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Research Article

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Interactive effects of banana stem ash and potassium-solubilizing fungi on peanut (*Arachis hypogaea* L.) growth and yield

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Abstract: Peanut (*Arachis hypogaea* L.) productivity in Indonesia averages approximately 1.0 t ha^{-1}, far below its potential yield of 3.5 t ha^{-1}, mainly due to poor pod filling associated with low soil potassium (K) availability. This study evaluated the integrated application of banana stem ash (BSA) containing 23.6% K_2O and potassium-solubilizing fungi (PSF), including *Aspergillus unguis*, *Metarhizium carneum*, and *Meyerozyma caribbica*, as a locally available nutrient-management strategy to enhance peanut yield. A split-plot design with three replications was applied, consisting of three BSA dosages (0, 500, and 1,000 kg ha^{-1}) and four fungal inoculation treatments. Growth, yield components, and K content in plant tissues and soils were measured at flowering and harvest. Data were analyzed using analysis of variance (ANOVA), followed by the least significant difference (LSD) test at 5%. Results showed that BSA at 1,000 kg ha^{-1} combined with *M. carneum* increased dry pod weight per plant by 48.2% (24.95 g vs. 16.84 g in the uninoculated control without BSA), while *M. caribbica* raised the proportion of filled pods to 85.09% compared with 53.86% in the uninoculated control without BSA. Soil available K_2O increased from 21.82 to 25.94 mg 100 g^{-1} under the highest BSA dose. These outcomes indicate a significant positive interaction between BSA and PSF for dry pod weight, whereas other variables were mainly influenced by BSA and/or PSF main effects. Because no conventional K-fertilizer control was included, the integrated use of PSF and BSA should be considered a potential complementary approach for improving peanut yield, soil K status, and nutrient-management sustainability in Indonesia.

Keywords: banana stem ash, organic fertilizer, peanut yield, potassium availability, potassium-solubilizing fungi

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1. Introduction

Peanut (*Arachis hypogaea* L.) is one of the most important grain legumes and oilseed crops cultivated in tropical and subtropical regions. Beyond its nutritional value as a source of oil, protein, carbohydrates, minerals, vitamins, and bioactive compounds, peanut contributes to food, feed, oil, and income-generation systems, particularly in smallholder farming contexts (Fletcher & Shi, 2016; Variath & Janila, 2017). However, productivity gains remain limited by soil nutrient deficiencies, particularly potassium (K), which directly affects pod filling and yield stability.

Peanut productivity in Indonesia remains low, averaging approximately 1.0 t ha^{-1} compared with its genetic potential of 3.5 t ha^{-1} (Kasno, 2007). This gap increases dependence on imports and weakens food security. One of the main constraints is suboptimal pod filling, which causes a high proportion of empty pods (cipo) during harvest (Adisarwanto, 2005). Potassium deficiency has been consistently identified as a key driver of this problem, highlighting the urgent need for better K management strategies.

Potassium is crucial for photosynthesis, carbohydrate metabolism, seed development, and stress tolerance (Sitepu et al., 2014). It also contributes to stomatal regulation and photosynthetic carbon gain under nutrient stress (Jákli et al., 2017). Yet, only 2–10% of total soil K is plant-available, with most K bound in insoluble mineral forms (Havlin et al., 2013; Pratama et al., 2016). This limited availability explains why K deficiency remains widespread in tropical soils and constrains legume productivity.

Conventional K inputs such as leucite, feldspar, and glauconite release K slowly and are poorly suited to immediate crop needs. Fungi can dissolve potassium bound to mineral rocks, thereby increasing the availability of potassium in the soil (Prajapati et al., 2012). Mineralization of potassium by fungi occurs through chelating reactions of mineral elements, acid hydrolysis, and secretion of macromolecules and polymers that release K from potassium-bearing minerals (Meena et al., 2016). Potassium-solubilizing fungi (PSF) can mobilize insoluble K through mechanisms such as organic acid production and mineral weathering, as reported in previous studies on K-solubilizing microorganisms (Prajapati et al., 2012; Meena et al., 2016; Olaniyan et al., 2022). Therefore, exploring PSF as biofertilizers represents a sustainable strategy for enhancing K availability in tropical legumes (Anwar et al., 2022).

Mineral ash or carbonized residues from plant biomass can serve as local sources of K and other mineral nutrients, potentially complementing conventional nutrient inputs. When applied at appropriate rates, organic and mineral amendments can improve soil chemical and biological conditions, including nutrient availability, cation exchange capacity, nutrient retention, and microbial habitat quality, although the magnitude of these effects depends on amendment type, soil properties, and application rate (Shu et al., 2022; Antonangelo et al., 2024; Garcia et al., 2024). Banana stems are abundant agricultural residues in tropical regions (Mohapatra et al., 2010) and can be converted into banana stem ash or controlled carbonized residues (BSA). The BSA used in this study contained 23.6% K_2O, 12.7% Ca, 5.2% Mg, 1.8% P, and 14.3% Si, indicating its potential as a low-cost mineral nutrient source. Nevertheless, the potential interaction between BSA and PSF remains poorly studied in Indonesia, presenting a critical research gap in sustainable peanut nutrient management.

This study investigates the integration of PSF and BSA to improve K availability and peanut productivity. The novelty lies in combining two eco-friendly, locally available resources as a potential complement to conventional K nutrient management. We hypothesized that this integrated approach would stimulate plant growth, enhance pod filling, and increase yield. The findings are expected to provide empirical evidence for sustainable agronomic practices, strengthen food security, and support environmentally sound farming systems.

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2. Materials and Methods

2.1 Study site and soil characteristics

The experiment was conducted during a single 110-day peanut growing cycle at the Experimental Farm of the Faculty of Agriculture, Hasanuddin University, South Sulawesi, Indonesia (5°11′S, 119°27′E; altitude 25 m asl). The site has a tropical monsoon climate with an average temperature of 27–30°C, annual rainfall of approximately 2,500 mm, and relative humidity of 70–85%. The soil was classified as Ultisol (sandy loam), acidic with a pH of 5.85, containing 1.14% organic carbon, 0.12% total nitrogen, a C/N ratio of 10, and 9.76 ppm available phosphorus (P_2O_5). The initial exchangeable K was 0.15 cmolc kg^{-1}, while the cation exchange capacity (CEC) was 20.09 cmolc kg^{-1} and available K_2O was 16.06 mg 100 g^{-1}. Baseline soil properties were analyzed following standard procedures: Walkley–Black for organic carbon, Kjeldahl for nitrogen, Bray I for phosphorus, ammonium acetate extraction for exchangeable K, and standard extraction for available K_2O.

2.2 Experimental design

The experiment was conducted under field conditions using a split-plot design with three replications. The three replications were arranged as field blocks to account for field heterogeneity. Within each block, the main plots consisted of three levels of banana stem ash (BSA) application: 0 kg ha^{-1} (B0), 500 kg ha^{-1} (B1), and 1,000 kg ha^{-1} (B2), and these main-plot treatments were randomly assigned within each block. The subplots consisted of four fungal treatments: no inoculation (C0), *Aspergillus unguis* (C1), *Metarhizium carneum* (C2), and *Meyerozyma caribbica* (C3), which were randomly assigned within each BSA main plot. Each experimental unit was a 3 × 2 m subplot separated by 0.5 m alleys, with ridges of 15 cm height. Thus, the experiment comprised 12 treatment combinations (3 BSA levels × 4 PSF treatments) and 36 subplot experimental units. With a plant spacing of 30 × 20 cm, each subplot contained approximately 100 planting holes. Five representative plants from the central rows of each subplot were used for plant-level growth and yield-component observations, while border plants were excluded from the sampling area. For treatment-level ANOVA, the subplot mean was used as the experimental unit; the five sampled plants within each subplot were treated as subsamples and not as independent replications.

2.3 Inoculum preparation of potassium-solubilizing fungi

Three fungal isolates, *A. unguis*, *M. carneum*, and *M. caribbica*, were obtained from the Soil Microbiology Laboratory, Hasanuddin University, and their identity was confirmed through morphological and molecular characterization (ITS rDNA sequencing, BLAST analysis >99% homology). These isolates were selected based on prior screening for potassium-solubilizing ability from leucite potassium rock deposits (Anwar et al., 2022). The isolates were mass-cultured on sterilized rice substrate (4.5 kg total) that had been soaked for 24 h, portioned into 100 g units, autoclaved at 121°C for 15 min, cooled, inoculated, and incubated at 27–30°C for 14 days. After incubation, the mycelium-covered rice substrate was blended and air-dried. Final spore concentrations were 2.58 × 10^8 spores g^{-1} for *A. unguis*, 2.38 × 10^8 spores g^{-1} for *M. carneum*, and 1.72 × 10^8 spores g^{-1} for *M. caribbica*, as determined using haemocytometer counting following standard plant pathology procedures (Dhingra & Sinclair, 1995). Because each treatment received 1 g inoculum $plant^{-1}$, the actual propagule dose differed among isolates; therefore, fungal treatment comparisons should be interpreted as responses to the prepared inocula rather than strictly equalized propagule doses.

2.4 Banana stem ash production process

Banana stem ash was produced through controlled carbonization under limited-oxygen conditions. Banana stems were cut into small pieces and sun-dried for 4–7 days. The dried

stems were placed in a small drum that was tightly sealed to restrict oxygen entry, and the small drum was then positioned inside a larger drum and heated using a gas stove. A thermometer was attached to the larger drum, and heating was maintained until the temperature reached 300°C for 3 h. This process was not intended to achieve open-air complete combustion; rather, it produced a controlled carbonized ash or charred residue derived from banana stems. The resulting material was removed from the small drum, cooled, sun-dried, and ground using a grinder. The material is referred to as BSA in this manuscript because it was the mineral-rich residue used as the K-containing amendment. Its composition was 23.6% K_2O, 12.7% Ca, 5.2% Mg, 1.8% P, and 14.3% Si (Anwar et al., 2021).

2.5 Crop maintenance and harvesting

A local Barru peanut landrace, obtained from farmer-maintained seed sources in Barru Regency, South Sulawesi, was planted with a spacing of 30 × 20 cm, using two seeds per hole at a depth of 3 cm. Seedlings were thinned to one plant per hole after establishment. Fungal inoculant (1 g per plant containing approximately 10^8 spores g^{-1}) was applied near the planting hole, and BSA was evenly spread according to the treatment dose and incorporated into the soil. No conventional synthetic K fertilizer comparator was included in the experiment. The nutrient-management treatments consisted of BSA as the K-containing amendment and PSF inoculation, while other field-management practices were kept uniform across plots. Irrigation was supplied as needed during establishment and dry periods to maintain adequate soil moisture, and all plots received the same watering regime. Plant management included manual weeding at 21 days after planting (DAP), regular monitoring of pests and diseases, and hilling during flowering to enhance pod development. Plants were harvested at 110 DAP when the leaves had dried and pod color indicated physiological maturity. Harvest observations were based on representative sample plants from the central rows of each subplot, and per-plant variables were calculated from these sampled plants.

2.6 Plant observations

Data collected included vegetative growth (plant height and number of branches), biomass (fresh and dry), and yield components (number of pods, percentage of filled pods, pod weight, seed weight, and 100-seed weight). Physiological and soil parameters included K concentration in plant tissues at flowering and harvest, K concentration in pod shells and seeds, and available soil K_2O at harvest. Tissue K concentration was determined using atomic absorption spectrophotometry (AAS) after wet digestion and expressed as a percentage. Soil K was determined from soil extracts and reported as available K_2O (mg 100 g^{-1}). Thus, exchangeable or available soil K variables were clearly separated from plant tissue K concentration variables.

2.7 Data analysis

Data were subjected to split-plot analysis of variance (ANOVA) using SAS 9.4. Normality and homogeneity of variance were tested before analysis. The subplot mean was used as the experimental unit for treatment-level ANOVA, with the five sampled plants within each subplot treated as subsamples. Differences among treatment means were evaluated using the least significant difference (LSD) test at $p \leq 0.05$. Main effects and interaction effects were reported when statistically significant.

3. Results

3.1 Vegetative growth

Banana stem ash and PSF inoculation influenced several vegetative growth variables. Plant height was significantly affected by both BSA and PSF ($p < 0.05$), whereas their interaction was not significant. As shown in Table 1, the tallest plants were observed under 1,000 kg ha^{-1}

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BSA (B2: 56.33 cm), which was significantly higher than the control (B0: 50.93 cm) but not different from 500 kg ha^{-1} BSA (B1: 54.33 cm). Among fungal treatments, *M. carneum* (C2: 56.64 cm) produced taller plants than C0 and C1 and was comparable with *M. caribbica* (C3: 55.20 cm).

Table 1. Plant height (cm) of peanut plants at 35 DAP as affected by BSA and PSF.

BSA	C0	C1	C2	C3	Mean BSA	LSD0.05 (BSA)
B0	49.35	47.94	54.15	52.28	50.93b	3.61
B1	51.85	54.01	55.51	55.96	54.33ab	
B2	52.78	54.94	60.26	57.36	56.33a	
Mean PSF	51.32q	52.30q	56.64p	55.20pq		

Note: C0 = no inoculation; C1 = *A. unguis*; C2 = *M. carneum*; C3 = *M. caribbica*. Means followed by the same letters in the Mean BSA column or Mean PSF row are not significantly different according to the LSD test at $p \leq 0.05$.

The number of branches was not significantly affected by BSA, PSF, or their interaction ($p > 0.05$). The B2 × C2 combination produced the highest numerical branch number (10.63 branches plant^{-1}), followed by B2 × C3 (10.30 branches plant^{-1}), as presented in Figure 1. Because the treatment effects were not statistically significant, these values should be interpreted only as numerical patterns rather than evidence of a treatment effect.

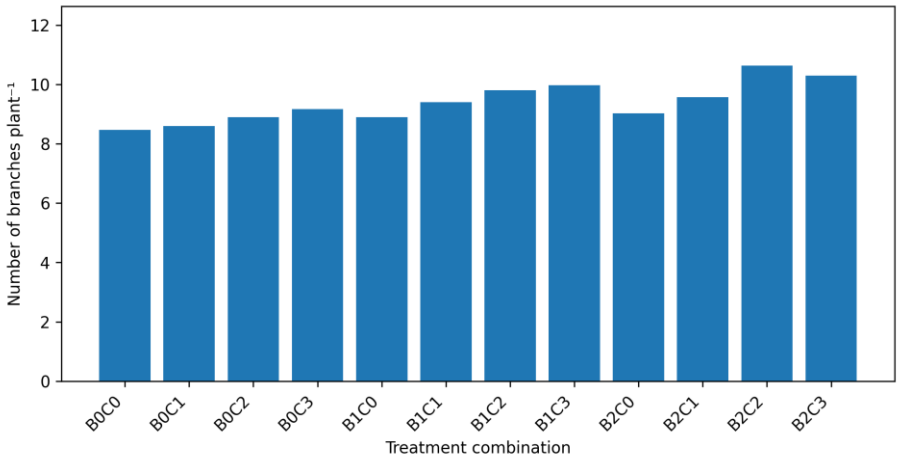

Figure 1. Average number of peanut plant branches at 35 days after planting. Values are treatment means; BSA, PSF, and BSA × PSF effects were not significant at $p \leq 0.05$.

Fresh biomass was significantly affected by BSA application ($p < 0.05$), but not by PSF or the BSA × PSF interaction. As shown in Table 2, B2 (149.70 g plant^{-1}) was significantly higher than B0 (113.81 g plant^{-1}), whereas B1 (139.94 g plant^{-1}) was intermediate and did not differ significantly from either B0 or B2. Dry biomass showed a clearer BSA response, with B2 and B1 significantly higher than B0 (Table 3). These results indicate that BSA application improved biomass accumulation, while PSF and BSA × PSF interaction effects were not statistically supported at this vegetative stage.

Table 2. Fresh biomass of peanut plants (g plant^{-1}) as influenced by BSA and PSF.

BSA	C0	C1	C2	C3	Mean BSA	LSD0.05 (BSA)
B0	107.72	113.05	114.45	120.00	113.81b	26.87
B1	128.05	140.73	143.36	147.62	139.94ab	
B2	132.44	150.96	159.35	156.05	149.70a	

Note: Means followed by the same letters in the Mean BSA column are not significantly different according to the LSD test at $p \leq 0.05$. PSF and BSA × PSF interaction effects were not significant.

Table 3. Dry biomass of peanut plants (g plant^{-1}) under BSA and PSF treatments.

BSA	C0	C1	C2	C3	Mean BSA	LSD0.05 (BSA)
B0	42.35	42.91	44.72	47.79	44.44b	5.52
B1	51.45	51.91	50.10	50.89	51.09a	
B2	51.56	48.83	55.13	55.08	52.65a	

Note: Means followed by the same letters in the Mean BSA column are not significantly different according to the LSD test at $p \leq 0.05$. PSF and BSA × PSF interaction effects were not significant.

3.2 Yield components and pod filling

Yield components responded more strongly to BSA than to PSF alone. Pod number was significantly influenced by BSA ($p < 0.05$), while PSF and the BSA × PSF interaction were not significant. The highest pod count was recorded under B2 (18.80 pods plant^{-1}), significantly higher than B0 and B1 (Table 4). This indicates that sufficient K supply from ash improved reproductive allocation and pod initiation.

Table 4. Number of pods per peanut plant as affected by BSA and PSF.

BSA	C0	C1	C2	C3	Mean BSA	LSD0.05 (BSA)
B0	12.90	13.70	15.17	16.03	14.45b	2.73
B1	15.37	15.07	15.83	15.43	15.43b	
B2	16.60	18.03	19.33	21.23	18.80a	

Note: Means followed by the same letters in the Mean BSA column are not significantly different according to the LSD test at $p \leq 0.05$. PSF and BSA × PSF interaction effects were not significant.

The percentage of filled pods was significantly affected by both BSA and PSF ($p < 0.05$), although their interaction was not significant. B2 (78.63%) and B1 (78.39%) exceeded B0 (66.36%), confirming the role of BSA in enhancing pod filling. Among fungi, *M. caribbica* produced the highest filled pod percentage (80.86%), followed by *M. carneum* and *A. unguis* (Table 5).

Dry pod weight per plant was significantly influenced by BSA, PSF, and their interaction ($p < 0.01$). The highest dry pod weight was obtained from B2 × C2 (24.95 g plant^{-1}), which was 48.2% higher than B0 × C0 (16.84 g plant^{-1}). This result indicates a significant positive BSA × PSF interaction for dry pod weight, meaning that the effect of fungal inoculation depended on the BSA level (Table 6).

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Table 5. Percentage of filled pods under BSA and PSF treatments.

BSA	C0	C1	C2	C3	Mean BSA	LSD0.05 (BSA)
B0	53.86	66.17	67.91	77.50	66.36b	10.19
B1	76.09	77.46	80.03	80.00	78.39a	
B2	61.67	83.82	83.96	85.09	78.63a	
Mean PSF	63.87q	75.81p	77.30p	80.86p		

Note: Means followed by the same letters in the Mean BSA column or Mean PSF row are not significantly different according to the LSD test at $p \leq 0.05$. LSD0.05 for PSF = 10.92.

Table 6. Dry pod weight per plant (g) as affected by the BSA × PSF interaction.

BSA	C0	C1	C2	C3	LSD0.05 (BSA)
B0	16.84	18.10	17.64	18.89	2.44
B1	17.46	20.88	21.34	22.00	
B2	18.25	22.07	24.95	24.36	

Note: LSD0.05 for comparing BSA within the same PSF level = 2.44; LSD0.05 for comparing PSF within the same BSA level = 1.68. These simple-effect comparisons were interpreted within the split-plot design. C0 = no inoculation; C1 = *A. unguis*; C2 = *M. carneum*; C3 = *M. caribbica*.

Dry seed weight and 100-seed weight were also improved by BSA application. The highest dry seed weight occurred under B2 (13.78 g plant^{-1}), which was 27.0% greater than B0 (10.85 g plant^{-1}), while B1 was statistically similar to B2 (Table 7). Similarly, the highest 100-seed weight was obtained with B2 (58.25 g), 20.2% higher than B0 (48.46 g), while B1 was intermediate (Table 8). PSF and interaction effects were not significant for these two variables, indicating that K supply from BSA directly promoted seed development irrespective of fungal inoculation.

Table 7. Dry seed weight of peanut sample plants (g plant^{-1}).

BSA	C0	C1	C2	C3	Mean BSA	LSD0.05 (BSA)
B0	9.99	10.48	11.20	11.73	10.85b	1.48
B1	12.02	12.68	13.47	13.69	12.96a	
B2	12.95	12.56	15.37	14.25	13.78a	

Note: Means followed by the same letters in the Mean BSA column are not significantly different according to the LSD test at $p \leq 0.05$. PSF and BSA × PSF interaction effects were not significant.

Table 8. Weight of 100 dry peanut seeds (g).

BSA	C0	C1	C2	C3	Mean BSA	LSD0.05 (BSA)
B0	45.53	50.75	48.30	49.27	48.46b	6.13
B1	57.29	51.93	49.71	54.76	53.42ab	
B2	59.98	60.85	60.87	51.30	58.25a	

Note: Means followed by the same letters in the Mean BSA column are not significantly different according to the LSD test at $p \leq 0.05$. PSF and BSA × PSF interaction effects were not significant.

3.3 Potassium availability and uptake

Potassium concentration in plant tissue at flowering was significantly affected by both BSA and PSF ($p < 0.05$), while the interaction was not significant. B2 produced the highest tissue K concentration (1.02%), followed by B1 (0.56%) and B0 (0.20%). Among PSF treatments, *M. carneum* (0.83%) and *M. caribbica* (0.72%) exceeded the uninoculated control and *A. unguis* (Table 9). These results indicate that BSA and PSF affected K accumulation in plant tissue at flowering, although the underlying solubilization and uptake processes were not directly measured.

Table 9. Potassium concentration in plant tissue at flowering (%).

BSA	C0	C1	C2	C3	Mean BSA	LSD0.05 (BSA)
B0	0.13	0.12	0.27	0.30	0.20c	0.22
B1	0.24	0.36	0.87	0.77	0.56b	
B2	0.84	0.83	1.34	1.07	1.02a	
Mean PSF	0.40q	0.44q	0.83p	0.72p		

Note: Means followed by the same letters in the Mean BSA column or Mean PSF row are not significantly different according to the LSD test at $p \leq 0.05$. LSD0.05 for PSF = 0.22.

K concentration in pod shells and plant tissues increased consistently with BSA application. BSA significantly affected K in pod shells ($p < 0.05$), with B2 recording the highest concentration (0.37%), followed by B1 and B0 (Table 10). Similarly, K concentration in plant tissues was highest in B2 (1.49%), significantly higher than B1 and B0 (Table 11). These results demonstrate that BSA contributed substantially to K enrichment in both structural and vegetative tissues.

Table 10. Potassium concentration in peanut pod shells (%).

BSA	C0	C1	C2	C3	Mean BSA	LSD0.05 (BSA)
B0	0.09	0.12	0.20	0.30	0.17c	0.03
B1	0.27	0.32	0.34	0.31	0.31b	
B2	0.30	0.33	0.32	0.52	0.37a	

Note: Means followed by the same letters in the Mean BSA column are not significantly different according to the LSD test at $p \leq 0.05$. PSF and BSA × PSF interaction effects were not significant.

Table 11. Potassium concentration in peanut plant tissue (%).

BSA	C0	C1	C2	C3	Mean BSA	LSD0.05 (BSA)
B0	0.61	0.41	0.53	0.53	0.52c	0.21
B1	0.62	0.79	0.97	1.31	0.92b	
B2	1.28	1.54	1.55	1.60	1.49a	

Note: Means followed by the same letters in the Mean BSA column are not significantly different according to the LSD test at $p \leq 0.05$. PSF and BSA × PSF interaction effects were not significant.

Seed K content was significantly affected by both BSA and PSF ($p < 0.05$). B2 produced the highest seed K concentration (2.42%), surpassing B0 and B1. Among fungi, *M. caribbica* (2.33%) and *M. carneum* (2.32%) produced the highest mean seed K concentrations, while C0

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recorded the lowest value (Table 12). Available soil K_2O at harvest also increased with BSA application; the highest value was recorded under B2 (25.94 mg 100 g^{-1}), followed by B1 (25.24 mg 100 g^{-1}) and B0 (21.82 mg 100 g^{-1}), as shown in Table 13.

Table 12. Potassium concentration in peanut seeds (%).

BSA	C0	C1	C2	C3	Mean BSA	LSD0.05 (BSA)
B0	0.94	1.30	1.99	2.09	1.58c	0.06
B1	1.67	2.28	2.40	2.30	2.16b	
B2	2.01	2.51	2.59	2.59	2.42a	
Mean PSF	1.54q	2.03p	2.32p	2.33p		

Note: Means followed by the same letters in the Mean BSA column or Mean PSF row are not significantly different according to the LSD test at $p \leq 0.05$. LSD0.05 for PSF = 0.35.

Table 13. Available soil K_2O content at harvest (mg 100 g^{-1}).

BSA	C0	C1	C2	C3	Mean BSA	LSD0.05 (BSA)
B0	17.81	20.94	22.20	26.35	21.82b	1.69
B1	27.25	22.34	26.75	24.62	25.24a	
B2	24.76	24.39	32.23	22.39	25.94a	

Note: Means followed by the same letters in the Mean BSA column are not significantly different according to the LSD test at $p \leq 0.05$. PSF and BSA × PSF interaction effects were not significant.

4. Discussion

This study indicates that the integration of BSA and PSF can improve K availability, pod filling, and yield components of peanut under tropical soil conditions. The clearest evidence of a treatment interaction was found in dry pod weight per plant, where the combination of 1,000 kg ha^{-1} BSA with *M. carneum* produced the highest value. This finding supports a significant positive interaction between BSA and PSF for dry pod weight, although a formal greater-than-additive test was not performed. Therefore, the interaction should be interpreted as evidence that the response to fungal inoculation depended on BSA application rather than as a demonstrated greater-than-additive mechanism.

The effect of BSA on vegetative growth and biomass was consistent with its role as a mineral nutrient source. BSA improved plant height, dry biomass, pod number, seed weight, 100-seed weight, tissue K concentration, and residual soil K. For fresh biomass, B2 was significantly higher than B0, whereas B1 was statistically intermediate. These responses are agronomically important because K contributes to photosynthesis, enzyme activation, stomatal regulation, assimilate transport, and seed development (Sitepu et al., 2014; Hasanuzzaman et al., 2018). Potassium deficiency can restrict photosynthetic carbon gain and reduce assimilate movement to reproductive organs (Jákli et al., 2017), which may help explain the improvement in pod filling under higher BSA rates.

The contribution of PSF was most visible in filled pod percentage, dry pod weight, tissue K concentration at flowering, and seed K concentration. Previous studies have shown that potassium-solubilizing microorganisms may release K from mineral sources through organic acids, chelating substances, and other metabolites that disrupt K-bearing mineral structures (Rogers et al., 1998; Prajapati et al., 2012; Meena et al., 2016; Olaniyan et al., 2022). In the present study, these processes were not directly measured; therefore, organic acid production and fungal-mediated K mobilization are presented as plausible mechanisms rather than

demonstrated mechanisms. The stronger response under *M. carneum* and *M. caribbica* may reflect isolate-specific differences in K-solubilizing capacity, rhizosphere adaptation, or compatibility with ash-derived inputs, but it may also be influenced by the unequal spore densities of the inocula applied.

The observed BSA × PSF interaction in dry pod weight indicates that the two inputs functioned in a complementary manner for this specific yield variable. BSA supplied K_2O, Ca, Mg, P, and Si and may also have modified soil chemical conditions that favor nutrient availability. Organic and mineral amendments are known to improve soil cation exchange capacity, nutrient retention, microbial habitat quality, and crop yield responses, although these effects vary with amendment composition and soil context (Shu et al., 2022; Antonangelo et al., 2024; Garcia et al., 2024). In this study, microbial habitat quality, fungal establishment, and enzyme or organic acid activity were not measured directly; therefore, the proposed rhizosphere explanation should be considered a possible interpretation rather than direct evidence.

The increase in available soil K_2O at harvest under BSA treatments suggests that BSA had residual fertility potential. This is important for tropical soils, where nutrient leaching and low nutrient retention can reduce fertilizer efficiency. However, because BSA supplied several nutrients simultaneously, including K_2O, Ca, Mg, P, and Si, the observed yield response cannot be attributed exclusively to K. Moreover, residual effects were assessed only at the end of one growing season, so longer-term effects across successive cropping cycles remain uncertain.

From a sustainable agriculture perspective, the use of banana stem residues and PSF provides a locally available nutrient-management option. Banana stems are abundant agricultural byproducts in tropical areas, and their conversion into BSA can reduce waste while supplying mineral nutrients. PSF inoculation adds a biological approach that may improve nutrient-use efficiency. Similar eco-friendly strategies have been emphasized as complementary approaches to synthetic inputs because they can improve soil health and reduce nutrient losses when properly managed (Shu et al., 2022; Li et al., 2023; El-Abdeen et al., 2024; Garcia et al., 2024). Nevertheless, this study did not include a conventional synthetic K fertilizer comparator; therefore, the findings support BSA and PSF as potential complementary options rather than a proven replacement for synthetic K fertilizers.

Several limitations should be considered when interpreting these findings. The experiment was conducted at one location, on an Ultisol sandy loam, during a single growing season, with only three field replications. The study did not include a conventional synthetic K fertilizer treatment, and BSA supplied several nutrients simultaneously, making it difficult to isolate the K-specific contribution. The fungal inoculum treatments also differed in spore density, and fungal establishment, organic acid production, enzymatic activity, and microbial community changes were not directly measured. In addition, residual effects were not evaluated across multiple seasons. Future studies should include a conventional K-fertilizer comparator, standardized viable propagule doses, direct measurements of fungal activity, and multi-location, multi-season validation.

5. Conclusion

The integrated application of banana stem ash and potassium-solubilizing fungi improved potassium availability, vegetative growth, pod filling, and yield components of peanut under the conditions of this single-location field experiment. The application of 1,000 kg ha^{-1} BSA consistently enhanced soil and tissue K status, while *M. carneum* and *M. caribbica* contributed to higher dry pod weight and filled pod percentage. The strongest dry pod weight response occurred when 1,000 kg ha^{-1} BSA was combined with *M. carneum*, indicating a significant positive interaction between mineral nutrient supply and fungal inoculation for this yield variable. Because the study did not include a conventional synthetic K fertilizer comparator and did not directly measure fungal activity, BSA and PSF should be regarded as a potential

complementary nutrient-management approach rather than a proven replacement for synthetic K fertilizers. Future studies should validate these responses across soil types, locations, seasons, and fertilizer comparison treatments, and should evaluate residual effects over successive cropping seasons.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

Andi Rahayu Anwar: Conceptualization, methodology, investigation, data curation, and writing - original draft. **Ambo Ala**: Supervision, methodology, validation, and writing - review and editing. **Tutik Kuswinanti**: Supervision, validation, and writing - review and editing. **Elkawakib Syam'un**: Supervision, methodology, and validation. **Syamsia Syamsia**: Formal analysis, visualization, and writing - review and editing. **Noerfitryani Noerfitryani**: Data curation, visualization, and writing - review and editing. All authors have read and approved the final manuscript.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

Ethics Statement

This study did not involve human participants, animal subjects, or identifiable personal data. Therefore, ethical approval was not required.

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