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Synergistic Effects of Multicomponent Bioameliorants on Soil Fertility and Doubling Soybean Yield under Dryland Conditions in Indonesia

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ABSTRACT

Indonesia's soybean output averages 0.6−0.8 t·ha⁻¹, far lower than the potential yield of 2−3 t·ha⁻¹. Imports still account for more than 60% of national need. The prevalence of dryland areas with low fertility and inadequate water-holding capacity remains a major barrier to enhancing domestic soybean productivity. This study evaluated how bioameliorants improved soil chemical characteristics and soybean productivity. A randomized block design was used with six treatments: P1 (bioameliorant mixture at 30 t·ha⁻¹), P2 (bioameliorant mixture at 20 t·ha⁻¹), P3 (chicken manure at 30 t·ha⁻¹), P4 (cow manure at 30 t·ha⁻¹), P5 (control, no bioameliorant), and P6 (rice husk charcoal at 30 t·ha⁻¹). Each treatment had three replications. The criteria studied were vegetative growth, physiological indices, leaf area index (LAI), net assimilation rate (NAR), relative growth rate (RGR), and yield components. Data was evaluated using analysis of variance (ANOVA) and HSD at 5%. The results demonstrated that bioameliorants considerably increased growth and yield over the control. P2 had the most leaves (204 per plant), leaf area (5,417.94 cm²), and dry biomass (168.72 g/plant), but P1 had the highest grain output (2.8 t·ha⁻¹). The control yielded just 1.2 t·ha⁻¹, and the 1000-seed weight was consistent among treatments (about 175 g). Bioameliorant mixes, especially at 20−30 t·ha⁻¹, improve soil quality, increase soybean growth, and double yield in dryland conditions, while also supporting sustainable waste utilization and soil health restoration.

Keywords: chicken manure, cow dung, rice husk charcoal, soil amendment, soil fertility

INTRODUCTION

Drylands in Indonesia have enormous potential for expansion as agricultural producing areas, notably for soybeans (Dewi & Nadhira 2025). As an agricultural country, Indonesia has a significant demand for soybeans, both for domestic consumption and for the processing industry (Rahim *et al*. 2023). Soybeans are the primary raw material for a variety of strategic food products, including tofu, tempeh, soy sauce, and soy milk, which have become an integral part of people's diets. However, domestic soybean output is insufficient to meet national demand (Hulu & Sri Rahayu 2024). Indonesian soybean output averages 1.5 t·ha⁻¹, which is significantly lower than the potential yield of 2−3 t·ha⁻¹ (Rinaldi *et al*. 2023). As a result, Indonesia continues to rely heavily on soybean imports to meet domestic demand, accounting for more than 80% of total national demands (Bayu 2024). This circumstance shows a significant imbalance between output and demand, requiring more effective land management measures to boost domestic soybean production.

One of the limiting issues for soybean output in Indonesia is the reliance on dryland agriculture (Suherman *et al*. 2025). Dryland has restrictions, such as poor water availability, organic matter content, and nutrient retention capacity (Janke *et al*. 2025). Dryland soil is generally coarse in texture, resulting in rapid loss of water and nutrients, ultimately limiting plant productivity (Huntley 2023). Under these conditions, soybeans frequently encounter water and nutrient stress, resulting in unsatisfactory vegetative development and crop yields (Chaudhari *et al.* 2024). Therefore, developing soil management innovations, particularly the use of organic-based bioameliorants, is critical for improving soil functionality and increasing soybean yield in dryland areas in a sustainable manner.

To address the limits of dry land, various measures have been explored, including the introduction of superior stress-tolerant varieties (Yofa *et al*. 2021), chemical fertilization (Naorem *et al*. 2023), and water-saving irrigation systems (Chen *et al*. 2024). However, water-saving irrigation systems in dryland areas are frequently hampered by low water availability and inadequate infrastructure, making large-scale deployment difficult (Roy *et al*. 2025; Tandane *et al*.

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2026). Furthermore, such systems are largely concerned with water management and do not directly address soil fertility and nutrient retention, which remain significant limits in dryland agriculture. Furthermore, excessive and continuous use of chemical fertilizers has been shown to erode soil structure, diminish soil organic matter, and negative impact microbial activity, ultimately leading to decreased soil quality and increasing reliance on external inputs (Abebe *et al*. 2022). Therefore, more ecologically friendly and sustainable solutions are necessary to increase soil ecosystem function. One promising solution is the use of bioameliorants, which are organic soil supplements made from materials like animal dung, compost, and biochar. These materials work through a variety of mechanisms, including increasing soil organic matter, improving soil aggregation, increasing water-holding capacity (Astiko *et al*. 2024), improving soil structure, and stimulating microbial activity, which is critical for nutrient availability (Astiko *et al*. 2023).

Previous study has demonstrated that bioameliorants can improve plant development in drylands (Suherman *et al*. 2025). Bioameliorants such as chicken manure and cow dung, for example, are high in nitrogen and organic matter and can improve soil quality. Chicken manure is recognized for its high nitrogen content, which is essential for vegetative plant growth, but cow dung includes a lot of carbon, which helps to build soil structure (Sitters *et al*. 2020). Rice husk charcoal is also an efficient bioameliorant because it increases soil water-holding capacity and improves soil aeration (Astiko *et al*. 2025), making it ideal for dryland settings with limited water availability. In addition, bioameliorants promote the activity of soil microorganisms, which are essential for nutrient cycling. Bacteria and fungus help break down organic materials into forms that plants can absorb (Javed *et al*. 2022). This helps plants use nutrients more efficiently, which can improve soybean growth and output (Sree *et al*. 2025). Bioameliorants can also help to minimize soil erosion, a common problem in drylands with loose soil texture. Furthermore, the use of bioameliorants is in line with the Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger) through increasing local food production to reduce imports and strengthen food sovereignty (Kpammah *et al*. 2026), SDG 12 (Responsible Consumption and Production) by utilizing organic waste such as livestock manure and rice husk charcoal into environmentally friendly value-added products (Waheed *et al*. 2025), and SDG 13 (Climate Action) through efforts to reduce greenhouse gas emissions by recycling organic waste while improving soil quality (Afshar & Mofatteh 2024). This study compared the effectiveness of bioameliorants i.e. chicken manure, cow dung, rice husk charcoal, and their mixtures at levels of 20 and 30 t·ha^{-1}. The goal of this study was to identify the most effective type and amount of bioameliorant for boosting vegetative growth, biomass, and soybean output in dryland environments. The study's findings are expected to give scientific insights as well as practical recommendations for farmers seeking to increase soybean yield sustainably and close the production-to-national-needs mismatch.

METHODS

Research Site

This study was carried out in a dryland location in South Sulawesi, Indonesia (3°59'49.09"S and 119°40'37.12"E). The site represents a typical tropical dryland ecosystem, with Regosol soil that is relatively juvenile, sandy in texture, loose in structure, and has a limited water-holding capacity. The area has a tropical environment, with a distinct dry season. The average annual rainfall is between 1,500 and 2,000 mm, with unequal distribution throughout the year. Rainfall is concentrated during the wet season, whereas the dry season from May to October sees significantly less precipitation, often less than 100 mm each month. The average daily temperature ranges from 28.5 °C to 29.2 °C, resulting in high evapotranspiration rates and low soil moisture availability. These conditions are typical of dryland agricultural systems, where water scarcity and low soil fertility are significant restraints on crop output.

Research Design

The experiment used a Randomized Block Design (RBD) with six bioameliorant treatments: a mixed bioameliorant at 30 t·ha^{-1} (P1), a mixed bioameliorant at 20 t·ha^{-1} (P2), chicken manure at 30 t·ha^{-1} (P3), cow dung at 30 t·ha^{-1} (P4), a control without bioameliorant (P5), and rice husk charcoal at 30 t·ha^{-1} (P6). The application rates of 20 and 30 t·ha^{-1} were chosen based on previously published ranges of organic amendments, which typically vary between 10 and 40 t·ha^{-1} depending on soil conditions and amendment types (Agbede *et al*. 2024; Çamlıca & Yaldız 2025). The 20 t·ha^{-1} rate is a moderate application level, whereas 30 t·ha^{-1} is a higher input level. This allows for the examination of dose-dependent effects of bioameliorants on soil characteristics and plant performance.

The bioameliorant combination included chicken manure, cow dung, and rice husk charcoal in equal parts (1:1:1, w/w). Two application rates were used: 20 and 30 t·ha^{-1}. The experimental plot size was 2 m × 3 m (6 m²). The application rates were converted into plot-scale quantities, yielding 18 kg per plot for the 30 t·ha^{-1} treatment and 12 kg for the 20 t·ha^{-1} treatment. The 30 t·ha^{-1} treatment used a mixture of 6 kg chicken manure, 6 kg cow dung, and 6 kg rice husk charcoal per plot. The 20 t·ha^{-1} treatment used a mixture of 4 kg chicken manure, 4 kg cow dung, and 4 kg rice husk charcoal per plot. Bioameliorants employed in this investigation were procured locally. Chicken manure and cow dung were sourced from surrounding farms, while rice husk charcoal was derived from rice milling byproduct. Before application, all bioameliorant ingredients underwent a fermentation procedure to improve breakdown and nutrient availability.

All ingredients were fermented under regulated moisture levels (50−70%), considered to be optimal for microbial activity during composting operations (Haug 2018). Fermentation was carried out utilizing a leaf mold solution as a biological activator, which contained indigenous microorganisms capable of speeding up the degradation of organic matter and mineralization of nutrients. The use of local microorganisms (MOL) as bioactivator has been shown to improve composting efficiency and organic fertilizer quality (Gan *et al*. 2020). The solution was prepared by diluting leaf mold extracted in water (1:10, v/v) and then spraying it uniformly on a mixture of chicken manure, cow dung, and rice husk charcoal. The mixture was periodically turned to guarantee proper aeration and uniform decomposition, as turning has been shown to improve microbial activity and heat distribution during organic matter decomposition. The use of animal manure and biochar-based materials has also been shown to improve composting efficiency and organic matter stabilization (Suherman *et al*. 2025). The fermentation process was carried out for four weeks until the materials darkened in color, were more friable, and released a lower odor, indicating partial stabilization of organic matter. Following fermentation, the bioameliorant mixture was applied to the soil at the prescribed treatment doses and evenly integrated into the topsoil layer (0−20 cm) during site preparation prior to planting.

Anjasmoro, a superior soybean cultivar, was planted at a 30 cm × 20 cm spacing, with two to three seeds each hole. After germination, the seedlings were trimmed to leave only one plant per hole. Watering, weeding, and treating pests and diseases as needed are all part of plant maintenance.

Observed Parameters

Plant growth, biomass, physiological indices, and yield components were among the metrics monitored. Vegetative growth data were plant height (cm), number of leaves, and leaf area (cm²). Plant height was measured using a ruler from the base of the stem to the plant's tallest point. Each sample plant had its leaves counted manually. Leaf area was calculated using a non-destructive method based on leaf length and width measurements, with a correction factor, or by using a leaf area meter when applicable. Fresh and dry weights were included in the biomass parameters. Fresh weight was determined by weighing plant samples right after harvesting using a digital balance. Dry weight was measured after oven-drying the samples at 70 ℃ until a consistent weight was achieved, indicating full moisture elimination.

The leaf area index (LAI), net assimilation rate (NAR), and relative growth rate (RGR) were estimated using standard growth analysis methods based on weekly observations (Nasrullah *et al.* 2026; Pabón-Garcés *et al*. 2025). The LAI was calculated as the ratio of total leaf area to ground surface area occupied by the plant. Formulas 1 and 2 were used to determine NAR and RGR, respectively. *W* represents plant dry weight (g), *L* represents leaf area (cm²), and *t* represents time (day).

$$NAR = (W_2 - W_1) / (t_2 - t_1) \times (\ln L_2 - \ln L_1) / (L_2 - L_1)$$

$$RGR = (\ln W_2 - \ln W_1) / (t_2 - t_1)$$

Observations were taken at weekly intervals from two weeks after planting (WAP) until the generative stage. Physiological indices were determined using sequential sampling intervals. At harvest, yield components were measured: seed weight per plant (g), 1000-seed weight (g), and production per hectare ($t \cdot ha^{-1}$). Growth was observed weekly from two weeks after planting (WAP) until the generative period, with yield measurements taken after harvest. The collected data were examined using analysis of variance (ANOVA) to assess the effect of the treatments. If significant differences were discovered, a second HSD (Honestly Significant Difference) or Tukey test was used at the 5% level to distinguish between treatments.

RESULTS AND DISCUSSION

Soil Chemical Properties

The soil chemistry analysis revealed that the initial soil condition (control) was relatively poor in fertility. This was suggested by low organic carbon content (1.30%), low total nitrogen (0.10%), and restricted accessible phosphorus (31 ppm), whereas soil pH ranged from slightly acidic to neutral (6.66) (Table 1). These characteristics are typical of marginal dryland soils: poor organic matter and nutrient availability, as well as limiting agricultural output. The use of bioameliorants significantly improved soil chemical characteristics when compared to control. The multicomponent treatments (P1 and P2) demonstrated the most significant gains, notably in terms of soil organic carbon and nutrient availability. Organic carbon levels increased dramatically to 2.65% in P1 and 1.91% in P2, showing significant soil organic matter enrichment. The accessible phosphorus (P_2O_5) increased significantly from 31 ppm in the control to 178 ppm in P1 and 135 ppm in P2. Potassium availability boosted, with P1 having the highest value (349 ppm). Furthermore, soil pH changed toward neutral (7.03−7.29), which is beneficial for nutrient availability and uptake. The improved soil chemical

Table 1 Soil chemical properties under different bioameliorant treatments

Treatment	pH (H_2O)	Organic C (%)	Total N (%)	C/N Ratio	Available P_2O_5 (ppm)	Available K_2O (ppm)
P1 (Mix 30 t·ha^{-1})	7.03	2.65	0.11	24	178	349
P2 (Mix 20 t·ha^{-1})	7.29	1.91	0.11	17	135	204
P3 (Chicken manure 30 t·ha^{-1})	6.69	1.48	0.13	11	64	174
P4 (Cow dung 30 t·ha^{-1})	6.55	1.80	0.14	13	117	163
P5 (Control)	6.66	1.30	0.10	12	31	158
P6 (Rice husk charcoal 30 t·ha^{-1})	6.34	1.56	0.13	12	32	229

Note: These values represent soil chemical properties measured after treatment application. Soil pH was determined in an H_2O suspension. Organic carbon was determined using the Walkley–Black method, total nitrogen using the Kjeldahl method, and available phosphorus and potassium were determined using standard extraction methods.

characteristics can be attributed to the combined impacts of organic matter addition and increased nutrient release from bioameliorants. Increased organic carbon helped to increase soil structure, aggregation, and water retention capacity while also acting as a microbial substrate (Quan *et al*. 2020). The increased availability of phosphate and potassium indicates improved nutrient mineralization and reduced fixation, both of which are required for plant metabolic processes (Chaudhari *et al.* 2024). The move to neutral pH enhances nutrient solubility and availability, especially in dryland soils where nutrient restrictions are widespread (Astiko *et al*. 2023).

Among the treatments, the multicomponent bioameliorant (P1) consistently showed the greatest improvement in most soil indices, demonstrating a synergistic impact of integrating several organic ingredients. In contrast, single-source supplements such as chicken manure (P3), cow dung (P4), and charcoal (P6) exhibited moderate gains, implying that certain materials may have more specific but limited effects. For example, cow dung had the highest nitrogen content, although charcoal was more successful at increasing potassium availability (Ali *et al*. 2025). These findings demonstrate the effectiveness of combined bioameliorant techniques in increasing total soil fertility (Rizwan *et al*. 2025; Sebahire *et al.* 2024).

Vegetative Growth of Soybeans

The results showed that applying bioameliorant had a substantial effect on most parameters of soybean vegetative development in dry ground, except for plant height, which did not change significantly across treatments (Table 1). This suggests that the plant's response to improving soil conditions is better reflected in physiological metrics like leaf number, area, and biomass than in plant height. Vegetative plant development is determined not only by an increase in height, but also by leaf area and biomass, both of which have a direct impact on photosynthetic capability. A wider leaf area enhances the plant's ability to catch light, whereas biomass indicates adequate nutrition availability to sustain new tissue growth (Feng *et al*. 2023). Thus, enhanced soil fertility attained through bioameliorants is critical in providing optimal nutrition and physical conditions, thereby enabling a long-term increase in leaf area and biomass (Suherman *et al*. 2025).

The bioameliorant mixed treatment (P2 and P1) outperformed the single treatment and the control in terms of leaf number and area. P2 had more leaves (204.2) than the control (82.4), and its leaf area was significantly wider (5,417.94 cm²) than the control's (2,184.85 cm²). Improved vegetative growth in P1 and P2 is strongly linked to increased soil fertility, specifically higher organic carbon and nutrient availability. This significant increase suggests that the combination of bioameliorants efficiently improves soil physical and chemical properties, improving the availability of water and nutrients for plants (Amiroh *et al*. 2025). The mixture's components each play a distinct role: chicken manure, as a nitrogen-rich bioameliorant, supports leaf formation (Qiu *et al*. 2021); cow dung contributes to increasing organic carbon content, which improves soil structure (Castro-Herrera *et al*. 2022); and rice husk charcoal increases soil porosity, improving aeration and water-holding capacity (Anshori *et al*. 2023). The synergy among these three materials explains why the mixed treatment outperforms the single treatment (Suherman *et al*. 2025). Previous research has shown that combining organic manure and biochar results in synergistic benefits on soil fertility and plant performance (Wang *et al.* 2021). Such combinations have been shown to considerably increase soil organic carbon, nutrient availability, and microbial activity when compared to individual amendments (Chen *et al*. 2020). In addition, the complementary roles of manure as a nutrient source and biochar as a nutrient retention agent help to improve soil chemical characteristics and crop productivity (Huang *et al.* 2025). The lack of substantial changes in plant height between treatments shows that bioameliorants have a greater impact on plant metabolic capacity through better physiology and nutrition availability than on stem elongation alone. This demonstrates the phenomena of partial etiolation, in which plants grow higher without accumulating enough biomass due to nutritional restrictions (Armarego-Marriott *et al*. 2020).

Plant Biomass

The results showed that the application of bioameliorant had a substantial effect on soybean biomass in dry land, both fresh and dry weight (Table 2). The maximum fresh weight was recorded in treatment P2 (349.29 g), followed by P1 (289.55 g), whereas the control (P5) gave just 154.16 g. A similar trend was observed for dry weight, with P2 recording the highest value of 168.72 g, much larger than that of the control (75.31 g). P1 also made a significant contribution, with a dry weight of 139.18 g. While the single bioameliorant treatments (P3, P4, and P6) produced more biomass than the control, their values were still lower than the mixture treatments. The proportion of dry weight compared to fresh weight observed in this study was higher than previously reported values in well-watered settings. This could be linked to the dryland environment, where restricted soil moisture availability can diminish plant water content while increasing the relative accumulation of dry matter. Plants tend to grow better structural biomass in response to water stress. Under dryland conditions, plants respond to water stress by increasing their dry matter percentage relative to fresh biomass. This is due to reduced tissue water content and higher structural biomass allocation (Groszyk & Szechyńska-Hebda 2021). The relatively higher dry matter proportion observed in this study is consistent with plant responses to water scarcity conditions. Drought stress has been demonstrated to diminish plant tissue water content and alter biomass allocation, resulting in a larger proportion of dry matter buildup than under well-watered conditions (Yan *et al*. 2023). These physiological changes represent plants' adaptive mechanisms for dealing with water scarcity in dryland environments.

The study found that using bioameliorant mixes at 20 and 30 t·ha⁻¹ considerably enhanced soil chemical characteristics in dryland environments. Soil pH rose from 6.66 in the control to 7.03−7.29 in the mixture treatments, and organic carbon content increased from 1.30% to 1.91−2.65% (Table 2), showing improved soil fertility in terms of nutrient availability and organic matter content. These gains were strongly related to the increase in plant biomass shown in the bioameliorant mixture treatments (P1 and P2), which was reflected in higher fresh and dry weights. The rise in biomass shows a synergistic effect of the mixed organic materials, producing more balanced macronutrients (N, P, and K) while also enhancing soil pH and overall soil physical and chemical qualities. Increased nitrogen and phosphorus availability facilitated vegetative development and biomass buildup (Groszyk & Szechyńska-Hebda 2021). Furthermore, increasing organic carbon levels improved soil structure and water retention, promoting root development and nutrient uptake efficiency (Montagnani *et al*. 2022). These findings show that using bioameliorants in combination is more successful than using them alone to improve soil fertility and plant performance (Chen *et al*. 2020). Previous studies have revealed similar findings, with integrated organic amendments greatly improving soil characteristics and biomass production (Suherman *et al*. 2025). Thus, the mixture of bioameliorants enhanced soybean plant biomass while also considerably improving soil fertility in dryland in a sustainable manner.

P2 (mix 20 $t \cdot ha^{-1}$) produced more biomass than P1 (mix 30 $t \cdot ha^{-1}$), indicating that even low doses can enhance plant development. Nutrient availability at 20 $t \cdot ha^{-1}$ is sufficient to meet soybeans' physiological needs, therefore raising the dose to 30 $t \cdot ha^{-1}$ does not result in considerable increases. Similar findings have been observed in previous studies, where lower or moderate application rates resulted in higher crop yield than higher doses, particularly in field conditions. This shows that increased biomass is a direct reflection of the plant's physiological efficiency in converting photosynthesis into vegetative growth (Park *et al*. 2024). Thus, this experiment confirms that bioameliorants play an important role in alleviating dryland soil conditions and allowing plants to produce more biomass (Table 2). Using bioameliorants at a dose of 20 $t \cdot ha^{-1}$ resulted in increased fresh and dry plant weight, leading to higher soybean output during the generative phase.

Growth Index

The Net Assimilation Rate (NAR) figures represent the difference in response amongst bioameliorant treatments (Table 3). The control (P5) had the highest NAR value (0.762 g m^{-2} $week^{-1}$), however this advantage was only transient as it did not result in optimal biomass accumulation. This shows that, while

Table 2 Effect of bioameliorants on vegetative growth of soybeans on dryland

Treatment	Number of leaves (leaflet)	Plant height (cm)	Leaf area (cm^2)	Wet weight (g)	Dry weight (g)	LAI
P1 (Mix 30 $t \cdot ha^{-1}$)	171.0^{a}	85.2	4535.69^{a}	289.55^{a}	139.18^{a}	0.0504^{a}
P2 (Mix 20 $t \cdot ha^{-1}$)	204.2^{a}	96.6	5417.94^{a}	349.29^{a}	168.72^{a}	0.0602^{a}
P3 (Chicken manure 30 $t \cdot ha^{-1}$)	130.8^{b}	82.4	3469.27^{b}	210.12^{ab}	102.65^{b}	0.0385^{b}
P4 (Cow dung 30 $t \cdot ha^{-1}$)	148.2^{b}	80.2	3932.56^{b}	236.71^{a}	115.21^{b}	0.0437^{b}
P5 (Control)	82.4^{c}	93.8	2184.85^{c}	154.16^{b}	75.31^{b}	0.0243^{c}
P6 (Rice husk charcoal 30 $t \cdot ha^{-1}$)	120.0^{b}	77.8	3183.61^{b}	195.84^{b}	94.78^{b}	0.0354^{b}

Note: Numbers followed by different letters in the same column indicate significant differences according to the HSD test at the 5% level the control group's leaves have a reasonably high photosynthetic efficiency per unit area, the soil's low nutrients and water prohibit the assimilation process from being sustained over time. In contrast, treatments P1 (0.759) and P2 (0.727) had rather consistent NAR levels. Despite not being as high as the controls, this consistency helped to increase biomass accumulation. Treatment P6 (rice husk charcoal 30 t·ha⁻¹) had the lowest NAR value (0.486), suggesting that while it enhanced soil physical qualities, its contribution to nutrient supply was less than that of the bioameliorant combination.

Meanwhile, the Relative Growth Rate (RGR) revealed an interesting pattern (Table 3), indicating a relative rise in plant biomass per unit weight over time. RGR values in bioameliorant treatments ranged from 0.05 to 0.08 g g^{-1} $week^{-1}$, with P2 (0.052) and P3 (0.052) having the highest values, followed by the control (P5) at 0.054. Although the control had a relatively high RGR, this was not consistent with its reduced biomass accumulation and seed yield, which can be attributed to nutritional constraints that limit long-term growth despite short-term relative increases. This phenomenon is compatible with plant growth theory, stating that RGR does not necessarily correlate with total biomass accumulation due to constraints in resource availability and allocation efficiency (Cwalina-Ambroziak *et al.* 2021).

A contrasting pattern was found in P3, which likewise had reasonably high RGR and NAR values but did not produce biomass accumulation equivalent to the bioameliorant mixture treatments (P1, P2). This suggests that, while nutrient availability in P3 was not a limiting factor, plant development may have been affected by less balanced nutrient input and inferior soil conditions compared to the combined treatments. High NAR values indicate active photosynthetic absorption; however, this does not always imply increased biomass accumulation, as biomass output is heavily controlled by carbon allocation and partitioning across plant organs. Previous findings have shown that plant growth responses are influenced not only by absorption rates, but also by how assimilates are allocated to structural biomass, which ultimately affects total biomass production (Cwalina-Ambroziak *et al.* 2021). In contrast, the mixed bioameliorant treatments offered a more balanced nutrient supply as well as better soil physical and chemical characteristics, promoting both photosynthetic activity and efficient biomass synthesis. As stated in plant growth analysis theory, high RGR must be supported by effective assimilate conversion into structural biomass to sustain plant growth and production (Fu *et al*. 2012). This condition was more pronounced in P2, resulting in increased dry weight and yield than in both the control and single-source treatments. Thus, whereas the control had competitive NAR and RGR values, the bioameliorant treatments, notably P1 and P2, demonstrated improved physiological consistency. The combination of chicken manure, cow dung, and rice husk charcoal enhanced soil physical characteristics, increased organic matter content, and offered a better-balanced supply of macro- and micronutrients (Hadiarto *et al*. 2025). These conditions promoted steady net photosynthetic rates (NAR) and relative growth (RGR), resulting in higher soybean biomass and yield (Sattar *et al*. 2023).

Yield

Bioameliorants considerably boosted soybean yield components (Table 4). The highest seed weight per plant was achieved in P2 (63.27 g), higher than in P1 (52.19 g), while the control yielded just 28.24 g. The weight of 1000-seeds remained generally consistent throughout all treatments (±175 g), showing that the

Table 3 Effect of bioameliorant on physiological index of soybean on dry land

Treatment	NAR ($g{\cdot}m^{-2}{\cdot}week^{-1}$)	RGR ($g{\cdot}g^{-1}{\cdot}\ week^{-1}$)
P1 (Mix 30 $t{\cdot}ha^{-1}$)	0.759^{ab}	0.050^{ab}
P2 (Mix 20 $t{\cdot}ha^{-1}$)	0.727^{ab}	0.052^{ab}
P3 (Chicken manure 30 $t{\cdot}ha^{-1}$)	0.777^{bc}	0.052^{b}
P4 (Cow dung 30 $t{\cdot}ha^{-1}$)	0.671^{ab}	0.051^{ab}
P5 (Control)	0.762^{a}	0.054^{a}
P6 (Rice husk charcoal 30 $t{\cdot}ha^{-1}$)	0.486^{c}	0.051^{b}

Note: Numbers followed by different letters in the same column indicate significant differences according to the HSD test at the 5% level.

Table 4 Effect of bioameliorant on soybean yield on dry land

Treatment	Seed weight·$plant^{-1}$ (g)	Weight of 1000 seeds (g)	Production ($t{\cdot}ha^{-1}$)
P1 (Mix 30 $t{\cdot}ha^{-1}$)	52.19^{b}	175.00	2.800^{a}
P2 (Mix 20 $t{\cdot}ha^{-1}$)	63.27^{a}	175.00	2.500^{a}
P3 (Chicken manure 30 $t{\cdot}ha^{-1}$)	38.49^{c}	175.00	1.742^{b}
P4 (Cow dung 30 $t{\cdot}ha^{-1}$)	43.20^{c}	175.00	1.954^{b}
P5 (Control)	28.24^{d}	174.31	1.200^{c}
P6 (Rice husk charcoal 30 $t{\cdot}ha^{-1}$)	35.54^{c}	175.00	1.607^{d}

Note: Numbers followed by different letters in the same column indicate significant differences according to the HSD test at the 5% level.

bioameliorant treatment did not affect the physical quality of the seeds. Production per hectare increased significantly. P1 had the highest yield (2.8 t·ha^{-1}), followed by P2 (2.5 t·ha^{-1}), whereas the control yielded just 1.2 t·ha^{-1}. This suggests that using bioameliorants can enhance soybean yield by more than twice as much as not using them. This illustrates the efficacy of bioameliorants in improving dryland soil conditions and thereby enhancing soybean productivity (Astiko *et al*. 2023).

Bioameliorant treatments, especially the 20−30 t·ha^{-1} mix, resulted in increased soybean growth and yield, suggesting a synergistic effect amongst organic materials. This combination makes P1 and P2 the most effective treatment. P2 used a lower dose (20 t·ha^{-1}), but the findings are not significantly different from P1. The 20 t·ha^{-1} dose was sufficient for good vegetative development, as indicated by biomass accumulation and growth indices. However, the reproductive phase, notably seed production and grain filling, requires higher nutrient availability, particularly phosphorus and potassium, which play important roles in energy transfer, assimilate translocation, and seed development. As a result, the enhanced nitrogen intake in P1 may have contributed to increased yield formation, even if vegetative growth responses were not significantly different. This shows that P2 is more input-efficient while still delivering optimal outcomes. These findings align with the principle of efficient use of organic materials in sustainable agriculture (Zulfiqar *et al*. 2019).

The apparent difference between vegetative growth and yield responses can be attributed to the different physiological requirements of plant growth phases. The 20 t·ha^{-1} treatment was sufficient for vegetative development. However, the higher yield in P1 (30 t·ha^{-1}) is likely associated with increased nutrient demand during the reproductive phase, particularly phosphorus and potassium, which play key roles in seed formation and assimilate translocation (Vemulakonda *et al*. 2024). Furthermore, crop productivity is affected by the efficiency with which biomass is partitioned into reproductive organs, rather than only its accumulation. Previous studies have also shown that increasing input levels does not necessarily result in proportional yield gains, with optimal responses generally occurring at moderate nutrient levels (Bhattarai *et al*. 2026). Practically, this experiment shows that using bioameliorants not only boosts soybean output but also has environmental benefits by utilizing local organic waste. This helps to meet SDG 2 (Zero Hunger) by increasing local food production, SDG 12 (Responsible Consumption and Production) by recycling organic waste, and SDG 13 (Climate Action) by reducing emissions and improving soil (Astiko *et al.* 2023).

CONCLUSION

This study shows that bioameliorant application has a substantial effect on vegetative development, physiological indicators, and soybean production in dryland. Mixed bioameliorant treatments at 30 t·ha^{-1} (P1) and 20 t·ha^{-1} (P2) significantly enhanced leaf number, leaf area, biomass, and growth indices (LAI, NAR, and RGR) compared to the control group. P2 had the most leaves (204), leaf area (5,417.94 cm^2), and dry weight (168.72 g), but P1 yielded the most (2.8 t·ha^{-1}). Bioameliorant application increased soybean production by more than two-fold compared to the control yield of 1.2 t·ha^{-1}.

The single bioameliorant treatments (chicken manure, cow dung, and rice husk charcoal) enhanced growth and yield compared to the control, but they remained lower than the bioameliorant mixture. The weight of 1000-seeds remained steady (±175 g), demonstrating that the bioameliorant did not impact their physical quality. The bioameliorant mixture treatment at a dose of 20 t·ha^{-1} (P2) was shown to be more efficient than the 30 t·ha^{-1} dose, resulting in higher productivity (2.5 t·ha^{-1}) with reduced inputs. This study indicates that the application of bioameliorants not only boosts soybean productivity in dryland, but also contributes positively to organic waste management, improves soil fertility, and supports the accomplishment of SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Based on the study's findings, farmers in dryland areas are advised to use mixed bioameliorants (chicken manure, cow dung, and rice husk charcoal) at a dose of 20 t·ha^{-1} as an effective and sustainable option, as it can increase soybean yields by more than two folds compared to the control with lower input requirements compared to a dose of 30 t·ha^{-1}. Additionally, using bioameliorants based on local organic waste helps reduce reliance on chemical fertilizers, gradually improves soil quality, and supports environmentally friendly agricultural practices that are consistent with national food security and productivity.

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REFERENCES

Abebe TG, Tamtam MR, Abebe AA, Abtemariam KA, Shigut TG, Dejen YA, Haile EG. 2022. Growing use and impacts of chemical fertilizers and assessing alternative organic fertilizer sources in Ethiopia. *Applied and. Environmental. Soil Science*. 2022(18): 1–14. https://doi.org/10.1155/2022/4738416

Adewoyin JA, Arimoro FO. 2023. Animal manure as a biostimulant in bioremediation of oil-contaminated soil: the role of earthworms. *Environmental. Monitoring and. Assessment*. 195(2): 293. https://doi.org/10.1007/s10661-022-10884-1

Afshar M, Mofatteh S. 2024. Biochar for a sustainable future: environmentally friendly production and diverse applications. *Results in Engineering.* 23: 102433. https://doi.org/10.1016/j.rineng.2024.102433

Agbede TM, Oyewumi A, Agbede GK, Adekiya AO, Adebiyi OTV, Abisuwa TA, Ijigbade JO, Ogundipe CT, Wewe AO, Olawoye OD, Eifediyi EK. 2024. Impacts of poultry manure and biochar amendments on the nutrients in sweet potato leaves and the minerals in the storage roots. *Scientific Reports*. 14: 16598. https://doi.org/10.1038/s41598-024-67486-9

Ali A, Jabeen N, Chachar Z, Chachar S, Ahmed S, Ahmed N, Laghari AA, Sahito ZA, Farruhbek R, Yang Z. 2025. The role of biochar in enhancing soil health & interactions with rhizosphere properties and enzyme activities in organic fertilizer substitution. *Frontiers in Plant Science*. 16: 1595208. https://doi.org/10.3389/fpls.2025.1595208

Amiroh A, Yunus A, Purwanto E, Haryanto ET, Lestari MW. 2025. Effectiveness of organic ameliorant for improving physical, chemical, and biological properties of drought-stress in soil. *IOP Conference Series: Earth and Environmental Science*. 1497: 012002. https://doi.org/10.1088/1755-1315/1497/1/012002

Anshori A, Suswatiningsih TE, Viandari NA, Mujiyo M, Purwaningsih H, Budiarti SW, Pustika AB, Cahyaningrum H. 2023. Ameliorant of rice husk charcoal supports rice cultivation in dry land. *IOP Conference Series: Earth and Environmental Science*. 1168: 012007. https://doi.org/10.1088/1755-1315/1168/1/012007

Armarego-Marriott T, Sandoval-Ibañez O, Kowalewska Ł. 2020. Beyond the darkness: recent lessons from etiolation and de-etiolation studies. *Journal of Experimental Botany*. 71(4): 1215–1225. https://doi.org/10.1093/jxb/erz496

Astiko W, Ernawati NML, Silawibawa IP. 2023. The application of several bioameliorant formulations to increase soil nutrient concentration and yields maize-soybeans intercropping flexible to climate change in suboptimal land North Lombok, Indonesia. *IOP Conference Series: Earth and Environmental Science*. 012036. https://doi.org/10.1088/1755-1315/1253/1/012036

Astiko W, Ernawati NML, Silawibawa IP. 2024. Effects of soil tillage on the agronomic performance of maize-soybean intercropping in dry land North Lombok, Indonesia. *International Journal of Innovative Science and Research Technology*. 9(3): 753–758. https://doi.org/10.38124/ijisrt/IJISRT24MAR380

Astiko W, Sudirman FMT, Ernawati NML, Muthahanas I. 2025. Optimization of growth and yield of glutinous corn with the application of ameliorant formulation plus mycorrhiza on sandy soil. *Asian Journal of Agricultural and Horticultural Research*. 12: 83–94. https://doi.org/10.9734/ajahr/2025/v12i1361

Bayu A. 2024. Dampak penetapan tarif impor kedelai di Indonesia dengan analisis keseimbangan parsial. cendekia niaga. *Journal of Trade Development and Studies*. 8: 159–168. https://doi.org/10.52391/jcn.v8i2.904

Bhattarai K. Khanal N. Thilakarathna MS, Lupwayi NZ, Rahman N, Otani J, Shrestha B, Lemke RL, Kroebel R. 2026. Crop diversification with high-value perennial seed crops drives profitability in crop rotations in Northwestern Canada. *Frontiers in Agronomy*. 7: 1732922. https://doi.org/10.3389/fagro.2025.1732922

Bhunia S, Bhowmik A, Mallick R, Mukherjee J. 2021. Agronomic efficiency of animal-derived organic fertilizers and their effects on biology and fertility of soil. *Agronomy.* 11: 823. https://doi.org/10.3390/agronomy11050823

Çamlıca M, Yaldız G. 2025. The roles of chicken manure and biochar applications in enhancing the morphological, yield, crude protein content and antioxidant activities of basil. *Düzce Üniversitesi Bilim ve Teknoloji Dergisi*. 13: 964–981. https://doi.org/10.29130/dubited.1616349

Castro-Herrera D, Prost K, Schäfer Y, Kim D, Yimer F, Tadesse M, Gebrehiwot M, Brüggemann N. 2022. Nutrient dynamics during composting of human excreta, cattle manure, and organic waste affected by biochar. *Journal of. Environmental. Quality*. 51: 19–32. https://doi.org/10.1002/jeq2.20312

Chaudhari SK, Santra P, Machiwal D, Kumar M, Singh VK, Reddy KS, Kundu S. 2024. *Soil, Water, and Nutrient Management in Drylands*, in: Lal, R. (Ed.), *Managing Soil Drought (Advances in Soil*

Sciences), 21. Florida (US): Chemical Rubber Company Press. https://doi.org/10.1201/b23132-4

Chen B, Zhao M, Liu C, Feng M, Ma S, Liu R, Chen K. 2020. Comparison of copper binding properties of DOM derived from fresh and pyrolyzed biomaterials: Insights from multi-spectroscopic investigation. *Science of The Total Environment.* 721: 137827. https://doi.org/10.1016/j.scitotenv.2020.137827

Chen W, Wang L, Guo C. 2024. Synergistic regulation of water-saving cultivation and dryland farming and its sustainable development pathways. *Geographical Research Bulletin*. 3: 416–437.

Cwalina-Ambroziak B, Stępień A, Waśkiewicz A, Grzywińska-Rąpca M. 2021. The effect of foliar fertilization with micronutrients on disease severity and mycotoxin concentrations in the grain of winter spelt (*Triticum aestivum* spp. spelta L.): A case study. *Agronomy*. 11: 678. https://doi.org/10.3390/agronomy11040678

Dewi DS, Nadhira A. 2025. Dampak pola tanam tumpangsari jagung dan kedelai terhadap produktivitas dan kesuburan tanah pada lahan kering. *All Fields of Science Journal Liaison Academia and Society.* 5: 14–24. https://doi.org/https://doi.org/10.58939/.v5i2.788

Feng H, Guo J, Peng C, Kneeshaw D, Roberge G, Pan C, Ma X, Zhou D, Wang W. 2023. Nitrogen addition promotes terrestrial plants to allocate more biomass to aboveground organs: a global meta-analysis. *Global Change Biology*. 29: 3970–3989. https://doi.org/10.1111/gcb.16731

Fu H, Yuan G, Cao T, Ni L, Li W, Zhu G. 2012. Relationships between relative growth rate and its components across 11 submersed macrophytes. *Journal of Freshwater Ecology*. 27: 471–480. https://doi.org/10.1080/02705060.2012.684102

Gan J, Peng Y, Chen Q, Hu G, Xu Q, Jin L, Xie H. 2020. Reversible covalent chemistry of carbon dioxide unlocks the recalcitrance of cellulose for its enzymatic saccharification. *Bioresource Technology*. 295: 122230. https://doi.org/10.1016/j.biortech.2019.122230

Groszyk J, Szechyńska-Hebda M. 2021. Effects of 24-epibrassinolide, bikinin, and brassinazole on barley growth under salinity stress are genotype- and dose-dependent. *Agronomy*. 11: 259. https://doi.org/10.3390/agronomy11020259

Hadiarto A, Firdaus M, Mejaya IMJ, Hidayat Y. 2025. Rice husk and chicken manure as raw materials for bio-charcoal briquettes for sustainable energy development. *Analisis Kebijakan Pertanian*. 20: 95–105. https://doi.org/10.21082/akp.v20i1.95-105

Haug RT. 2018. *The Practical Handbook of Compost Engineering*. London (UK): Routledge Press. https://doi.org/10.1201/9780203736234

Hilty J, Muller B, Pantin F, Leuzinger S. 2021. Plant growth: The what, the how, and the why. *New Phytologist*. 232: 25–41. https://doi.org/10.1111/nph.17610

Huang C, Hou S, Wang B, Song Y, Abulatijiang A, Min J, Sheng J, Jiang P, Wang Z, Cheng J. 2025. Effects of a combination of biochar and cow manure on soil nutrients and cotton yield in salinized fields. *Journal of Arid Land*. 17: 1014–1026. https://doi.org/10.1007/s40333-025-0054-2

Hulu A, Rahayu AYS. 2024. Study of policy innovation strategy to accelerate achievement of Indonesian soybean self-sufficiency in 2035. *Asian Journal of Social and Humanities*. 2: 1419–1430. https://doi.org/10.59888/ajosh.v2i6.275

Huntley BJ. 2023. Soil, water and nutrients, in: *Ecology of Angola*. Cham (CH): Springer International Publishing. https://doi.org/10.1007/978-3-031-18923-4_6

Janke C, Kirkegaard J, Hunt J, Barton L, Bell L, Karunaratne S, Macdonald LM, Pasut C, Stockmann U, Tavakkoli E, Vadakattu G, Wasson A, Farrell M. 2025. The pros and cons of increasing soil organic matter in dryland cropping systems. *Crop & Pasture Science*. 76. https://doi.org/10.1071/CP24257

Javed A, Ali E, Binte Afzal K, Osman A, Riaz S. 2022. Soil fertility: factors affecting soil fertility, and biodiversity responsible for soil fertility. *International Journal of Plant, Animal and Environmental Sciences.* 12. https://doi.org/10.26502/ijpaes.202129

Khumairah FH, Irwandhi, Hibatullah FH, Ambarita DDM, Hendra, Islamiati A, Nurbaity A, Herdiyantoro D, Kamaluddin NN, Simarmata T. 2025. Revealing the import dilemma and attributing factors to Indonesia's inability to achieve soybean self-sufficiency: A bibliometric analysis and systematic literature review. *International Journal of Agricultural Sustainability*. 23: 2492546. https://doi.org/10.1080/14735903.2025.2492546

Kpammah M, Oyelude EO, Adonadaga MG. 2026. Biochar for sustainable agriculture: potential to mitigate climate change and advance sustainable development goals in Ghana: Review. *Discover Sustainability*. 7: 571. https://doi.org/10.1007/s43621-025-01199-5

Mon WW, Toma Y, Ueno H. 2024. Combined effects of rice husk biochar and organic manures on soil chemical properties and greenhouse gas emissions from two different paddy soils. *Soil Systems*. 8: 32. https://doi.org/10.3390/soilsystems8010032

Montagnani C, Gentili R, Brundu G, Caronni S, Citterio S. 2022. Accidental introduction and spread of top invasive alien plants in the European union through human-mediated agricultural pathways: What should we expect? *Agronomy*. 12: 423. https://doi.org/10.3390/agronomy12020423

Naorem A, Jayaraman S, Dang YP, Dalal RC, Sinha NK, Rao CS, Patra AK. 2023. Soil constraints in an arid environment: challenges, prospects, and implications. *Agronomy*. 13: 220. https://doi.org/10.3390/agronomy13010220

Nasrullah N, Wakil AS, Shamsurahaman S. 2026. Evaluation of sugar beet growth indices affected by biological fertilizer and nitrogen under delayed planting conditions. *Plant Science Today*. 13: 1–9. https://doi.org/10.14719/pst.10815

Pabón-Garcés G, Vásquez-Hernández L, Yaguana-Jiménez G, Aguirre-Mejía P. 2025. Vegetative growth analysis of *Schoenoplectus californicus* (totora): Dynamics and physiological mechanisms in high-altitude Andean lakes. *Ecologies*. 6: 71. https://doi.org/10.3390/ecologies6040071

Park BG, Lee JH, Shin EJ, Kim EA, Nam SY. 2024. Light quality influence on growth performance and physiological activity of coleus cultivars. *International Journal of Plant Biology*. 15: 807–826. https://doi.org/10.3390/ijpb15030058

Qiu Z, Li M, Song L, Wang C, Yang S, Yan Z, Wang Y. 2021. Study on nitrogen-retaining microbial agents to reduce nitrogen loss during chicken manure composting and nitrogen transformation mechanism. *Journal of Cleaner Production*. 285: 124813. https://doi.org/10.1016/j.jclepro.2020.124813

Quan Z, Li S, Zhang X, Zhu F, Li P, Sheng R, Chen X, Zhang LM, He JZ, Wei W, Fang Y. 2020. Fertilizer nitrogen-use efficiency and fates in maize cropping systems across China: Field 15N tracer studies. *Soil and Tillage Research*. 197: 104498. https://doi.org/10.1016/j.still.2019.104498

Rahim I, Rusli R, Ambar AA, Sukmawati S, Suherman S. 2023. Penambahan cendawan *Pleurotus* sp pada biochar sekam padi dan tongkol jagung untuk stimulator di lahan berpasir. *Jurnal Galung Tropika.* 12: 90–96. https://doi.org/10.31850/jgt.v12i1.1059

Rinaldi J, Arya NN, Mahaputra IK, Elisabeth DAA, Resiani NMD, Arsana IGKD, Silitonga TF. 2023. Production factors, technical, and economic efficiency of soybean (*Glycine max* L. Merr.) farming in Indonesia. *The Open Agriculture Journal*. 8. https://doi.org/10.1515/opag-2022-0194

Rizwan N, Khan QU, Khan MZ, Law D, Elsadek MF, Altwaijry N, Tan DKY, Yasin M. 2025. Effect of biochar and cattle manure fortified with potassium fertilizer on maize yield and soil properties. *Agronomy and Soil Science*. 71(1): 1–16. https://doi.org/10.1080/03650340.2025.2517866

Roy S, Rathour SK, Mehta A, Dwivedi R, Surabhi, Pandey A, Barman A, Bagrecha S, Singh SV. 2025. Precision water management under dryland region: climate-resilient strategies, in: Pramanick, B., Singh, S.V., Maitra, S., Celletti, S., Hossain, A. (Eds.), *Climate-Smart Agricultural Technologies: Approaches for Field Crops Production Systems*. Berlin (DE): Springer Nature. https://doi.org/10.1007/978-981-96-7699-6_7

Sattar MT, Raza A, Ali S, Bashir S, Kanwal F, Khan I, Raza MA, Hussain S, Shen F. 2023. Integrating by-products from bioenergy technology to improve the morpho-physiological growth and yield of soybean under acidic soil. *Chemosphere*. 327: 138424. https://doi.org/10.1016/j.chemosphere.2023.138424

Sayaka B, Swastika DKS, Saputra YH. 2021. *Challenges of soybean self-sufficiency policy in Indonesia*. Bristol (UK): IOP Publishing Ltd. https://doi.org/10.1088/1755-1315/648/1/012035

Sebahire F, Faridullah F, Irshad M, Bacha AUR, Hafeez F, Nduwamungu J. 2024. Effect of biochar on composting cow manure and kitchen waste. *Land*. 13: 1545. https://doi.org/10.3390/land13101545

Sitters J, Kimuyu DM, Young TP, Claeys P, Olde VH. 2020. Negative effects of cattle on soil carbon and nutrient pools reversed by megaherbivores. *Nature Sustainability*. 3: 360–366. https://doi.org/10.1038/s41893-020-0490-0

Sree SS, Al-zharani M, Nasr FA, Alneghery LM, Kumar TTA, Sureshkumar BT, Mohamed JMM, Ravichandran M, Dineshkumar R. 2025. Innovative bio-amelioration strategies for sustainable reclamation of salt-affected agroecosystems: A review. *Plant Soil*. 516: 67-114. https://doi.org/10.1007/s11104-025-07749-0

Suherman S, Kurniawan E, Asysyuura A, Asmi H, Fitriani I, Zulkifli Z, Halil FA. 2025. Comparative study of soil amendment and organic fertilizer use to optimize agricultural dryland. *Biological Environment and Pollution*. 5: 2025–2056. https://doi.org/10.31763/bioenvipo.v5i1.893

Supriyadi S, Widjajani BW, Murniyanto E. 2022. The effect of rice husk biochar and cow manure on some soil characteristics, N and P uptake and plant growth of soybean in Alfisol. *Journal of Tropical Soils.* 27: 59–66. https://doi.org/10.5400/jts.2022.v27i2.59-66

Tandane HJ, Francisco BF, Maholele AJ, Sitoe MM. 2026. Irrigation challenges, water access, and adaptation strategies in smallholder farming: evidence from Gaza Province, Mozambique. *Global Challenges*. 10: 1–9. https://doi.org/10.1002/gch2.202500342

Vemulakonda AL, Saad AA, Kumar SS, Wani OA, Singh L, Babu S, Khan IM, Wani FJ, Jan SK, Elhindi KM, Mattar MA. 2024. Revealing the nexus between fertilizer composition and the performance of common bean (*Phaseolus vulgaris* L.) genotypes in the Himalayan heartland of India. *Sustainability*. 16: 6234. https://doi.org/10.3390/su16146234

Waheed A, Xu H, Qiao X, Aili A, Yiremaikebayi Y, Haitao D, Muhammad M. 2025. Biochar in sustainable agriculture and climate mitigation: mechanisms, challenges, and applications in circular bioeconomy. *Biomass and Bioenergy*.193: 107531. https://doi.org/10.1016/j.biombioe.2024.107531

Wang J, Zhang Y, Cui K, Fu T, Gao J, Hussain S, Algarni TS. 2021. Pyrometallurgical recovery of zinc and valuable metals from electric arc furnace dust. *Journal of Cleaner Production*. 298: 126788. https://doi.org/10.1016/j.jclepro.2021.126788

Yan S, Weng B, Jing L, Bi W. 2023. Effects of drought stress on water content and biomass distribution in summer maize *(Zea mays* L.). *Frontiers in Plant Science*. 14: 1118131. https://doi.org/10.3389/fpls.2023.1118131

Yofa RD, Perdana RP, Aldillah R, Muslim C, Sunarsih, Agustian A. 2021. Strategies to increase soybean production by increasing the distribution of new superior varieties. *IOP Conference Series: Earth and Environmental Science*. 892: 012067. https://doi.org/10.1088/1755-1315/892/1/012067

Zulfiqar F, Navarro M, Ashraf M, Akram NA, Munné-Bosch S. 2019. Nanofertilizer use for sustainable agriculture: Advantages and limitations. *Plant Science*. 289: 110270. https://doi.org/10.1016/j.plantsci.2019.110270