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The Effect of Biological Fertilizers on Growth and Yields of Soybean (Glycine max L. Merr.) under Drought Stress toward SDG 2

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ABSTRACT

Objective: *Soybean (Glycine max L. Merr.) is an important source of vegetable protein and a major food commodity. However, expanding soybean cultivation into dryland areas is constrained by drought stress, which adversely affects plant growth and productivity. This study aimed to evaluate the effects of biological fertilizers and drought stress on soybean growth and yield.* ***Method:*** *The experiment was conducted from October 2019 to January 2020 in a greenhouse using a factorial Randomized Block Design with three replications. The first factor was biological fertilizer application, consisting of no fertilizer, Plant Growth-Promoting Rhizobacteria (PGPR) at 10 g L^{-1}, and Arbuscular Mycorrhizal Fungi (AMF) at 10 g $polybag^{-1}$. The second factor was drought stress based on soil water availability (SWA): 100%–100%, 100%–50%, 50%–100%, and 50%–50% during vegetative and generative phases.* ***Results:*** *Biological fertilizers did not significantly affect soybean growth or yield. In contrast, drought stress significantly reduced plant height, leaf number, leaf area, root length, plant dry weight, pod number, seed number, and seed yield, with the greatest reductions occurring under 50% SWA during both growth phases. No significant interaction was observed between biological fertilizers and drought stress treatments.* ***Novelty:*** *Identify water availability as the primary determinant of soybean productivity under drought conditions, supporting sustainable food production and SDG 2 (Zero Hunger).*

INTRODUCTION

In terms of food commodities, soybeans (Glycine max L. Merr.) rank third behind maize and rice and are a source of vegetable protein. About 7,291 tonnes of soybeans were produced in Banten in 2015, compared to just 863,183 tonnes in Indonesia. In the meantime, Indonesia imported 2,256,931.7 tonnes of soybean seeds in 2015 to meet domestic demand, and that amount rose to 2,671,914.1 tonnes in 2017. One tactic and endeavour to boost soybean yield is the extension of soybean planting regions to less-than-ideal ground, such as dry land (Celis et al., 2024; Peterson et al., 2018; Sharma et al., 2024). Soybeans must contend with maize and rice for the best land. It is anticipated that the area planted to soybeans will grow as unsuitable land is developed.

Through the use of PGPR inoculants as components of biofertilizers, dry land can be utilised for agricultural purposes by increasing the diversity of microorganisms and nutrients in the soil (Putrie et al., 2013). PGPR treatment increased plant biomass and N nutrient uptake in soybean plants. It is well established that mycorrhizal treatment boosts soybean plant growth and yield (Suherman et al., 2012).

The scarcity of water is the primary issue in arid regions (Chitsaz & Azarnivand, 2017; Karimi et al., 2024; Morante-Carballo et al., 2022). One of the limiting factors in soybean cultivation is drought or limited water availability (Staniak et al., 2023; Wang et al., 2022; Zanon et al., 2016). In addition to reducing plant development, severe drought stress can have an impact on a number of physiological and biochemical functions, including respiration, photosynthesis, translocation, ion uptake, carbohydrates, and nutrient metabolism (Abdalla, 2011; Azadeh et al., 2014; Sarkar et al., 2015). Soybean plant development and output could be decreased by administering water during the vegetative period of 100% field capacity (FC)-generative 50% FC. The growth and output of soybean plants are more severely impacted by water deprivation during the generative phase than during the vegetative phase (Kazgöz Candemir & Ödemiş, 2026; Miladinov et al., 2020; Yobi et al., 2020). It is anticipated that using biological fertilisers will provide a way to grow soybeans on arid soil with little water. Accordingly, studies on the water supply phase for soybean plants and the impact of water scarcity on each stage of development are required (He et al., 2019; Wei et al., 2018).

This study is also relevant to the achievement of Sustainable Development Goal (SDG) 2, which aims to end hunger and promote sustainable agriculture. Improving soybean productivity under drought-prone conditions is essential to strengthening food security, particularly in dryland farming systems. Understanding the effectiveness of biological fertilizers and the impacts of water limitation may provide insights for developing adaptive cultivation strategies that support sustainable soybean production in the face of increasing climate-related challenges.

RESEARCH METHOD

This study is experimental in nature. The study was carried out at Universitas Sultan Ageng Tirtayasa, Serang-Banten, at the Green House Laboratory of the Faculty of Agriculture. From October 2019 to January 2020, the study was conducted.

Polybags, hoes, small shovels, scales, analytical scales, ovens, measuring cups, labels, dirt sieves, bamboo, markers, meters, brown folders, stationery, and cameras were among the equipment utilised in this investigation. The Argo Mulyo variety of soybean seeds, paddy soil, water, urea fertiliser, TSP, KCl, and biological fertilisers, specifically PGPR and AMF, were the materials employed in this investigation.

A factorial randomised block design (RBD) with three replications and two components was employed in this quantitative study design. Biological fertiliser (P) is the first factor, and drought stress (K) is the second. There are three levels in the first factor of biological fertiliser (P): p0: No biological fertiliser is applied (0 g); p1: Bacterial biofertilizer (PGPR) (10 g.L-1.polybag-1); and p2: Fungal biofertilizer (AMF) (10 g.polybag-1). The second element is drought stress (K), which has four levels: k1: 100% Vegetative Phase - 100% Generative Phase SWA; k2: 100% Vegetative Phase - 50% Generative Phase SWA; k3: 50% Vegetative Phase - 100% Generative Phase SWA; and k4: 50% Vegetative Phase - 50% Generative Phase SWA. Twelve therapy combinations are available. 36 experimental units were created by repeating each treatment combination three times. Each experimental unit had two polybags containing one plant, for a total of 72 plants. Plant height 2–5 weeks after planting (WAP), number of leaves 2–5 WAP, leaf area, root length, dry plant weight, number of full pods, number of seeds, weight of 100 seeds, and dry seed weight per plant were the growth and yield parameters measured in this study.

Analysis of variance was then used to examine the data gathered from the measurement of soybean plant growth and yield factors. A second Duncan Multiple Range Test (DMRT) will be conducted at a 5% confidence interval level if the analysis of variance results significantly affect the F-test. There were multiple phases to the study's implementation, specifically: Paddy soil from the Kemenduran region of the Serang Regency was utilised as the planting medium. Plant residues and other material were removed from the soil by excavating it from the top surface to a depth of around 20 cm. Next, under air dry weight circumstances, the soil was placed in a 35 cm × 40 cm non-perforated polybag containing 5 kilogramme of planting media per polybag. Pure seeds of the Argo Mulyo cultivar were utilised. The seeds are whole or complete, free of flaws, uniformly sized, and clean or dirt-free.

The biological fertiliser treatment is adapted to the biological fertiliser application. PGPR biological fertilisers are applied directly to soybean seeds by soaking them in a PGPR solution. To do this, make a PGPR solution with a concentration of 10 g.L-1, soak the soybean seeds for around half an hour, drain them, and plant them. As much as 10 g.polybag-1 of FMA biological fertilisers are applied directly into the planting hole as granules that contain AMF fungi.

To plant soybean seeds, use a small shovel to dig a planting hole that is 3 cm deep. After that, two soybean seeds are placed in each planting hole or polybag, and the earth is once again covered. KCl 0.11 g.polybag-1, TSP 0.11 g.polybag-1, and urea 0.06 g.polybag-1 are the doses of fertiliser administered at 2 WAP. In the form of TSP 0.06 g.polybag-1 and KCl 0.06 g.polybag-1, further fertilisation is administered at 5 WAP. The application of fertiliser involves burying it in the soil surrounding the plant.

According to the drought therapy, maintenance involves watering once daily, specifically in the morning. Cutting soybean plants that produce more than one and leaving the best plants in each polybag is how thinning is done at 1 WAP. One WAP plant of the same age is placed in each planting hole during the morning replanting of polybags that do not support soybean plants. The purpose of weeding is to remove any weeds that might impede the growth of soybean plants from the area surrounding the seedlings and within the polybag. In accordance with agricultural circumstances, weeds are manually pulled out as they develop. Using the concepts of integrated pest management, pest and disease control is implemented when there are unsettling signs of pest or disease signs on the plants. Daily watering is done in accordance with drought management. at the time of planting till the plants reach old age.

RESULTS AND DISCUSSION

Results

Plant height

The results of the analysis test of the provision of biological fertilizers with drought stress on soybean plants (Table 1) did not show any interaction, but each factor had a different effect on the parameters of plant height. The biological fertilizer factor had an effect at 2-3 WAP while at 4-5 WAP it had no effect. The drought stress factor had an effect at 4-5 WAP.

Table 1. Effect of biological fertilizers and drought stress on soybean plant height

Plant Age (WAP)	Biofertilizer (P)	Drought Stress (K) k_1	k_2	k_3	k_4	Average
		.... cm				
2	p_0	44.00	41.00	45.00	41.67	42.92a
	p_1	36.83	36.67	38.17	36.50	37.04b
	p_2	44.33	45.50	46.33	43.83	45.00a
Average		41.72	41.06	43.17	40.67	
3	p_0	99.50	96.00	101.50	95.67	98.17a
	p_1	90.33	94.00	85.33	83.33	88.25b
	p_2	101.83	103.17	97.17	96.50	99.67a
Average		97.22	97.72	94.67	91.83	
4	p_0	161.33	152.33	145.50	132.33	147.88
	p_1	147.67	160.83	125.17	134.33	142.00
	p_2	162.00	166.50	126.83	127.83	145.79

Plant Age (WAP)	Biofertilizer (P)	Drought Stress (K) k_1	k_2	k_3	k_4	Average
		.... cm				
	Average	157.00a	159.89a	132.50b	131.50b	
	p_0	193.17	176.50	160.67	144.17	168.63
5	p_1	182.67	192.50	149.67	138.17	165.75
	p_2	194.33	200.00	150.17	143.00	171.88
	Average	190.06a	189.67a	153.50b	141.78b	

Note: numbers followed by the same letter in the same column or row indicate no difference based on the DMRT test at the 5% level.

The provision of biofertilizers has no effect, it is suspected that the fertilizer contained in AMF in the form of fungi is unable to adapt well to the root area so that it is less than optimal in infecting the roots of the host plant to produce intensive hyphae networks which results in less than optimal absorption of water, nutrients and minerals. PGPR also has no significant effect, it is suspected that the dose is not enough to affect growth and bacteria have not been able to colonize plant roots. This is in accordance with Pandini (2012), who states that the application of microbes does not affect plant growth because rhizobacterial activity tends to be slow and requires adaptation to the root environment. The provision of PGPR solution concentration also does not affect plant height, number of leaves, petiole length, leaf width, leaf length, or the time the first flower appears on papaya plants (Nasib et al., 2016).

Drought stress affects soybean growth. Water supply in the Vegetative Phase 50% - Generative Phase 50% SWA can reduce the height of soybean plants compared to water supply in the Vegetative Phase 100% - Generative Phase 100% SWA, Vegetative Phase 100% - Generative Phase 50% SWA and Vegetative Phase 50% - Generative Phase 100% SWA. This is because soybean plants are unable to grow optimally in water conditions of less than 60% SWA. Drought stress inhibits plant growth. Soybean plant height decreases with increasing drought stress phases. Lack of water can also affect the decline in soybean plant growth.

Number of leaves

Each element had a distinct impact on the number of leaves parameter, however the analysis test results of applying biofertilizers to soybean plants under drought stress (Table 2) did not reveal any interactions. At 4-5 WAP, the drought stress factor had an impact on the number of leaves parameter, but the biofertilizer factor had no effect.

It is believed that the dosage of biological fertilizers was insufficient to influence development and had not been able to colonize plant roots, which is why they had no effect. The findings of Cahyadi and Widodo (2017) demonstrated that biological fertilizers were unable to boost caisin plant growth in terms of root length, plant height, and leaf count.

The quantity of leaves on soybean plants is impacted by drought stress. Lack of water causes the photosynthesis process to be disrupted, which inhibits the growth of leaves on soybean plants. Growth problems and plant adaptation strategies, such as leaf shedding to minimize significant water loss, are the causes of the limited number of leaves during stress. Growth and photosynthesis will be inhibited by drought stress (Taiz & Zeiger, 2002). According to Saidah et al. (2018), growth problems and plant adaptation processes that cause leaf shedding to minimize significant water loss are the reasons for the sparse number of leaves during drought stress.

Table 2. The effect of administering biological fertilizers on drought stress on the number of leaves in soybean plants

Plant Age (WAP)	Biofertilizer (P)	Drought Stress (K) k1	k2	k3	k4	Average
		.... leaf blade				
2	p_0	4.00	4.00	4.00	4.00	4.00
	p_1	4.00	4.00	4.33	4.00	4.08
	p_2	4.00	4.00	4.00	4.00	4.00
Average		4.00	4.00	4.11	4.00	
3	p_0	6.33	6.33	6.00	6.00	6.17
	p_1	6.33	6.33	6.33	6.00	6.25
	p_2	6.00	6.67	6.00	6.00	6.17
Average		6.22	6.44	6.11	6.00	
4	p_0	11.33	11.67	7.33	7.33	9.42
	p_1	9.67	10.33	8.00	7.67	8.92
	p_2	10.67	11.00	7.33	7.67	9.17
Average		10.56a	11.00a	7.56b	7.56b	
5	p_0	16.33	16.33	9.33	11.33	13.33
	p_1	15.67	16.00	11.67	10.67	13.50
	p_2	16.33	17.33	11.67	10.67	14.00
Average		16.11a	16.56a	10.89b	10.89b	

Note: numbers followed by the same letter in the same column or row indicate no difference based on the DMRT test at the 5% level.

Leaf area (cm)

The results of the analysis test of the provision of biological fertilizers with drought stress on soybean plants (Table 3) did not show any interaction, but each factor had a different effect on the leaf area parameter. The biological fertilizer factor had no effect and the drought stress factor had an effect on the leaf area parameter.

Table 3. Effect of biological fertilizers on drought stress on the leaf area of soybean plants

Biofertilizer (P)	Drought Stress (K) k1	k2	k3	k4	Average
	.... cm^2				
p_0	418.73	473.77	169.82	151.88	303.55
p_1	406.31	418.34	199.21	151.87	293.94
p_2	457.00	535.30	235.11	187.77	353.80
Average	427.35a	475.81a	201.38b	163.84b	

Note: numbers followed by the same letter in the same column or row indicate no difference based on the DMRT test at the 5% level

During drought, plants reduce leaf area to reduce the evaporation area (transpiration). Leaf area decreases with increasing drought stress. The first physiological process affected by drought stress is a decrease in leaf size, which can reduce stomatal conductance and photosynthesis (Sulistyono et al., 2012). Changes in leaf and stomata size are mechanisms to avoid drought by reducing transpiration. During drought stress, plants can still continue their growth and development processes even though the number of leaves and leaf area are reduced.

Root length (cm)

The provision of biological fertilizers did not affect the root length parameter. Meanwhile, drought stress treatment affected the root length parameter. There was no interaction between the provision of biological fertilizers and drought stress treatment on the root length parameter Table 4.

Table 4. Effect of giving biofertilizers on drought stress on the root length of soybean plants

Biofertilizer (P)	Drought Stress (K) k1	k2	k3	k4	Average
	.... cm				
p_0	39.33	33.00	23.33	28.67	31.08
p_1	33.00	26.67	21.00	22.33	25.75
p_2	43.67	46.00	28.33	18.67	34.17
Average	38.67a	35.22a	24.22b	23.22b	

Note: numbers followed by the same letter in the same column or row indicate no difference based on the DMRT test at the 5% level

The decrease in root length during drought stress is caused by growth disorders due to inhibited cell division due to lack of water. Lack of water also disrupts the photosynthesis process so that the photosynthate formed is very little distributed to all parts of the plant body, including the roots, resulting in inhibited root formation. This also affects root growth so that in drought stress treatment, it causes a decrease in root length compared to those that are not stressed. Root growth is increasingly suppressed as drought stress increases. This is in accordance who stated that drought stress inhibits root formation, causing a decrease in plant root length and reducing root dry weight

Plant dry weight (g)

The results of the analysis test of the provision of biological fertilizers with drought stress on soybean plants (Table 5) did not show any interaction, but each factor had a different effect on the parameters of plant dry weight. The biological fertilizer factor had no effect and the drought stress factor had an effect on the parameters of plant dry weight

Provision of biological fertilizers had no effect, it is suspected that the application of biological fertilizers did not affect plant growth, it is suspected that rhizobacterial activity tends to be slow because it needs to adapt to the environment.

Table 5. Effect of biological fertilizer administration on drought stress on the dry weight of soybean plants

Biofertilizer (P)	Drought Stress (K) k_1	k_2	k_3	k_4	Average
	.... g				
p_0	4.21	4.54	2.26	2.01	3.25
p_1	3.81	4.55	2.16	1.66	3.05
p_2	4.43	5.45	2.25	1.84	3.49
Average	4.15a	4.85a	2.22b	1.84b	

Note: numbers followed by the same letter in the same column or row indicate no difference based on the DMRT test at the 5% level

Drought stress affects the dry weight of plants. Water supply in the Vegetative Phase 50% - Generative Phase 50% SWA can reduce the dry weight of soybean plants compared to water supply in the Vegetative Phase 100% - Generative Phase 100% SWA, Vegetative Phase 100% - Generative Phase 50% SWA and Vegetative Phase 50% - Generative Phase 100% SWA. The dry weight of soybean plants decreases with increasing drought stress phase. Drought stress inhibits plant growth so that it affects the dry weight of plants. The inhibition of soybean plant growth is caused by the disruption of the photosynthesis process due to lack of water so that the photosynthate produced also decreases. The results of the study by Lisar and Motafakkerazad (2012) showed that drought stress in food crops can reduce wet weight, dry weight, and harvest yields. Soybean varieties exposed to higher levels of drought stress will show a decrease in total dry weight (Suryaningrum et al., 2016).

Number of filled pods and number of seeds

The provision of biological fertilizers did not affect the parameters of the number of filled pods and the number of soybean seeds. While the drought stress treatment affected the parameters of the number of filled pods and the number of seeds. There was no interaction between the provision of biological fertilizers and the drought stress treatment on the parameters of the number of filled pods and the number of soybean seeds Table 6 and Table 7.

Table 6. Effect of the provision of biological fertilizers on drought stress on the number of filled pods of soybean plants

Biofertilizer (P)	**Drought Stress (K)**				**Average**
	k1	**k2**	**k3**	**k4**	
	.... g				
p_0	35.33	24.00	22.00	14.00	23.83
p_1	31.33	22.67	21.67	13.67	22.33
p_2	30.33	29.67	20.67	16.67	24.33
Average	32.33a	25.44b	21.44b	14.78c	

Note: numbers followed by the same letter in the same column or row indicate no difference based on the DMRT test at the 5% level

Table 7. Effect of giving biofertilizer on drought stress on the number of soybean seeds

Biofertilizer (P)	Drought Stress (K)				Average
	k_1	k_2	k_3	k_4	
	.... g				
p0	80.33	44.00	46.00	35.33	51.42
p_1	73.00	46.67	51.00	26.00	49.17
p_2	71.00	61.33	50.00	31.67	53.50
Average	74.78a	50.67b	49.00b	31.00c	

Note: according to the DMRT test at the 5% level, numbers in the same column or row that are followed by the same letter indicate no change.

Provision of water in the 50% Vegetative Phase and 50% Generative Phase In the Vegetative Phase 100% - Generative Phase 100% SWA, Vegetative Phase 100% - Generative Phase 50% SWA, and Vegetative Phase 50% - Generative Phase 100% SWA, SWA can decrease the amount of filled pods and soybean seeds in comparison to water supply. Soybean plants that experience drought stress during the generative period produce significantly fewer pods and seeds. As the drought stress period lengthens, the number of pods and seeds decreases. This demonstrates that the amount of filled pods and seeds is more impacted by drought stress during the generative phase than during the vegetative phase. More pods and seeds are produced when the generative phase's water supply is reduced than when the vegetative phase's water supply is decreased.

100-seed weight, dry seed weight per plant, and dry seed weight per hectare

The weight of 100 seeds and the weight of dried seeds per plant were unaffected by the use of biological fertilizers. The weight of 100 seeds, the weight of dry seeds per plant, and the weight of dry seeds per hectare were all impacted by the drought stress treatment. On the weight of 100 seeds, there was an interaction between the application of biological fertilizers and the drought stress treatment; however, there was no interaction on the weight of dry seeds per plant or weight of dry seeds per hectare.

The lack of effect was attributed to a less-than-ideal environment, which included low light intensity, high temperatures with low humidity, and limited water. In addition, the microbes in the biological fertilizers were unable to adapt to the cultivation environment, resulting in a lack of symbiosis between microbes and plants. This caused the plants to absorb water, nutrients, and minerals more slowly during drought-stressed conditions, which ultimately led to a decrease in the food production process and a decrease in the number of seeds produced by soybean plants.

The weight of 100 seeds, the weight of seeds per plant, and the weight of dried seeds per hectare were all reduced in soybean plants under drought stress. As the drought stress period lengthened, the yield reductions for 100-seed weight, seed weight per plant, and dry seed weight per hectare grew. The amount of pods, seeds, and seed weight per plant are decreased when drought stress occurs during the reproductive phase because it prevents assimilates from being distributed to the reproductive portions (Saputra et al., 2015). The weight of soybean seeds is impacted by drought stress. Drought stress reduces the yield of soybean seeds (Li et al., 2013). According to the findings of a study conducted in He et al. (2016), plants under drought stress in the R5 phase (beginning seed filling) had a 15.2% lower yield in the weight of 100 soybean seeds than plants not under stress. Tables 8 and 9 show the findings of the 100-seed weight and the seed weight per plant.

Table 8. Effect of biofertilizer on drought stress on 100-seed weight

Biofertilizer (P)	**Drought Stress (K)**				**Average**
	k1	**k2**	**k3**	**k4**	
			.... g		
p_0	12.54b A	13.69b A	22.06a A	10.61b A	14.72
p_1	13.52a A	17.52a A	14.66a B	14.77a A	15.11
p_2	14.48a A	14.46a A	16.22a B	14.40a A	14.89
	74.78a	50.67b	49.00b	31.00c	

Note: numbers followed by the same lower case letter in each row or the same upper case letter in each column show no difference according to the DMRT test at the 5% level.

Table 9. Effect of giving biofertilizer on drought stress on dry weight of seeds per plant

Biofertilizer (P)	Drought Stress (K) k1	k2	k3	k4	Average
			.... g		
p_0	9.98	8.96	6.31	3.46	7.18
p_1	9.83	6.81	8.98	3.84	7.37
p_2	10.08	10.16	7.22	4.50	7.99
Average	8.64ab	7.50b	3.93c	3.93c	

Note: numbers followed by the same letter in the same column or row indicate no difference based on the DMRT test at the 5% level

Discussion

The findings showed that the application of PGPR and AMF biofertilizers did not significantly improve most soybean growth and yield parameters under the experimental conditions. This may indicate that the introduced microorganisms were unable to effectively colonize plant roots or adapt to the cultivation environment, thereby limiting their contribution to nutrient uptake and plant growth. Similar findings were reported by Pandini et al. (2012), who suggested that rhizobacterial activity requires adaptation to the root environment before exerting beneficial effects. Likewise, Nasib et al. (2016) and Cahyadi and Widodo (2017) found that biological fertilizers did not significantly enhance vegetative growth in several crop species. These results imply that the effectiveness of biofertilizers depends on environmental suitability, microbial compatibility, and appropriate application strategies.

In contrast, drought stress consistently reduced soybean vegetative growth, as reflected by decreases in plant height, leaf number, leaf area, root length, and plant dry weight. Reduced water availability limits cell expansion, photosynthesis, and assimilate production, ultimately restricting plant development. Plants exposed to drought commonly reduce leaf expansion and leaf number to minimize transpiration losses while maintaining survival under water-deficit conditions (Taiz & Zeiger, 2002; Sulistyono et al., 2012). Similar responses were reported by Saidah et al. (2018), who observed that drought-induced leaf reduction represents an adaptive mechanism to conserve water. The present findings therefore confirm that drought stress is a major limiting factor affecting soybean growth in dryland environments.

Drought stress also substantially reduced reproductive performance, including the number of filled pods, seed number, 100-seed weight, and dry seed yield per plant. The greatest yield reductions occurred when water limitation persisted during both vegetative and generative stages, indicating the importance of maintaining adequate water supply throughout crop development. These findings are consistent with Saputra et al. (2015), Li et al. (2013), and He et al. (2017), who reported that drought stress during reproductive stages restricts assimilate translocation and decreases soybean yield. Beyond their agronomic implications, these findings support SDG 2 (Zero Hunger) by emphasizing the importance of adaptive water management strategies to sustain soybean productivity and strengthen food security under increasingly water-limited conditions.

Beyond their agronomic implications, these findings are relevant to the achievement of SDG 2 (Zero Hunger), which emphasizes sustainable agricultural practices and food security. The identification of water availability as a more critical determinant of soybean productivity than biological fertilizer application highlights the importance of adaptive water management strategies in maintaining crop yields under dryland conditions. In the context of increasing climate variability, these findings may also support efforts to enhance the resilience of soybean production systems to drought stress.

CONCLUSION

Fundamental Finding: This study demonstrates that biological fertilizers, including PGPR and AMF, did not significantly improve the growth and yield of soybean plants under the tested conditions. In contrast, drought stress significantly affected soybean performance, with the most severe reductions in growth and yield observed under 50% soil water availability (SWA) during both vegetative and generative phases. The findings confirm that water availability is a critical factor influencing soybean productivity, and prolonged drought stress consistently decreases plant growth and yield. **Implication:** The results highlight the importance of effective water management in soybean cultivation, particularly in dryland agricultural systems. Since biological fertilizers alone were unable to mitigate the negative effects of drought stress, maintaining adequate soil moisture during both vegetative and generative stages should be prioritized to sustain soybean productivity in water-limited environments, contributing to SDG 2 (Zero Hunger) and supporting climate adaptation efforts under SDG 13 (Climate Action). **Limitation:** This study was conducted under greenhouse conditions using a single soybean variety and specific doses of biological fertilizers. Therefore, the findings may not fully represent field conditions or the responses of other soybean genotypes and biofertilizer formulations under varying environmental conditions. **Future Research:** Future studies should evaluate different soybean varieties, biofertilizer combinations, and application rates under field conditions to identify more effective strategies for enhancing drought tolerance. Further investigation into the physiological and molecular mechanisms involved in plant responses to biological fertilizers and drought stress is also recommended to support the development of sustainable soybean production systems in dryland areas.

AUTHOR CONTRIBUTIONS

Arief Septiawan contributed to the conceptualization of the study, experimental design, methodology development, data collection, formal analysis, and preparation of the original manuscript draft. **Rusmana Rusmana** contributed to supervision, validation of research methods, interpretation of results, and critical review of the manuscript. **Sri Ritawati** was responsible for laboratory and greenhouse experiment management, data curation, statistical analysis, and visualization of research findings. **Eltis Panca Ningsih** contributed to literature review, resource provision, manuscript editing, and overall project administration. All authors participated in discussing the results, reviewed the manuscript critically for intellectual content, and approved the final version of the manuscript for submission.

CONFLICT OF INTEREST STATEMENT

The authors state that no financial or personal conflicts of interest exist that may have affected the content or findings of this research.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors declare that no artificial intelligence (AI) tools or other digital writing assistants were used in the preparation, analysis, or writing of this manuscript. All stages of the research process, including data analysis, interpretation, and manuscript writing, were conducted solely by the authors. The authors take full responsibility for the originality, accuracy, and integrity of the content presented in this article.

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