grew (referred to as the plant growth rate or PGR), the yield of seeds, the weight of 100 seeds, the number of pods, and number of branches. The plant growth rate was calculated using equation Eq. 1 (Wahyuningsih *et al.,* 2021):

$$\mathrm{PGR} = \frac{[(\mathrm{TDWi - TDWi1})]/[(\mathrm{Ti\text{-}Ti10}]}{\mathrm{Ga}} \qquad (1)$$

Where:

PGR = Plant growth rate ($g/m^2/day$)

TDWi and TDWi1 = total dry weight: leaf dry weight + root dry weight gram per plant (g/plant) at planta ge of T1 and Ti-1, respectively

Ga = Land area occupied by plants (m^2)

The stress tolerance index (STI) was calculated based on Eq. 2 (Lamba *et al.,* 2023). The greater of STI value it means that the plant is more resistant to stress.

$$\mathrm{STI} = \frac{(\mathrm{Yp} \times \mathrm{Ys})}{\mathrm{Xp}^2} \qquad (2)$$

Where:

Yp = the yield under optimal water available

Ys = the yield in the 40% field capacity or flooded condition

Xp = the mean yield of all varieties under optimal condition.

Data analysis

Analysis of variance (ANOVA) and the least significant differences (LSD) test were used to statistically analyze the data in order to determine distinctions between treatments at a level of confidence of 0.05.

RESULTS AND DISCUSSION

Plant height

The plant height is influenced by the interaction

Table 2: Plant height at harvest of several soybean varieties at optimal soil moisture, 40% field capacity and flooded

Soybean variety	Plant height at harvest at different water availability (cm)		
	Optimal	40% field capacity	Water flooded
Dering 1	69.33cd	78.67a	77.17ab
Dering 2	62.83de	65.67cde	78.83a
Deja 1	65.33cde	75.17ab	48.00f
Deja 2	78.67a	86.17a	70.67bc
Devon 1	61.00e	76.83ab	71.83bc
Dega 1	61.33e	60.83e	71.00bc

Note: Means that are followed by the same letter(s) do not differ significantly based on LSD at 5%

of variety and soil moisture conditions, including optimal, 40% field capacity, and flooded conditions. Among these, the Deja 2 variety exhibits greater growth in terms of height compared to the other five varieties under optimal soil moisture conditions. In water-saturated soil conditions, Dering 1, Dering 2, Devon 1, and Dega 1 varieties were able to grow higher than those grown in optimal soil moisture (Tabel 2). Meanwhile, in soil moisture conditions of 40% field capacity, the Dering 1, Deja 1, and Devon 1 varieties were able to grow higher than those grown in optimal soil moisture (Table 2). This study showed that Dering 1 and Dering 2, two drought-tolerant varieties, were found to grow well under water-saturated soil conditions. This indicates that both varieties also have high tolerance to water-saturated soil conditions. Both varieties have the capability to sustain consistent growth throughout the entire lifecycle, starting from seed germination until the final harvest. This is evident in the increased plant height observed in water-saturated soil conditions, surpassing the growth achieved in optimal soil moisture conditions. According to Fletcher *et al.* (2023), one of the characteristics of tolerant-water-saturated soybean genotypes is the ability to maintain germination after 8 hours of flooded. Deja 1, a water-saturated soil stress tolerant soybean, exhibited contrasting characteristics. Additionally, it is noted for its significant resistance to drought conditions. Deja 1 can optimize water absorption in drought conditions so that the development of plant height is not disturbed, as seen from the appearance of higher plants in soil moisture conditions of 40% field capacity when compared to optimal soil moisture. This is in accordance with the statement of Vogel *et al.* (2021) which states that the inhibition of water absorption by sensitive soybean plants due to drought stress can affect their vegetative growth. The reduced plant height of the Dega 1 variety in comparison to other varieties when water availability is optimal can be attributed to genetic factors. Nevertheless, the resistance of Dega 1 to water stress observed in this research differs from findings in earlier studies. Nur'aini and Rachmawati (2022) found that Dega 1 could withstand drought better than it could waterlogging.

Plant growth

The findings show, the soybean growth rate beginning from 45 days to 55 days is influenced by variety and water availability (Fig. 1). The Dering 1, Deja 1 and Dega 1 varieties at soil moisture of 40% field capacity were able to grow faster than those grown at optimal soil moisture (around 80% field capacity). The results indicate that the three varieties exhibit tolerance to drought conditions. Under soil moisture conditions equivalent to 40% of field capacity, Dering 1 and Dega 1 varieties demonstrate a reduced shoot/root ratio, suggesting that the root systems of these two cultivars exhibit superior growth compared to the remaining varieties (Fig. 1). In contrast, Deja 2 and Dega 1 exhibited increased plant growth rates in waterlogged conditions compared to conditions with optimal soil moisture levels. This phenomenon was further evidenced by enhanced root growth and a decreased shoot/root ratio (Fig. 1).

impacted by both drought and waterlogging circumstances, leading to alterations in leaf and root morphology (Kirsnawati *et al.,* 2021), antioxidant enzyme systems (Khalegi *et al.*, 2019), photosynthesis and hormone levels (Wu *et al.*, 2022).

Leaf chlorophyll index

The leaf chlorophyll index of all varieties exhibited a progressive rise as the plants matured, commencing from 25 days after planting (DAP) to 55 DAP. In general,

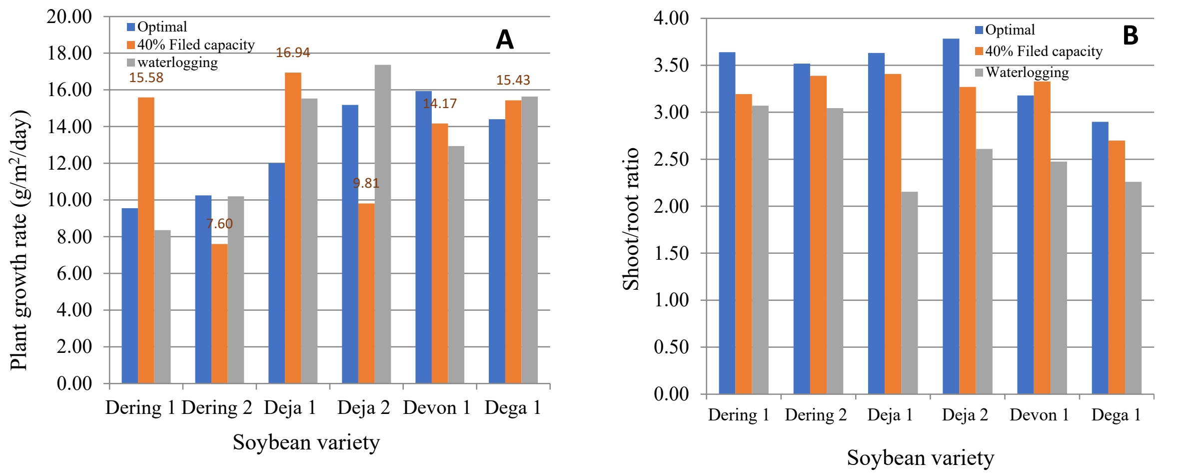
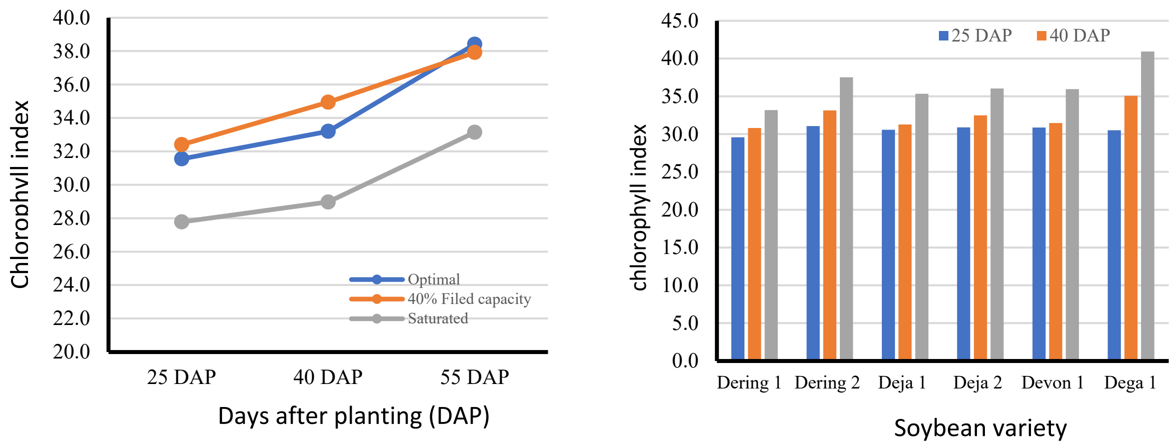


Fig. 1: Plant growth rate (A) and shoot/root ratio (B) of soybean varieties during the 45 – 55 days after planting under optimal soil moisture, 40% field capacity, and flooded.



A B

Fig. 2: Chlorophyll index and root nodules of soybean due to different soil moisture content and soybean varieties

leaf chlorophyll index was found to be greater in soil moisture conditions at 40% field capacity compared to optimal soil moisture levels, with the lowest index observed in optimal soil moisture and was lowest in waterlogged soil conditions (Fig. 2A). The chlorophyll content of the Deja 1 variety at 55 days (pod filling period) was higher than other varieties, followed by the Dering 2, Devon 1, Deja 2, Deja 1, and Dering 1 varieties, respectively (Fig. 2B). There was an exponential rise in the chlorophyll content of soybean leaves as the nitrogen content within the leaves increased. According to Maekawa and Kokubun (2005), soybeans with multiple nodules also have higher leaf N content, leaf chlorophyll, and rubisco than soybeans without nodules. Chlorophyll, the primary component of chloroplasts, plays a crucial role in the process of photosynthesis. As the content of chlorophyll in leaves increases, the rate of photosynthesis also rises. The function of chlorophyll in photosynthesis is to trigger the fixation of carbon dioxide (CO_2) to produce carbohydrates, provide ecosystem energy, and utilize solar energy (Nurcahyani *et al.*, 2019). The rate of photosynthesis increases with increasing leaf chlorophyll content.

Table 3: Number of branches when harvesting several soybean varieties at optimal soil moisture, 40% field capacity and flooded

Soybean variety	The number of branches/plants at harvest depends on water availability		
	Optimal	40% field capacity	Water flooded
Dering 1	3.67c	4.67a	3.67c
Dering 2	2.17fgh	2.33efg	3.33cd
Deja 1	3.67c	2.50ef	1.00i
Deja 2	4.50ab	3.67c	3.83bc
Devon 1	3.50cd	3.50cd	2.83de
Dega 1	1.67ghi	1.50hi	1.33i

Note: Means that are followed by the same letter(s) do not differ significantly based on LSD at 5%

Table 4: Number of pods when harvesting several soybean varieties at optimal soil moisture, 40% field capacity, and flooded

Soybean variety	Number of pods/plant at harvest depends on water availability		
	Optimal	40% field capacity	Water flooded
Dering 1	26.33ab	40.83a	28.67a
Dering 2	26.67ab	29.00b	23.67ab
Deja 1	28.00ab	34.83ab	19.00d
Deja 2	29.17ab	30.67b	18.67bc
Devon 1	33.67a	32.50ab	16.33bc
Dega 1	19.83b	18.67c	13.50c

Note: Means within a column and followed by the same letter(s) do not differ significantly based on LSD at 5%

Branch and pod number

The number of plant branches is influenced by the interaction of soybean variety and water availability (Table 3). In general, the number of branches of Dering 1 and Deja 2 varieties at all levels of water availability (optimal, 40% field capacity, and waterlogged) was greater than the Dering 2, Deja 1, Devon 1, and Dega 1. The results suggest that both Dering 1 and Deja 2 varieties exhibit tolerance to both drought and waterlogging. Under waterlogged conditions, there was no significant difference in the number of branches between the two varieties compared to when grown in optimal soil moisture conditions (Table 3). In the same environment, Dering 2 had more branches than when grown in the soil with optimal moisture conditions. It describes that the Dering 1, Deja 2, and Devon 1 varieties can grow well or are tolerant to water saturation stress, besides that the Dering 1 and Devon 1 varieties also grow taller under water-saturated conditions than when grown under optimal soil moisture conditions (Table 2). The discovery of Dering 1 and Dering 2, two drought-tolerant varieties, was intriguing. Despite being initially developed for drought conditions, this study revealed that both varieties exhibit strong growth even in water-saturated soil conditions. This observation further supports the earlier findings regarding plant height characters.

The study revealed that the number of pods produced by soybean plants is influenced by the interaction between soybean varieties and water availability (Table 4). In water-logged soil conditions, the Dering 1, Dering 2, and Deja 2 soybean varieties can produce the same number of pods compared to growing in optimal soil moisture conditions. At 40% field capacity, these three varieties were still capable of producing an equivalent number of pods as they would when grown in ideal soil moisture conditions. Meanwhile, the varieties of Dega 1, Deja 1, and Devon 1 are only adaptive to drought stress (40% field capacity) by producing the same number of pods/plants compared to growing in optimal soil moisture. Gebre *et al.* (2022) found that soybean seed yield was decreased by 51% due to drought stress. The number of pods experienced the most significant impact on yield, whereas both single-seed weight and the number of seeds per pod had minimal effects. According to Sulistyo *et al.* (2017), one of the soybean strategies in dealing with drought is to reduce the seed size and or the number of pods. The findings indicated a correlation among the traits of pod quantity, branch quantity, and plant height in soybean cultivars that exhibit tolerance to drought as well as water-saturated soil conditions. Hapsari *et al.* (2021) and Xu *et al.* (2021) stated that the branches number had a positive correlation to the pods

Table 5: Weight of 100 seeds of several soybean varieties in optimal soil moisture, 40% field capacity, and flooded

Soybean variety	100 seeds weight at harvest depends on water availability		
	Optimal	40% Field capacity	Water flooded
Dering 1	9.04ef	7.25gh	6.30h
Dering 2	10.44d	10.21d	9.61de
Deja 1	9.64de	8.89ef	8.65def
Deja 2	11.53c	10.49cd	10.71cd
Devon 1	6.95h	8.25fg	8.83def
Dega 1	17.91a	18.94a	15.97b

Note: Means that are followed by the same letter(s) do not differ significantly based on LSD at 5%

number produced by soybean plants. Agricultural management and genotype are two examples of factors that affect the number and growth of branches (Bao *et al.,* 2019; Chen *et al.,* 2020).

Seed size and seed yield

The findings of this study suggest that the size of seeds is primarily influenced by genetic factors, specifically the variety, rather than by the presence of water (Table 5). Sulistyo *et al.* (2021) reported that seed size is an agronomic character that is genetically controlled and has a high heritability value. The size of seeds is influenced by the genetic traits of the variety; however, the way different varieties respond to water availability differs based on their adaptability to such conditions. The Dering 2, Deja 1, and Deja 2 varieties, in soil moisture conditions of 40% field capacity or waterlogged soil, were able to produce the same large seed size compared to growing in optimal soil moisture (Table 5). Hence, the three varieties possess the ability to thrive in arid circumstances with a maximum of 40% field capacity or in inundated conditions. Meanwhile, the Devon 1 variety can produce larger seeds (weight) in soil moisture of 40% field capacity and waterlogged compared to growing in optimal soil moisture. The Dega 1 variety produces smaller seed sizes in waterlogged conditions.

With optimal water availability, the Devon 1 and Dega 1 varieties were able to produce higher seed yields, namely 6.28 g/plant and 6.27 g/plant, followed by Deja 1, Dering 1, Dering 2, and Devon 1 with yields of 5.69 g, 5.66 g, 5.53 g, and 3.71 g/plant, respectively (Fig. 3A). Under soil moisture at 40% of field capacity (drought stress), the Dering 2 variety can achieve the same results as optimal soil moisture conditions. It follows the variety description which is referred to as a variety tolerant to drought condition (Soehendi *et al.*, 2024). The Deja 2 variety exhibits a relatively low yield of 4.53 g/plant under ideal soil moisture conditions. Despite this, it is worth noting that this variety is classified as tolerant to water-saturated soil and can also withstand drought stress, as evidenced by its seed yield achievements. The tolerance index of the Dering 2 and Deja 2 varieties to drought stress at 40% soil moisture field capacity reached 1.03 and 0.83, respectively (Fig. 3B). At optimal soil moisture, the yield of the Deja 2 variety is higher than the Dering 2 variety.

In water-saturated soil conditions, the Dering 2 variety was able to produce 66% of seeds from plants grown in optimal soil moisture (5.53 g/plant), followed by the Deja 1 variety which reached 54% of plants grown in optimal soil moisture which produced seeds 5.69 g/plant (Fig. 3A). Despite the fact that the Deja 1 variety encountered a greater decrease in yield compared to the Dering 2 variety, the overall yield of 3.61 g/plant remained relatively similar to the Dering 2 variety, which produced 3.64 g of seeds per plant under flooded conditions. The tolerance index of the Dering 2 and Deja 1 varieties to water-saturated was reached 0.66 and 0.54, respectively. The tolerance indices of both varieties in the water-saturated exhibited higher values when compared to the remaining varieties, namely Dering 1, Deja 2, Devon 1, and Dega 2, respectively (Fig. 3B). According to Toai *et al.* (2010) the soybean flood-tolerant varieties produced higher grain yield than the susceptible varieties. In Indonesia, Nur'aini and Rachmawati (2022) reported that the early maturing soybean variety such as Dega 1 is more tolerant to drought stress than to waterlogging.

Root nodules

Varieties and environmental factors did not interact to affect the quantity of root nodules at harvest or 55 DAP. This is different from Pandey *et al.* (2022)

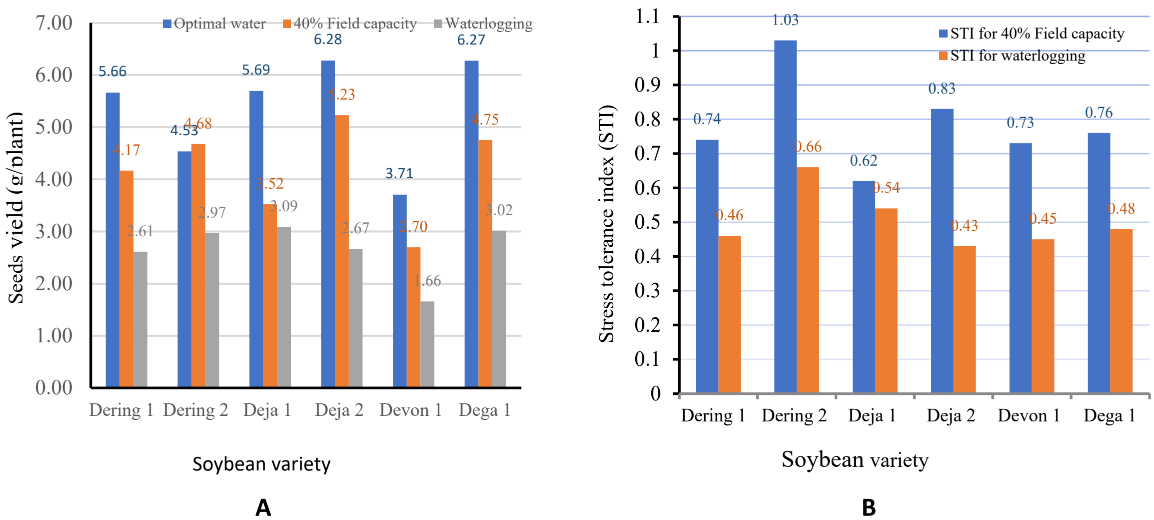


Fig. 3: Planting seed yield (A) and STI of several soybean varieties at optimal soil moisture, 40% field capacity, and flooded

and Yamane and Iijima (2015) who said that the number of nodules decreased when grown under water logging condition, and Sinclair *et al.* (1988) who stated that the number of nodules was also not affected by mild drought treatment. The highest number of root nodules at the age of 55 DAP was achieved by Devon 1 with 104.44 nodules followed by Deja 2 with 98.17 nodules, while the lowest number of root nodules was achieved by Dega 1 with 49.50 nodules followed by Deja 1 and Dering 2 with 70.28 and 73.33 nodules. At harvest time, the root nodules number was lower than at 55 DAP. Dering 1 and Deja 2 exhibited the highest number of root nodules at the time of harvest, whereas Dega 1 demonstrated the lowest count (Table 6). Devon 1 which had the highest root nodules number at 55 DAP experienced a high decrease in the number of root nodules at harvest. Variations in ranking between two different plant ages suggest the presence of certain varieties capable of preserving the quantity of root nodules, while other varieties exhibited a reduced ability to sustain the number of root nodules. In this study, Dering 1 was a variety that was able to keep the root nodules number than other varieties, while Devon 1 performed worse at sustaining the quantity of root nodules until harvest. The number of root nodules at harvest is also affected by the number of root nodules at the previous stage. This is evident in Dega 1, where the lowest number of root nodules was observed at the age of 55 DAP and during harvest. The number of root nodules in this study was higher than Haryati and Hamdani (2023) who reported Dega 1 with 17.24 nodules. Samudin and Kuswantoro (2018) reported that the presence of Rhizobium populations also affected the root nodules number.

In contrast to the relationship observed with the number of root nodules, the fresh weight of root nodules did not show any significant interaction between variety and environmental conditions. This finding diverges from previous studies where researchers noted a decrease in nodule fresh weight under flooded conditions (Pandey *et al.*, 2022; Nguyen *et al.*, 2015; Yamane and Iijima 2015). At 55 DAP, Devon 1 and Dering 1 had the highest fresh weight compared to other varieties, namely 3.32 and 3.27 g, respectively. Dega 1 had the lowest nodule fresh weight, namely 2.63 g. At harvest time the highest fresh weight was achieved by Dering 1 with 2.55 g, while the lowest was achieved by Deja 1 with 1.74 g. The decline in fresh weight of root nodules during harvest may be attributed to a reduction in the number of root nodules at that time (Table 7). Samudin and Kuswantoro (2018) reported that the root nodules number and root nodules dry weight were found to positively impact the root dry weight, suggesting a potential relationship between the root nodules fresh weight and the root nodules number. This is also reinforced by the statement of Zhuang et al.

Table 6: Number of root nodules at 55 DAP and harvest of several soybean varieties

Soybean variety	Number of root nodules	
	55 DAP	Harvest
Dering 1	83.67bc	51.44a
Dering 2	73.33c	36.67abc
Deja 1	70.28c	23.94bc
Deja 2	98.17ab	41.61a
Devon 1	104.44a	39.17ab
Dega 1	49.50d	21.00c

Note: Means in the same column that are followed by the same letter(s) do not differ significantly based on LSD at 5%

Table 7: Fresh weight of root nodules at at 55 DAP and harvest of several soybean varieties

Soybean variety	Fresh weight of root nodules	
	55 DAP	Harvest
Dering 1	3.27^{a}	2.55^{a}
Dering 2	2.79^{bc}	2.05^{bc}
Deja 1	3.09^{ab}	1.74^{c}
Deja 2	3.24^{ab}	2.27^{ab}
Devon 1	3.32^{a}	2.17^{abc}
Dega 1	2.63^{c}	1.95^{bc}

Note: Means in the same column that are followed by the same letter(s) do not differ significantly based on LSD at 5%

(2021) which states that the number of root nodules and fresh weight of root nodules are controlled by the GmSPX5 and GmNF-YC4 genes through regulating the transcription of several downstream genes.

CONCLUSION

The inadequate soybean harvests experienced by farmers in Indonesia can be attributed to a multitude of factors, encompassing both environmental and genetic influences. The disparity in productivity between research-scale soybean planting and actual farmer fields can be as high as 55%. This discrepancy is primarily attributed to the prevalent rice-rice-soybean or rice-soybean-soybean planting patterns. As a result, water availability problems, such as scarcity or surplus, emerge as the primary constraint in achieving optimal yields. Soybean seeds planted immediately after rice harvesting typically encounter low germination rates due to the high soil moisture content. Transitioning to the advanced vegetative stage, with the decline in groundwater levels, presents new obstacles due to the increased demand for water essential for the flowering and pod-filling stages. Another issue arises when soybean seeds are planted prior to the commencement of the rice planting season. Excessive water also presents problems for soybean pod filling and maturation. Planting appropriate soybean varieties can address the issue of water availability. In this study, Dering 2 and Deja 2 soybean varieties are tolerant to drought stress up to soil moisture of 40% field capacity by which, both varieties were able to grow and produce the same seed yield, 100 seed weight, and number of pods/plants as good as grown under optimal soil moisture, with the STI reached 1.03 and 0.83, respectivelyIn the meantime, Dering 2 and Deja 1 are examples of varieties that exhibit tolerance to water-saturated soil conditions. These two varieties are capable of maintaining similar levels of number of branches, 100 seeds weight, and plant height when grown in flooded soil as they would in soil with optimal moisture levels. Furthermore, they experience a relatively lower reduction in yield compared to other varieties, as indicated by their STI values of 0.66 and 0.54. An interesting discovery is the existence of soybean varieties that can adapt to both drought and waterlogged conditions, such as Dering 2. The Dering 2 variety has been developed and released to address drought issues. However, it has also demonstrated its efficacy in soil conditions characterized by excessive waterlogging. Likewise, the Deja 2 type, created and introduced for water-saturated settings, was identified in this investigation as showing resilience to drought circumstances.

AUTHOR CONTRIBUTIONS

Purwantoro provided genetic material, collected data and made graphical abstract; R.D. Purwaningrahayu designed the research and collected data; H. Kuntyastuti designed the study and collected data; A. Harsono as the first correspondent author provided the study idea, drafted the article, and reviewed the final manuscript; Nuryati collected data and documentation during the study; A. Sulistyo analyzing the data, drafting the graphical abstract and reviewed the final manuscript; Z. Yursak collected data and documentation during the study; R. Soehendi analyzed the data and interpreted the results; Trustinah analyzed the data and interpreted the results; H. Kuswantoro drafted the article and reviewed final manuscript; M.J. Mejaya provided the study idea, drafted the article, and reviewed the final manuscript; D. Harnowo provided the study idea and drafted the manuscript.

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ABBREVIATIONS

%	Percent
ANOVA	Analysis of variance
CBS	Central Bureau of Statistics
cm	Centimeter
CO_2	Carbon dioxide
DAP	Days after planting
et al	And others
Eq.	Equation
Fig.	Figure
g	Gram
Ga	Land area occupied by plants
GDP	Gross domestic product
KCl	Kalium chloride (Potassium chloride)
kg	Kilogram
kg/ha	Kilogram per hectare
LSD	Least Significant Differences
m	Meter
N	Nitrogen
PGR	Plant growth rate
SP-36	Super phosphate 36
STI	Stress tolerance index
TDWi	Total dry weight
t/ha	Ton per hectare
V1	First vegetative phase of soybean
V2	Second vegetative phase of soybean
V3	Third vegetative phase of soybean
V4	Fourth vegetative phase of soybean
Xp	The mean yield of all varieties under optimal condition
Yp	The yield under optimal water available
Ys	The yield in the 40% field capacity or flooded condition

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