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# Enhancing Sorghum Growth and Yield Production on Post-Limestone-Mining Land through Myco-Seed Cookies Application for Land Rehabilitation

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## Abstract

Limestone mining activities have expanded significantly in Indonesia. These lands, characterized by high pH, low organic matter, and limited nutrient availability, pose a challenge for agricultural rehabilitation. Myco-Seed Cookies (MSC) is a novel plant growth medium enriched with arbuscular mycorrhizal fungi (AMF), specifically designed to enhance plant resilience in degraded environments, particularly on post-limestone mining land. This study examined the effects of MSC application on sorghum growth and performance in post-limestone-mining land as a means of land restoration and forage yield development. A randomized complete block design was implemented with four treatments (0, 13, 26, and 53 g MSC per planting hole), each replicated three times. The results revealed that the 53 g MSC treatment significantly enhanced seed viability, AMF colonization, plant growth (height, stem diameter, and leaf number), time to flowering, biomass yield, and Brix content ($p < 0.01$). Conversely, control plants showed higher nutrient content ($p < 0.01$), attributed to late sorghum maturation and abiotic stress responses. This study concluded that MSC application, particularly at 53 g, effectively improved sorghum performance and supported post-mining land rehabilitation, offering a sustainable solution for increasing forage production on degraded soils.

*Keywords*: arbuscular mycorrhizal fungi, forage, growth characteristics, growth performance, *Sorghum bicolor* var 'Samurai 2'

## Introduction

According to Statistics Indonesia, the volume of limestone mining production increased from 6,748,418 $m^3$ in 2021 to 8,336,106 $m^3$ in 2022. Limestone mining poses several environmental challenges, including landscape deformation, ecosystem degradation, and changes in groundwater levels and quality (Ganapathi & Phukan, 2020). The rise in production correlates with an expansion of limestone mining areas. Post-mining lands, often underutilized, present an opportunity for agricultural development, particularly for forage crop cultivation. However, these post-mining soils have high pH levels, low organic matter, limited total nitrogen, and low available phosphorus (Pratiwi et al., 2021)The soil texture is predominantly clayey, with clay content

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ranging from 27.6% (Nasir et al., 2024) to 30.51% (Harwanto et al., 2023). Such conditions often result in nutrient deficiencies in plants and low microbial activity in the soil (Pratiwi et al., 2021).

The utilization of post-mining land for forage cultivation is a strategic approach to increasing livestock feed availability. *Sorghum bicolor* L. Moench is a versatile cereal crop suitable for food (Meena, 2020) and feed (Hossain et al., 2022). The 'Samurai 2' sorghum variety is commonly used as animal feed, with a yield ranging from 10.37 to 24.78 t/ha depending on the harvest stage (Iftikhar et al., 2024). Malalantang et al. (2019) reported that when planted at a dense spacing (25 × 25 cm), 'Samurai 2' sorghum could yield up to 46.05 t/ha. Previous studies have examined sorghum cultivation on various post-mining lands, including former nickel (Leomo et al., 2025), coal (Wulandari et al., 2024), and tin mining sites (Wulandari et al., 2023). Applying biological fertilizers, such as arbuscular mycorrhizal fungi (AMF), can enhance sorghum growth and productivity. AMF has been shown to improve plant morphology and productivity (Gebremeskel et al., 2024) and enhance nutrient uptake, including phosphorus, water, and essential minerals, particularly on degraded lands (Wahab et al., 2023). Despite its potential, the direct application of AMF remains less effective due to the prolonged establishment period and the risk of fungal wash-off during rainfall events.

To address these challenges, a novel plant growth medium, Myco-Seed Cookies (MSC), has been developed to deliver essential nutrients while reducing the cost of forage plant nurseries. The MSC technology has been applied to *Canavalia ensiformis* (Armaji et al., 2025) and *Gynura procumbens* (Mulyati et al., 2023). However, no studies have investigated the application of MSC to sorghum cultivated on post-limestone-mining lands. Evaluating MSC use in such settings is critical to assess its efficacy and potential contribution to land rehabilitation and forage crop production. Therefore, this study aimed to examine the effects of MSC application on sorghum growth characteristics and growth performance in post-limestone-mining land as a means of land restoration and forage yield development.

## Material and Methods

### Research Area

This study was conducted from October 2022 to February 2023. The sorghum cultivation was carried out on post-limestone mining land owned by PT Solusi Bangun Indonesia, located in Klapanunggal Subdistrict, Bogor Regency, Indonesia. Arbuscular mycorrhizal fungi (AMF) colonization levels were analyzed at the Forest Biotechnology and Bioremediation Laboratory, Biotech Center, IPB University. Meanwhile, dry matter production and nutrient content analysis were conducted at the Department of Animal Nutrition and Feed Technology, Faculty of Animal Science, IPB University.

### Myco-Seed Cookies Treatment

Myco-seed cookies is a planting medium composed of arbuscular mycorrhizal fungi (AMF), organic fertilizer, zeolite gravel, sawdust, and adhesive. The MSC production technique is a mixture of organic fertilizer, zeolite gravel, sawdust, adhesive as much as 5 kg with 700 grams of AMF, 1 gram of MSC consists of 30 spores of AMF. The treatments consisted of a control (M0), application of 13 g MSC (M1), 26 g MSC (M2), and 53 g MSC (M3). The AMF genera consisted of *Acaulospora tuberculata*, *Glomus manihotis*, *Glomus etunicatum*, *Glomus* sp., and *Gigaspora margarita*. The AMF was obtained from the greenhouse of the Agrostology Laboratory, Division of Forage Plant Science Technology and Pasture.

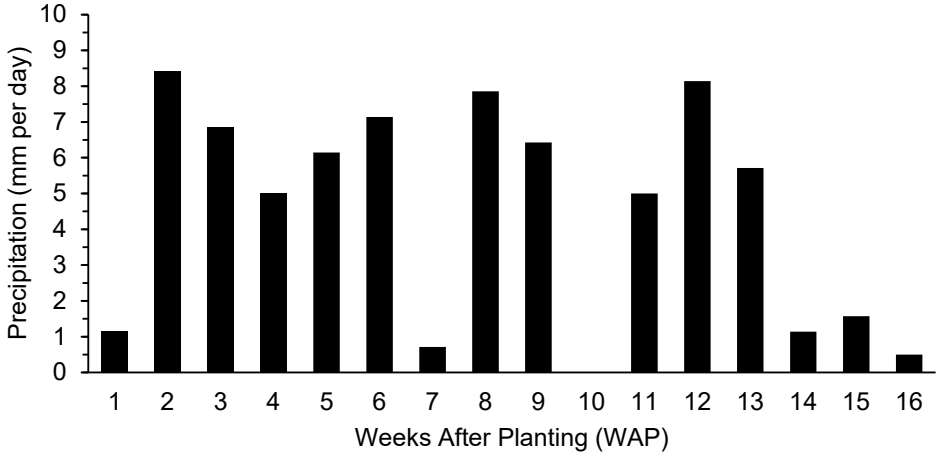
### Field Setup And Cultivation Methods

Land preparation began with area measurement and establishing twelve plots, each measuring 4 × 2 meters, with a 1-meter spacing between plots (Figure 1). Sorghum planting was conducted using a no-tillage

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**Figure 1**

*Weekly Precipitation Data from October 9, 2022, to January 28, 2023, in Nambo Village, Klapanunggal Subdistrict, Bogor Regency, Based on BMKG records*




system. In the control plots, seeds were directly sown into planting holes, whereas in the MSC treatments, seeds were inserted into MSC seed balls using a direct seeding method. Each plot contained six rows with ten planting holes per row, and each hole was sown with five 'Samurai 2' sorghum seeds that had been pre-treated with insecticide. Irrigation was performed daily in the morning. Weed control was carried out every four weeks to remove weeds, as their growth was relatively slow. The first fertilization was applied at the fifth week after planting (WAP) using NPK fertilizer at a rate of 200 kg/ha, followed by a second application at the tenth WAP at a dosage of 400 kg/ha. Observations of growth parameters were carried out weekly. Plant height was measured vertically from the ground surface to the top of the tallest plant using a standard ruler. In contrast, stem diameter was measured using a vernier caliper at the first internode from the ground surface. The number of leaves was calculated by counting them manually. Harvesting was conducted at the sixteenth WAP by cutting all sorghum plants approximately 10 cm above ground level, at the first node, using pruning shears. The harvested plants were then separated into stems, leaves, and panicles. Finally, the Brix value of the samples was measured using a Brix refractometer. Sorghum root samples were washed sequentially with 10% (w/v) KOH and 2% (w/v) HCl, then stained with 0.05 trypan blue solution to assess arbuscular mycorrhizal fungi (AMF) colonization levels. The percentage of root colonization was calculated by the number of mycorrhizal root colonization in a microscopic point of view (containing spores, hyphae, and/or vesicles) divided by the total number of points of view. The harvested sorghum shoot biomass from this study was analyzed for its nutritional composition using near infrared reflectance spectroscopy (NIRS) technology (Büchi NIRFlex N-500).

**Research Design and Data Analysis**

The study used a randomized complete block design with the planting location as the blocking factor. Four treatments were applied with three replications, resulting in 60 samples per replication. The treatments consisted of a control (M0), application of 13 g MSC (M1), 26 g MSC (M2), and 53 g MSC (M3). The data were analyzed using analysis of variance (ANOVA). When significant effects were detected, post hoc analysis was performed using Duncan's multiple range test (DMRT). All statistical analyses were conducted with IBM SPSS Statistics 25 software.

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## Results and Discussion

### Soil Chemical Analysis

Composite soil samples were collected, homogenized, and sampled from reclamation land at post-limestone mining sites at five representative locations to a depth of 20 cm before the sorghum cultivation for detailed chemical analysis (Widawati & Suliasih, 2019). The soil characteristics were analyzed at the Indonesian Center for Biodiversity and Biotechnology (ICBB) laboratory. The samples were analyzed for chemical properties, including pH, organic carbon, nitrogen, phosphorus, potassium, cation exchange capacity (CEC), $K^+$, $Na^+$, $Ca^{2+}$, $Mg^{2+}$, base saturation, exchangeable acidity ($Al^{3+}$), exchangeable acidity ($H^+$), and soil texture fractions. The soil in the post-limestone mining area, as presented in Table 1, exhibits the following agrochemical characteristics: it is slightly alkaline (pH 7.40–7.80), has low mineral content, and predominantly consists of silt.

### Precipitation Rate

The planting and harvesting processes occurred from early October 2022 to late January 2023. The precipitation levels during the study period are shown in Figure 1. The highest precipitation occurred in the second week, with 8.43 mm, while the lowest was recorded in the tenth week, which recorded no precipitation at all. Overall, the precipitation observed during the study period was within a range that aligns well with the local climatic conditions (Putri & Wibowo, 2023). This is likely because Bogor is a region with high rainfall levels (Handayani et al., 2023).

**Table 1**

*Physical and Chemical Properties of Post-Limestone-Mining Soil*

| Parameter | Unit | Value | Category* |
|---|---|---|---|
| pH | | | |
| $H_2O$ | - | 7.80 | slightly alkaline |
| KCl | - | 7.40 | neutral |
| Organic carbon | % | 2.03 | moderate |
| Total nitrogen | % | 0.06 | very low |
| C/N ratio | - | 34.00 | very high |
| Available P (Olsen/Bray I) | mg/kg | 4.90 | very low |
| $P_2O_5$ (HCl 25%) | mg/100g | 37.00 | moderate |
| $K_2O$ (HCl 25%) | mg/100g | 69.00 | very high |
| Cation exchange capacity (CEC) | cmol(+)/kg | 20.85 | moderate |
| $K^+$ | cmol(+)/kg | 0.29 | low |
| $Na^+$ | cmol(+)/kg | 0.08 | very low |
| $Ca^{2+}$ | cmol(+)/kg | 51.29 | very high |
| $Mg^{2+}$ | cmol(+)/kg | 4.86 | high |
| Base saturation | % | 100 | very high |
| Exchangeable acidity ($Al^{3+}$) | cmol(+)/kg | <0.05 | - |
| Exchangeable acidity ($H^+$) | cmol(+)/kg | 0.15 | - |
| Sand | % | 34.00 | - |
| Silt | % | 44.00 | - |
| Clay | % | 22.00 | - |

*Note*. *The classification of soil chemical properties is based on the guidelines of the Pusat Penelitian Tanah (1983).

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### Seed Viability of 'Samurai 2' Sorghum

The application of MSC in direct seeding techniques significantly increased the viability percentage of sorghum seeds ($p < 0.01$). In post-limestone mining soils, MSC treatment improved seed viability by up to 9.22% (Figure 2). The fiber content and sedimentary rock fragments within the MSC contributed to maintaining soil moisture, thereby supporting seed viability. According to Rajaseger et al. (2023), moisture balance in the planting medium is a critical factor influencing successful seedling establishment. Moreover, the addition of sedimentary rock fragments can enhance water retention and circulation within the growth medium, thereby positively affecting plant growth (Zheng et al., 2021).

### AMF Colonization Rate

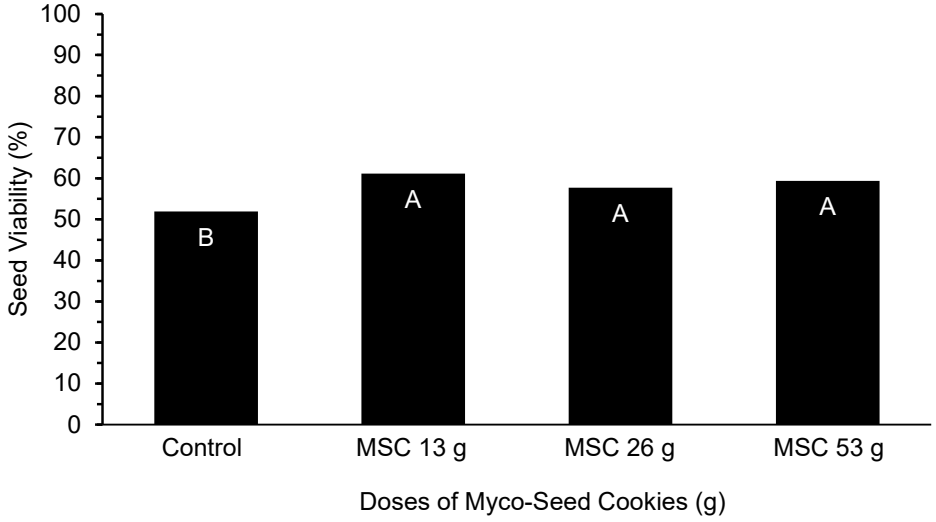
Measuring colonization levels is essential to evaluate the effectiveness of mycorrhiza application on plants. The AMF colonization level in 'Samurai 2' sorghum plants grown in post-limestone mining land is shown in Figure 3. The treatment without adding MSC resulted in a colonization level of 52.33%, which increased with larger MSC sizes ($p < 0.01$). The post-mining land in this study naturally harbors mycorrhiza, leading to sorghum root colonization. This finding is consistent with research by Harwanto et al. (2023) who discovered several types of mycorrhiza colonizing native plants in post-mining limestone land. The highest colonization rate was observed in the M3 treatment, which directly correlated with the size of the MSC applied. High colonization rates can be attributed to higher doses, which correlate with the mycorrhizal population in MSC. Eck et al. (2022) stated that higher doses of AMF applied to host plants enhance plant growth and increase the mycorrhiza's colonization level. Applying mycorrhiza during the early stages of planting (seeding) can significantly improve mycorrhizal colonization in roots. Sulistiono et al. (2017) reported that mycorrhiza during the nursery stage resulted in higher infection levels than those applied after the nursery stage.

### 'Samurai 2' Sorghum Growth Characteristics

Measurement of growth characteristics of sorghum cultivated on reclaimed limestone mining land provides valuable insights into

**Figure 2**

*Seed Viability of 'Samurai 2' Sorghum Treated with Varying Doses of Myco-Seed Cookies on Post-Limestone Mining Land*




*Note*. Different capital letters indicate significant differences ($p < 0.01$).

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the crop's tolerance to marginal soils. The weekly increase in plant height is presented in Table 2. The control plants exhibited superior height during the initial growth phase; however, overall plant height increased with the application of MSC treatments, with treatment M3 demonstrating the most significant improvement. The enhancement in sorghum height is associated with improved nutrient uptake. MSC treatment facilitated better nutrient absorption compared to the control. Inoculation with AMF influences plant nutrient availability and uptake (Saboor et al., 2021).

Additionally, AMF inoculation induces the secretion of acid phosphatase (ACP) in roots, which aids in the mobilization and absorption of organic phosphate (Sato et al., 2019). Phosphorus availability plays a crucial role in plant height development. Molla (2024) reported that phosphorus deficiency adversely affects plant morphology, including plant height. Increased plant height due to AMF inoculation has also been documented in *Linum usitatissimum* L. (Kakabouki et al., 2023), *Gossypium hirsutum* (Ramazanoglu et al., 2025), and *Sorghum bicolor* (L.) Moench (Chandra et al., 2022). Treatments with higher MSC volumes resulted in better plant height than lower volumes, which is attributed to a greater colonization of AMF inoculum in the roots (Figure 3), optimizing water and nutrient uptake. Wahab et al. (2023) stated that AMF enhances plant development by improving the absorption of essential nutrients such as phosphorus, water, and minerals.

The growth of sorghum stem diameter on reclaimed mining land is presented in Table 3. Initially, there was no significant difference in stem diameter among treatments; however, significant differences emerged from the sixth week of measurement until the end of the cultivation period. The stem diameter in MSC-treated plants was greater than that of the

**Table 2**

*Plant Height of 'Samurai 2' Sorghum Treated with Varying Doses of Myco-Seed Cookies on Post-Limestone-Mining Land*

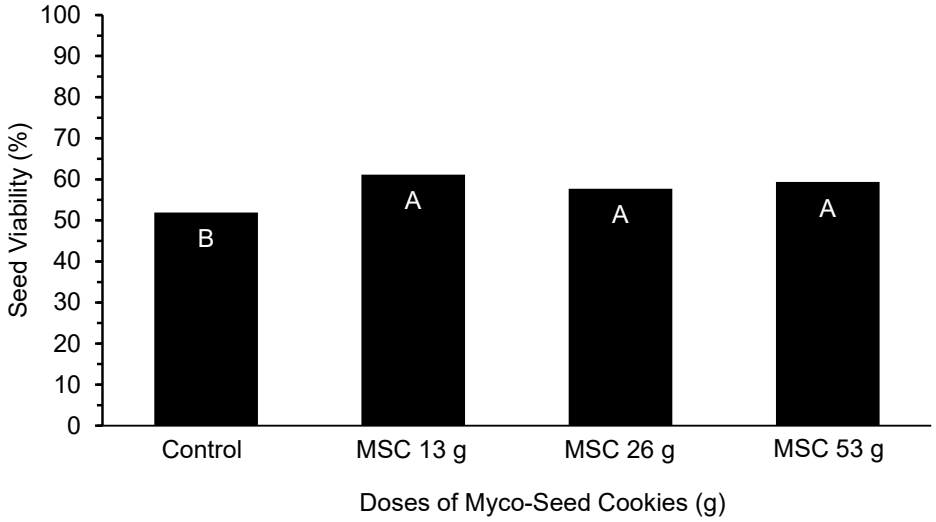
| Weeks after planting | Control | 13 g MSC | 26 g MSC | 53 g MSC | SEM | *p* value |
|---|---|---|---|---|---|---|
| 1 | 2.18 A | 2.05 B | 2.09 B | 2.07 B | 0.063 | <0.001 |
| 2 | 3.44 A | 3.12 C | 3.21 B | 3.21 B | 0.084 | <0.001 |
| 3 | 5.01 A | 4.08 C | 4.51 B | 4.51 B | 0.099 | <0.001 |
| 4 | 6.71 C | 6.79 C | 7.03 B | 7.65 A | 0.241 | <0.001 |
| 5 | 9.61 D | 10.82 C | 11.85 A | 11.40 B | 0.304 | <0.001 |
| 6 | 16.42 D | 20.67 C | 21.40 B | 23.42 A | 0.869 | <0.001 |
| 7 | 37.82 D | 40.48 C | 47.65 B | 49.95 A | 2.016 | <0.001 |
| 8 | 45.11 D | 58.27 C | 61.31 B | 68.63 A | 3.062 | <0.001 |
| 9 | 59.13 D | 67.69 C | 71.39 B | 77.07 A | 2.996 | <0.001 |
| 10 | 71.53 C | 82.89 B | 90.42 A | 91.74 A | 2.665 | <0.001 |
| 11 | 98.69 C | 112.04 B | 112.43 B | 115.71 A | 2.705 | <0.001 |
| 12 | 119.19 D | 124.22 C | 129.27 B | 134.16 A | 2.911 | <0.001 |
| 13 | 134.12 B | 135.44 B | 138.57 A | 140.39 A | 2.993 | <0.001 |
| 14 | 148.06 C | 148.56 C | 158.18 B | 161.76 A | 3.276 | <0.001 |
| 15 | 152.72 D | 155.18 C | 161.44 B | 164.12 A | 3.228 | <0.001 |
| 16 | 154.42 C | 156.51 C | 164.24 B | 167.14 A | 3.272 | <0.001 |

*Notes*. Different superscripts (A, B, etc.) in the same row indicate a significant effect ($p < 0.01$) between treatments. SEM = standard error of the mean, MSC = miko-seed cookies.

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**Figure 3**

*AMF Colonization Rate in 'Samurai 2' Sorghum Roots Treated with Varying Doses of Myco-Seed Cookies Post-Limestone Mining Land*




*Note*. Different capital letters indicate significant differences ($p < 0.01$).

**Table 3**

*Stem Diameter of 'Samurai 2' Sorghum Treated with Varying Doses of Myco-Seed Cookies on Post-Limestone-Mining Land*

| Weeks after planting | Control | 13 g MSC | 26 g MSC | 53 g MSC | SEM | *p value* |
|---|---|---|---|---|---|---|
| 4 | 2.14 | 2.09 | 2.11 | 2.12 | 0.075 | 0.265 |
| 5 | 2.88 | 2.89 | 2.89 | 2.92 | 0.096 | 0.630 |
| 6 | 3.58 B | 4.35 A | 4.34 A | 4.35 A | 0.110 | <0.001 |
| 7 | 4.36 C | 5.81 B | 5.79 B | 6.11 A | 0.132 | <0.001 |
| 8 | 5.15 C | 7.45 A | 7.02 B | 7.36 A | 0.146 | <0.001 |
| 9 | 6.65 D | 8.68 B | 8.45 C | 8.81 A | 0.167 | <0.001 |
| 10 | 6.28 D | 9.83 C | 10.36 B | 10.76 A | 0.196 | <0.001 |
| 11 | 7.19 D | 10.73 C | 12.27 B | 12.66 A | 0.200 | <0.001 |
| 12 | 8.28 D | 11.44 C | 13.71 B | 14.32 A | 0.237 | <0.001 |
| 13 | 9.13 D | 12.03 C | 14.97 B | 15.55 A | 0.238 | <0.001 |
| 14 | 9.71 D | 12.59 C | 15.29 B | 15.78 A | 0.244 | <0.001 |
| 15 | 10.20 D | 13.03 C | 15.33 B | 15.83 A | 0.256 | <0.001 |
| 16 | 10.25 D | 13.07 C | 15.06 B | 15.74 A | 0.307 | <0.001 |

*Notes*. Different superscripts (A, B, etc.) in the same row indicate a significant effect ($p < 0.01$) between treatments. SEM = standard error of the mean, MSC = miko-seed cookies.

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control, with the widest diameter observed in treatment M3. This growth pattern corresponds with plant height growth, indicating a correlation between the two parameters. Similar findings were reported by Silva et al. (2014) in sorghum and Santana et al. (2023) in maize. Furthermore, stem diameter growth is influenced by arbuscular mycorrhizal fungi (AMF), which Asmarahman et al. (2023) found to enhance seedling diameter effectively.

The MSC treatment on sorghum grown in reclaimed limestone mining land did not significantly affect the increase in leaf number (Table 4) during the first to third weeks after planting, but showed a significant effect in subsequent measurements. Gradually, MSC treatment enhanced the leaf number of sorghum plants, with the M3 treatment achieving up to 14 leaves. Compared to MSC treated plants, the control plants had the lowest leaf count. Similar findings were reported by Husein et al. (2022) on maize and sorghum grown in control and mycorrhizal soils. Leaf growth is influenced by several factors such as water, temperature, nutrients, and light (Walter & Schurr, 2005). Mycorrhiza facilitates plant absorption of water and nutrients (Buba & Muhammad, 2020; Khan et al., 2022; Rustikawati et al., 2022), thereby supporting leaf growth.

**Time to Flowering of 'Samurai 2' Sorghum**

Time to flowering data indicate that sorghum can reproduce even when cultivated on reclaimed limestone mining land (Figure 4). The earliest and latest flowering plants were observed in treatments M3 and M0 (control), respectively. Sorghum in the M3 treatment flowered at 13.3 weeks (approximately 93 days), which is closest to the time to flowering of sorghum grown in normal soil compared to other treatments. The typical time to flowering for sorghum in normal

**Table 4**

*Number of Leaves of 'Samurai 2' Sorghum Treated with Varying Doses of Myco-Seed Cookies on Post-Limestone-Mining Land*

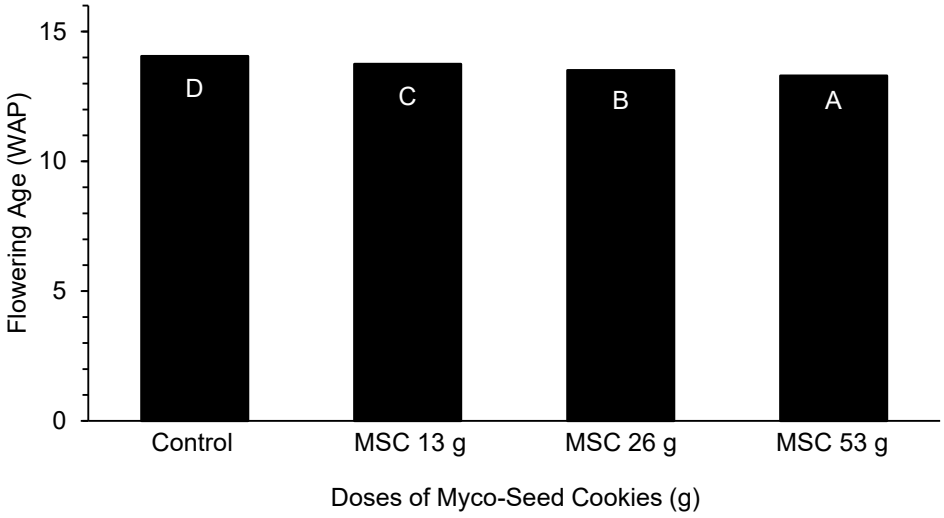
| Weeks after planting | Control | 13 g MSC | 26 g MSC | 53 g MSC | SEM | *p value* |
|---|---|---|---|---|---|---|
| 1 | 2.28 | 2.28 | 2.28 | 2.26 | 0.129 | 0.938 |
| 2 | 3.28 | 3.28 | 3.28 | 3.26 | 0.129 | 0.938 |
| 3 | 4.28 | 4.28 | 4.28 | 4.26 | 0.129 | 0.938 |
| 4 | 4.76 B | 4.85 AB | 4.96 A | 4.97 A | 0.188 | 0.007 |
| 5 | 5.21 C | 5.42 B | 5.58 AB | 5.68 A | 0.234 | <0.001 |
| 6 | 5.68 B | 5.80 B | 6.37 A | 6.50 A | 0.263 | <0.001 |
| 7 | 6.10 C | 6.26 C | 6.83 B | 7.30 A | 0.292 | <0.001 |
| 8 | 6.60 D | 6.87 C | 7.25 B | 7.89 A | 0.333 | <0.001 |
| 9 | 7.07 C | 7.32 C | 7.73 B | 8.39 A | 0.359 | <0.001 |
| 10 | 7.49 D | 7.86 C | 8.33 B | 9.09 A | 0.379 | <0.001 |
| 11 | 7.93 D | 8.37 C | 9.17 B | 9.90 A | 0.400 | <0.001 |
| 12 | 8.33 D | 8.72 C | 10.08 B | 10.83 A | 0.408 | <0.001 |
| 13 | 8.74 D | 9.73 C | 10.84 B | 11.73 A | 0.420 | <0.001 |
| 14 | 9.17 D | 10.34 C | 11.51 B | 12.63 A | 0.436 | <0.001 |
| 15 | 9.61 D | 10.99 C | 12.09 B | 13.36 A | 0.450 | <0.001 |
| 16 | 10.00 D | 11.69 C | 12.52 B | 14.03 A | 0.469 | <0.001 |

*Notes*. Different superscripts (A, B, etc.) in the same row indicate a significant effect ($p < 0.01$) between treatments. SEM= standard error of the mean, MSC = miko-seed cookies.

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**Figure 4**

*Time to Flowering of 'Samurai 2' Sorghum Treated with Varying Doses of Myco-Seed Cookies on Post-Limestone Mining Land*




Note. Different capital letters indicate significant differences ($p < 0.01$).

soil ranges from 42 to 53 days (Maftuchah et al., 2021) or 57 to 65 days (Kusumawardana et al., 2025). Although this is slower than the normal range, it still represents a promising opportunity for sorghum cultivation on reclaimed mining land. Accelerated flowering growth was observed in treatments with MSC. Rydlová & Püschel (2020) reported that time to flowering is influenced by plant size and nutrient uptake facilitated by AMF application.

**'Samurai 2' Sorghum Yield Production**

Published information regarding the production of forage sorghum on post-limestone mining land remains scarce, particularly concerning the use of MSC to improve biomass production under such conditions. Therefore, the present findings provide initial information on the response of forage sorghum to MSC application in post-limestone mining soil. The M3 treatment consistently produced the highest fresh and dry biomass, followed by a gradual decline as the volume of MSC decreased (Table 5). This pattern indicates that increasing MSC application created more favorable conditions for vegetative growth and biomass accumulation, presumably through improved nutrient supply, organic matter availability, and soil water retention. A comparable response was reported by Kuswoyo et al. (2025) for *Sorghum bicolor* cv. 'Samurai-1' cultivated on post-coal mining land in South Kalimantan. At each urea application rate, the addition of arbuscular mycorrhizal fungi increased both fresh and dry biomass compared with the corresponding treatment without AMF. Furthermore, the fresh and dry biomass production of sorghum exhibited patterns consistent with its growth characteristics. Matsui et al. (2016) reported a direct correlation between plant height and stem diameter with crop yield, indicating that taller plants with thicker stems tend to produce higher yields.

Crop productivity is strongly influenced by soil quality and the plant's ability to absorb nutrients. Malobane and Madzivhandila (2024) emphasized that mycorrhizal fungi can improve soil quality, even in marginal lands. This enhancement in soil condition likely contributes to the improved crop response under MSC treatment. Furthermore, optimal soil conditions must be supported by efficient nutrient uptake. According to Phoura et al. (2023), increased arbuscular mycorrhizal fungi (AMF) colonization

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in roots following mycorrhizal application significantly enhances phosphorus uptake. Phosphorus is a critical macronutrient that is pivotal in plant growth and productivity (Ma et al., 2024; McDowell et al., 2024).

The Brix percentage significantly increased across all treatments ($p < 0.01$), indicating enhanced nutrient uptake and utilization. The application of AMF in sorghum notably improved phosphorus absorption, which is directly associated with the increase in Brix values. This is attributed to the critical role of phosphorus in energy transfer processes, particularly in ATP formation, which facilitates carbohydrate synthesis and accumulation. Adequate phosphorus availability, therefore, contributes to higher sugar content in plant tissues, as reflected in elevated Brix levels (Bargaz et al., 2016; Bouras et al., 2021).

**Nutrient Production of 'Samurai 2' Sorghum**

The application of MSC in sorghum cultivation on post-limestone-mining land significantly affected all nutrient production parameters ($p < 0.01$), except for ether extract. The nutrient production observed in sorghum plants (Table 6) reflects the plant's nutrient response to environmental conditions and yield production. The control treatments generally exhibited the lowest nutrient production across all measured parameters. The observed effect was correlated with plant productivity, demonstrating a positive relationship between yield and nutrient production. Plants treated with MSC reached maturity earlier than control plants, which contributed to their enhanced productivity. Plant maturation resulted from more optimal nutrient uptake in MSC-treated plants, facilitated by an effective symbiotic relationship between mycorrhizae and plant roots. Mycorrhizal fungi form a symbiotic relationship with plant roots, extending the root system's reach into the soil (Putra et al., 2022). This fungal network helps plants access nutrients, especially phosphorus, more effectively than plants relying solely on their roots. Ether extract production was not significantly observed in this study. This result is likely due to the higher level of stress experienced by control plants compared to other treatments. He and Ding (2020) reported that plants subjected to abiotic stress exhibit mechanisms that enhance fatty acid accumulation. Elevated stress levels in control plants resulted in increased ether extract content, which counterbalanced the production advantage observed in MSC-treated plants. Conversely, nutrient production is strongly correlated with the forage dilution effect, wherein the concentration of nutrients declines with advancing plant maturity and increased biomass (Abdullah et al., 2025). Nonetheless, the aggregate nutrient yield tends to be elevated in high-biomass treatments, primarily attributed to the multiplying effect of superior harvest yield.

The production of fiber fractions in 'Samurai 2' sorghum increased significantly with increasing MSC application rates, with the 53 g MSC treatment resulting in the highest crude fiber, NDF (neutral detergent fiber), and ADF (acid detergent fiber) yields of 1.49, 2.65, and 1.11 t/ha, respectively, representing increases of approximately 63.7%, 67.7%, and 56.3% compared with the control. NDF and ADF production in sorghum is closely associated with biomass accumulation and the development of structural plant tissues, while arbuscular mycorrhizal fungal colonization has been reported to enhance nutrient acquisition, particularly phosphorus uptake, and promote sorghum growth and biomass production under nutrient-limited and abiotic-stress conditions (Symanczik et al., 2018; Watts-Williams et al., 2019, 2022). Therefore, the greater NDF and ADF production observed at higher MSC application rates suggests that MSC promoted biomass formation and the accumulation of structural cell-wall components in sorghum grown on post-limestone-mining land. However, greater fiber production does not necessarily indicate a decline in forage nutritional quality because the effects of fiber on voluntary intake and digestibility should primarily be evaluated based on NDF and ADF concentrations expressed as a proportion of dry matter rather than solely on the amount of fiber produced per unit area (Somegowda et al., 2021).

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**Table 5**

*Yield Production of 'Samurai 2' Sorghum Treated with Varying Doses of Myco-Seed Cookies on Post-Limestone-Mining Land*

| Parameter | Control | 13 g MSC | 26 g MSC | 53 g MSC | SEM | *p* value |
|---|---|---|---|---|---|---|
| Fresh yield (t/ha) | 18.54 C | 20.98 BC | 23.26 AB | 25.41 A | 0.404 | 0.005 |
| Dry yield (t/ha) | 2.33 C | 3.01 B | 3.55 B | 4.14 A | 0.074 | 0.001 |
| Stem-to-leaf ratio | 0.63 C | 0.53 B | 0.44 A | 0.38 A | 0.014 | 0.001 |
| Brix (%) | 11.59 C | 12.29 B | 12.86 AB | 13.46 A | 0.467 | <0.001 |

*Notes*. Different superscripts (A, B, etc.) in the same row indicate a significant effect ($p < 0.01$) between treatments. SEM = standard error of the mean, MSC = miko-seed cookies.

**Table 6**

*Nutrient Production (Dry Matter) of 'Samurai 2' Sorghum Treated with Varying Doses of Myco-Seed Cookies on Post-Limestone-Mining Land*

| Nutrient production (t/ha) | Control | 13 g MSC | 26 g MSC | 53 g MSC | SEM | *p* value |
|---|---|---|---|---|---|---|
| Ash | 0.33 D | 0.43 C | 0.49 B | 0.56 A | 0.015 | <0.001 |
| Crude protein | 0.33 C | 0.41 B | 0.48 A | 0.51 A | 0.013 | <0.001 |
| Ether extract | 0.15 | 0.17 | 0.17 | 0.15 | 0.005 | 0.307 |
| Crude fiber | 0.91 D | 1.15 C | 1.23 B | 1.49 A | 0.036 | <0.001 |
| NDF | 1.58 D | 2.04 C | 2.28 B | 2.65 A | 0.079 | <0.001 |
| ADF | 0.71 C | 0.95 B | 1.07 A | 1.11 A | 0.032 | <0.001 |

*Notes*. Different superscripts (A, B, etc.) in the same row indicate a significant effect ($p < 0.01$) between treatments. SEM = standard error of the mean, MSC = miko-seed cookies, NDF = neutral detergent fiber, ADF = acid detergent fiber.

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## Conclusion

The most favorable results were obtained with 53 g of MSC (M3). This treatment significantly enhanced seed viability, AMF colonization, growth characteristics, time to flowering, and overall yield performance, Brix content, and nutrient production. The application of 53 g of MSC can enhance sorghum establishment and productivity under post-limestone-mining soil conditions. Therefore, the M3 treatment represents a promising approach for supporting the rehabilitation and productive utilization of post-limestone-mining land through forage sorghum cultivation.

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## References

Abdullah, L., Kumalasari, N. R., Ramadani, J., Diapari, D., Sitompul, M. S., & Saputra, I. E. (2025). Effect of forage nutrient on sheep gas emission in different multi-species cropping system. *Journal of Water and Land Development, 66*, 53-60.

Armaji, Y., Abdullah, L., Karti, P. D. M. H., & Astuti, D. A. (2025). Effect of boron foliar fertilizer and Mycoseed-cookies on the morphological and seeds production of jack bean (*Canavalia ensiformis*). *Agrivita, 47*, 98-109. https://doi.org/10.17503/agrivita.v47i1.4423

Asmarahman, C., Prasetia, H., Iswandaru, D., & Febryano, I. G. (2023). The effectiveness analysis of arbuscular mycorrhizal fungi (AMF) and ameliorant treatments on the growth of red jabon seedling on soil medium post-lime mining. *International Journal of Design and Nature and Ecodynamics, 18*, 289-300. https://doi.org/10.18280/ijdne.180206

Bargaz, A., Nassar, R. M. A., Rady, M. M., Gaballah, M. S., Thompson, S. M., Brestic, M., Schmidhalter, U., & Abdelhamid, M. T. (2016). Improved salinity tolerance by phosphorus fertilizer in two Phaseolus vulgaris recombinant inbred lines contrasting in their P-efficiency. *Journal of Agronomy and Crop Science, 202*, 497-507. https://doi.org/10.1111/jac.12181

Bouras, H., Bouaziz, A., Bouazzama, B., Hirich, A., & Choukr-Allah, R. (2021). How phosphorus fertilization alleviates the effect of salinity on sugar beet (*Beta vulgaris* L.) productivity and quality. *Agronomy, 11*, 1491. https://doi.org/10.3390/agronomy11081491

Buba, T., & Muhammad, S. Y. (2020). Combine effects of soil nutrient levels and mycorrhiza inoculums from soils under Parkia biglobosa and Tamarindus indica on chlorophyll content of some cereal and legume crops. *Scientific African, 8*, e00369. https://doi.org/10.1016/j.sciaf.2020.e00369

Chandra, P., Singh, A., Prajapat, K., Rai, A. K., & Yadav, R. K. (2022). Native arbuscular mycorrhizal fungi improve growth, biomass yield, and phosphorus nutrition of sorghum in saline and sodic soils of the semi-arid region. Environmental and *Experimental Botany, 201*, 104982. https://doi.org/10.1016/j.envexpbot.2022.104982

Eck, J. L., Kytöviita, M.-M., & Laine, A.-L. (2022). Arbuscular mycorrhizal fungi influence host infection during epidemics in a wild plant pathosystem. *New Phytologist, 236*, 1922-1935. https://doi.org/10.1111/nph.18481

Ganapathi, H., & Phukan, M. (2020). Environmental hazards of limestone mining and adaptive practices for environment management plan. In M. H. Raj, S. Prabhakar, & S. Prachi (Eds.), *Environmental Processes and Management: Tools and Practice* (pp. 121-134). Springer. https://doi.

Received 12/8/2026; Revised 9/18/2026; Accepted 10/29/2026
https://doi.org/10.29244/jtcs.13.03.827-842

org/10.1007/978-3-030-38152-3_8

Gebremeskel, K., Birhane, E., Habtu, S., Haile, M., Chanyalew, S., Tadele, Z., & Assefa, K. (2024). Arbuscular mycorrhizal fungi improve morphological and yield performance of Eragrostis tef genotypes in Tigray, Ethiopia. *Scientific Reports, 14*, 29716. https://doi.org/10.1038/s41598-024-79628-0

Handayani, A. S., Permana, T., & Isoda, Y. (2023). Role of updraft in dry-season torrential rainfall in Greater Jakarta, Indonesia. *Atmospheric Science Letters, 24*, e1186. https://doi.org/10.1002/asl.1186

Harwanto, H., Karti, P. D. M. H., Suwardi, S., & Abdullah, L. (2023). Native plant composition and soil microfauna in limestone post-mining land as potential for development of ruminant forage. *Biodiversitas Journal of Biological Diversity, 24*, 6332-6342. https://doi.org/10.13057/biodiv/d241158

He, M., & Ding, N.-Z. (2020). Plant unsaturated fatty acids: Multiple roles in stress response. *Frontiers in Plant Science, 11*, 562785. https://doi.org/10.3389/fpls.2020.562785

Hossain, M. S., Islam, M. N., Rahman, M. M., Mostofa, M. G., & Khan, M. A. R. (2022). Sorghum: A prospective crop for climatic vulnerability, food and nutritional security. *Journal of Agriculture and Food Research, 8*, 100300. https://doi.org/10.1016/j.jafr.2022.100300

Husein, M., Umami, N., Pertiwiningrum, A., Rahman, M. M., & Ananta, D. (2022). The role of arbuscular mycorrhizal fungi density and diversity on the growth and biomass of corn and sorghum forage in trapping culture. *Tropical Animal Science Journal, 45*, 37-43. https://doi.org/10.5398/tasj.2022.45.1.37

Iftikhar, N., Karti, P. D. M. H., Kumalasari, N. R., Abdullah, L., & Amalia, G. T. (2024). Production of sorghum seed and straw biomass for feed as affected by different harvesting ages. *Journal of Tropical Crop Science, 11*, 329-334. https://doi.org/10.29244/jtcs.11.03.329-334

Kakabouki, I., Stavropoulos, P., Roussis, I., Mavroeidis, A., & Bilalis, D. (2023). Contribution of arbuscular mycorrhizal fungi (AMF) in improving the growth and yield performances of flax (Linum usitatissimum L.) to salinity stress. *Agronomy, 13*, 2416. https://doi.org/10.3390/agronomy13092416

Khan, Y., Shah, S., & Hui, T. (2022). The roles of arbuscular mycorrhizal fungi in influencing plant nutrients, photosynthesis, and metabolites of cereal crops: A review. *Agronomy, 12*, 2191. https://doi.org/10.3390/agronomy12092191

Kuswoyo, A., Abdullah, L., Karti, P. D. M. H., Human, S., Rostini, T., Mulyono, E. E., & Wawan, E. (2025). Forage production and nutritional quality of *Sorghum bicolor* cv. Samurai-1 in response to urea and arbuscular mycorrhizal fungi on post-coal mining land in South Kalimantan. *BIO Web of Conferences, 191*, 00031. https://doi.org/10.1051/bioconf/202519100031

Kusumawardana, A., Ilyas, S., Qadir, A., Trikoesoemaningtyas, T., & Human, S. (2025). Variability of agronomic characters and seed quality of 12 sorghum (*Sorghum bicolor*) genotypes. *Biodiversitas Journal of Biological Diversity, 26*, 628-635. https://doi.org/10.13057/biodiv/d260210

Leomo, S., Alam, S., Muhidin, & Sadimantara, G. R. (2025). The potential use of rhizobacteria and cover crop residue for improving the growth of sorghum on post-nickel mining soil in Southeast Sulawesi. *Journal of Degraded and Mining Lands Management, 12*, 7277-7285. https://doi.org/10.15243/jdmlm.2025.122.7277

Ma, J., Wang, G., Liu, X., Lei, B., & Xing, G. (2024). Effects of phosphorus application levels on its uptake and utilization in foxtail millet. *Agronomy, 14*, 2078. https://doi.org/10.3390/agronomy14092078

Maftuchah, M., Febriana, L., Sulistyawati, S., Reswari, H. A., & Septia, E. D. (2021). Morphological diversity and heritability of nine local sorghum (*Sorghum bicolor*) genotypes in East Java, Indonesia.

Received 12/8/2026; Revised 9/18/2026; Accepted 10/29/2026
https://doi.org/10.29244/jtcs.13.03.827-842

*Biodiversitas Journal of Biological Diversity, 22*, 1310-1316. https://doi.org/10.13057/biodiv/d220330

Malalantang, S. S., Abdullah, L., Karti, P. D. M. H., Permana, I. G., & Nurmahmudi. (2019). Agronomy characteristics of several types of sorghum from radiation mutations as a ruminant animal feed provide. *IOP Conference Series: Earth and Environmental Science, 399*, 012031. https://doi.org/10.1088/1755-1315/399/1/012031

Malobane, M. E., & Madzivhandila, M. R. (2024). Enhancement of soil arbuscular mycorrhizal fungi: A step towards restoring marginal soils. In A. D. Nciizah, A. Roopnarain, B. Ndaba, & M. E. Malobane (Eds.), *The Marginal Soils of Africa* (pp. 263-277). Springer. https://doi.org/10.1007/978-3-031-55185-7_14

Matsui, N., Nakata, K., Cornelius, C., & Macdonald, M. (2016). Diagnosing maize growth for determination of optimum fertilizer application time in Northern Malawi. *Journal of Agricultural Science, 8*, 50. https://doi.org/10.5539/jas.v8n5p50

McDowell, R. W., Pletnyakov, P., & Haygarth, P. M. (2024). Phosphorus applications adjusted to optimal crop yields can help sustain global phosphorus reserves. *Nature Food, 5*, 332-339. https://doi.org/10.1038/s43016-024-00952-9

Meena, R. S. (Ed.). (2020). *Soil Health Restoration and Management*. Springer Singapore. https://doi.org/10.1007/978-981-13-8570-4

Molla, K. A. (2024). A significant P value: How phosphorus controls plant height. *The Plant Cell, 36*, 213-214. https://doi.org/10.1093/plcell/koad284

Mulyati, W. S., Fassah, D., & Kumalasari, N. R. (2023). Impact of Miko-Seedcookies with arbuscular mycorrhizal fungi on the growth, yield, and chemical composition of Gynura procumbens. *Journal of Global Innovations in Agricultural Sciences, 11*, 491-497. https://doi.org/10.22194/JGIAS/23.1207

Nasir, M. N., Arbiwati, D., Nurcholis, M., & Andarini, R. N. S. (2024). Soil erodibility results of revegetation using Bitti plant at various ages reclamation of quarry, a limestone mine at PT Semen Tonasa, Pangkep District, South Sulawesi. *Journal of Sustainability, Society, and Eco-Welfare, 2*, 1-15. https://doi.org/10.61511/jssew.v2i1.2024.829

Phoura, Y., Ohtomo, R., Nakanishi, H., & Kamoshita, A. (2023). Effects of arbuscular mycorrhizal fungi inoculation on infection and growth of rice and pearl millet in upland fields with three water regimes. *Plant Production Science, 26*, 350-363. https://doi.org/10.1080/1343943X.2023.2251181

Pratiwi, P., Narendra, B. H., Siregar, C. A., Turjaman, M., Hidayat, A., Rachmat, H. H., Mulyanto, B., Suwardi, S., Iskandar, I., Maharani, R., Rayadin, Y., Prayudyaningsih, R., Yuwati, T. W., Prematuri, R., & Susilowati, A. (2021). Managing and reforesting degraded post-mining landscape in Indonesia: A review. *Land, 10*, 658. https://doi.org/10.3390/land10060658

Pusat Penelitian Tanah. (1983). *Kriteria penilaian sifat-sifat kimia tanah*. Pusat Penelitian Tanah.

Putra, B., Warly, L., Evitayani, E., & Utama, B. P. (2022). The role of arbuscular mycorrhizal fungi in phytoremediation of heavy metals and their effect on the growth of Pennisetum purpureum cv. Mott on gold mine tailings in Muara Bungo, Jambi, Indonesia. *Biodiversitas Journal of Biological Diversity, 23*, 478-485. https://doi.org/10.13057/biodiv/d230151

Putri, N. A., & Wibowo, A. (2023). Rainfall maps for the suitability of settlement area in Bogor Raya. *EnviroScienteae, 19*, 123. https://doi.org/10.20527/es.v19i2.15116

Rajaseger, G., Chan, K. L., Tan, K. Y., Ramasamy, S., Khin, M. C., Amaladoss, A., & Kadamb Haribhai, P. (2023). Hydroponics: Current trends in sustainable crop production. *Bioinformation, 19*, 925-938. https://doi.org/10.6026/97320630019925

Received 12/8/2026; Revised 9/18/2026; Accepted 10/29/2026
https://doi.org/10.29244/jtcs.13.03.827-842

Ramazanoglu, E., Yanardag, I. H., Sakin, E., Beyyavas, V., Cevheri, C. I., Cun, S., & Yanardag, A. B. (2025). Effects of arbuscular mycorrhizal fungi (AMF) and biochar on cotton plants: A comprehensive study. *Journal of Soil Science and Plant Nutrition*. https://doi.org/10.1007/s42729-025-02350-x

Rustikawati, R., Suprijono, E., Murcitro, B. G., Herison, C., & Sitohang, S. J. (2022). Amendment of mycorrhizae and its residual effect on growth and yield of maize (Zea mays) hybrids in coastal land. Biodiversitas *Journal of Biological Diversity, 23*, 5600-5605. https://doi.org/10.13057/biodiv/d231108

Rydlová, J., & Püschel, D. (2020). Arbuscular mycorrhiza, but not hydrogel, alleviates drought stress of ornamental plants in peat-based substrate. *Applied Soil Ecology, 146*, 103394. https://doi.org/10.1016/j.apsoil.2019.103394

Saboor, A., Ali, M. A., Danish, S., Ahmed, N., Fahad, S., Datta, R., Ansari, M. J., Nasif, O., Rahman, M. H. U., & Glick, B. R. (2021). Effect of arbuscular mycorrhizal fungi on the physiological functioning of maize under zinc-deficient soils. *Scientific Reports, 11*, 18468. https://doi.org/10.1038/s41598-021-97742-1

Santana, L. R., da Silva, L. N., Tavares, G. G., Batista, P. F., Cabral, J. S. R., & Souchie, E. L. (2023). Arbuscular mycorrhizal fungi associated with maize plants during hydric deficit. *Scientific Reports, 13*, 1519. https://doi.org/10.1038/s41598-023-28744-4

Sato, T., Hachiya, S., Inamura, N., Ezawa, T., Cheng, W., & Tawaraya, K. (2019). Secretion of acid phosphatase from extraradical hyphae of the arbuscular mycorrhizal fungus Rhizophagus clarus is regulated in response to phosphate availability. *Mycorrhiza, 29*, 599-605. https://doi.org/10.1007/s00572-019-00923-0

Silva, C., Silva, A. F. D., Vale, W. G. D., Galon, L., Petter, F. A., May, A., & Karam, D. (2014). Interferência de plantas daninhas na cultura do sorgo sacarino. *Bragantia, 73*, 438-445. https://doi.org/10.1590/1678-4499.0119

Somegowda, V. K., Vemula, A., Naravula, J., Prasad, G., Rayaprolu, L., Rathore, A., Blümmel, M., & Deshpande, S. P. (2021). Evaluation of fodder yield and fodder quality in sorghum and its interaction with grain yield under different water availability regimes. *Current Plant Biology, 25*, 100191. https://doi.org/10.1016/j.cpb.2020.100191

Sulistiono, W., Taryono, T., Yudono, P., & Irham, I. (2017). Early-arbuscular mycorrhizal fungi-application improved physiological performances of sugarcane seedling and further growth in the dry land. *Journal of Agricultural Science, 9*, 95. https://doi.org/10.5539/jas.v9n4p95

Symanczik, S., Lehmann, M. F., Wiemken, A., Boller, T., & Courty, P. E. (2018). Effects of two contrasted arbuscular mycorrhizal fungal isolates on nutrient uptake by *Sorghum bicolor* under drought. *Mycorrhiza, 28*, 779–785. https://doi.org/10.1007/s00572-018-0853-9

Wahab, A., Muhammad, M., Munir, A., Abdi, G., Zaman, W., Ayaz, A., Khizar, C., & Reddy, S. P. P. (2023). Role of arbuscular mycorrhizal fungi in regulating growth, enhancing productivity, and potentially influencing ecosystems under abiotic and biotic stresses. *Plants, 12*, 3102. https://doi.org/10.3390/plants12173102

Walter, A., & Schurr, U. (2005). Dynamics of leaf and root growth: Endogenous control versus environmental impact. *Annals of Botany, 95*, 891-900. https://doi.org/10.1093/aob/mci103

Watts-Williams, S. J., Emmett, B. D., Levesque-Tremblay, V., MacLean, A. M., Sun, X., Satterlee, J. W., Fei, Z., & Harrison, M. J. (2018). Diverse *Sorghum bicolor* accessions show marked variation in growth and transcriptional responses to arbuscular mycorrhizal fungi. *Plant, Cell & Environment, 42*, 1758–1774. https://doi.org/10.1111/pce.13509

Received 12/8/2026; Revised 9/18/2026; Accepted 10/29/2026
https://doi.org/10.29244/jtcs.13.03.827-842

Watts-Williams, S. J., Gill, A. R., Jewell, N., Brien, C. J., Berger, B., Tran, B. T. T., Mace, E., Cruickshank, A. W., Jordan, D. R., Garnett, T., & Cavagnaro, T. R. (2022). Enhancement of sorghum grain yield and nutrition: A role for arbuscular mycorrhizal fungi regardless of soil phosphorus availability. *Plants, People, Planet, 4*, 143–156. https://doi.org/10.1002/ppp3.10224

Widawati, S., & Suliasih. (2019). Role of indigenous nitrogen-fixing bacteria in promoting plant growth on post-tin mining soil. *Makara Journal of Science, 23*, 28-38. https://doi.org/10.7454/mss.v23i1.10801

Wulandari, D., Maulana, A. F., & Fathikasari, I. (2023). Potential use of indigenous arbuscular mycorrhizal fungi to improve soil productivity in tailing of tin mining: A greenhouse study scale. *IOP Conference Series: Earth and Environmental Science, 1263*, 012042. https://doi.org/10.1088/1755-1315/1263/1/012042

Wulandari, D., Nufus, M., Faridah, E., Maulana, A. F., & Tawaraya, K. (2024). Native arbuscular mycorrhizal fungi and Nauclea orientalis for potential reclamation of tropical coal mining areas. *Environmental Advances, 15*, 100462. https://doi.org/10.1016/j.envadv.2023.100462

Zheng, Y., Chen, N., Zhang, C., Dong, X., & Zhao, C. (2021). Effects of rock fragments on the soil physicochemical properties and vegetation on the Northeastern Tibetan Plateau. *Frontiers in Environmental Science, 9,* 693769. https://doi.org/10.3389/fenvs.2021.693769