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Morphophysiological Response of Edamame Soybean to Arbuscular Mycorrhizal Fungi (AMF) and Bioactive Compost Charcoal in Tidal Swamp Land

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ABSTRACT

Edamame soybean cultivation in Indonesia has great potential due to its high nutritional value and increasing market demand. However, the current productivity remains low, thereby hindering commercial development. This study aimed to enhance the growth and yield of edamame soybean plants through the application of Arbuscular Mycorrhizal Fungi (AMF) and bioactive compost charcoal on tidal swamp lands. The research was conducted using a split-plot design consisting of two AMF treatments and four levels of bioactive compost charcoal. The results indicated that the combination of AMF and bioactive compost charcoal significantly increased various growth parameters and yield. Although a dose of 10 ton/ha produced vegetative growth equivalent to that achieved by applying 15 ton/ha corn stalk compost, a dose of 15 ton/ha resulted in more optimal harvest outcomes, with pod numbers reaching 43.22 units per plant, pod weight of 91.67 g per plant, and pod weight of 1.545 kg per plot. Furthermore, the treatment also increased the percentage of AMF colonization in roots as well as phosphorus uptake, which contributed to the enhancement of plant productivity.

1. INTRODUCTION

Edamame soybean is a horticultural commodity and an important source of plant-based protein for improving community nutrition. Edamame soybeans are highly favored by the Indonesian public and in several developed countries such as Japan and the United States. Although edamame production in Indonesia achieves high yields (10–12 tons per hectare) compared to conventional soybeans (1.7–3.2 tons per hectare) (Hakim, 2013), the overall production is still insufficient to meet domestic demand. Data from the Indonesian Ministry of Agriculture (Kementerian Pertanian Republik Indonesia, 2020) indicate that domestic soybean production covers only about 30% of national consumption, necessitating significant imports to fill the gap. This production shortfall underscores the need to intensify and expand edamame cultivation, including through the use of underutilized lands such as tidal swamp areas. These lands have great potential for national food security, although they face challenges such as waterlogging, high soil acidity, and reduced nutrient availability. According to West Kalimantan BPS (2020), the province has 1,904,100 hectares of tidal swamp land suitable for agriculture.

Tidal swamp land presents several challenges for agricultural development, particularly for edamame soybean cultivation. These areas are characterized by high soil acidity, low nutrient availability, poor soil structure, and periodic waterlogging, which can negatively impact plant growth and yield (Harsono *et al.*, 2021). Improving the management of tidal swamp land is crucial to overcoming these limitations and enhancing agricultural productivity.

One promising approach to improving soil quality in tidal swamp lands is the addition of organic amendments such as biochar-enriched compost. Agricultural waste can be processed into biochar through pyrolysis and used as bioactive compost charcoal, which enhances soil fertility by increasing nutrient retention, improving soil aeration, and promoting beneficial microbial activity (Lehmann & Joseph, 2015). Compared to other soil amendments, biochar is particularly advantageous due to its long-term stability in the soil, its ability to mitigate soil acidity, and its potential to enhance water-holding capacity, making it suitable for challenging environments like tidal swamp lands (Laghari *et al*., 2016).

Additionally, biological agents such as Arbuscular Mycorrhizal Fungi (AMF) can further support plant growth by improving nutrient and water absorption, particularly in stressed soil conditions (Begum *et al*., 2019). However, the effectiveness of AMF and bioactive compost charcoal, especially in tidal swamp lands, as well as the interaction between these treatments, has not yet been extensively studied. Previous research by Sudiarti (2018), demonstrated that AMF application significantly enhanced edamame soybean growth, but did not explore the combined effects of AMF and bioactive compost charcoal on plant growth and yield in tidal swamp land conditions. Therefore, this study aims to assess the interaction between AMF and compost charcoal and evaluate their roles in improving the growth and yield of edamame soybeans in tidal swamp lands. The expected benefit of this study is to examine the potential of using bioactive compost charcoal and AMF to reduce chemical fertilizers, thereby supporting sustainable cultivation in tidal swamp lands.

2. MATERIALS AND METHODS

This research was conducted from May to July 2024 in Rasau Jaya Tiga Village, Kubu Raya Regency, with a type B flooding pattern. Type B inundation refers to a periodic flooding condition driven by tidal fluctuations, where the land is submerged during high tide and exposed during low tide. This pattern alters the soil's moisture, oxygen, and nutrient dynamics, thereby influencing plant growth. The study used a Randomized Block Design (RBD) with a split-plot pattern, where the main plot was the application of Arbuscular Mycorrhizal Fungi (AMF), and the subplots were bioactive compost charcoal treatments. AMF had two levels: M0 (without AMF) and M1 (with AMF), while the bioactive compost charcoal had four levels: A1 (15 tons/ha of corn stalk compost), A2 (5 tons/ha of bioactive compost charcoal), A3 (10 tons/ha of bioactive compost charcoal), and A4 (15 tons/ha of bioactive compost charcoal). Each treatment was repeated three times, with a total of 1,800 plants. Corn stalk compost was used as a comparator to the bioactive compost charcoal treatment because it is commonly used by farmers in the study area.

The production of bioactive compost charcoal commenced with the production of rice husk biochar via pyrolysis. Next, harvested corn stalks were chopped into pieces measuring 1–2 cm and mixed with poultry manure and rice husk biochar in a 1:1:1 weight ratio, each at 20 kg, until a homogeneous mixture was achieved. After mixing, 10 g of agri-

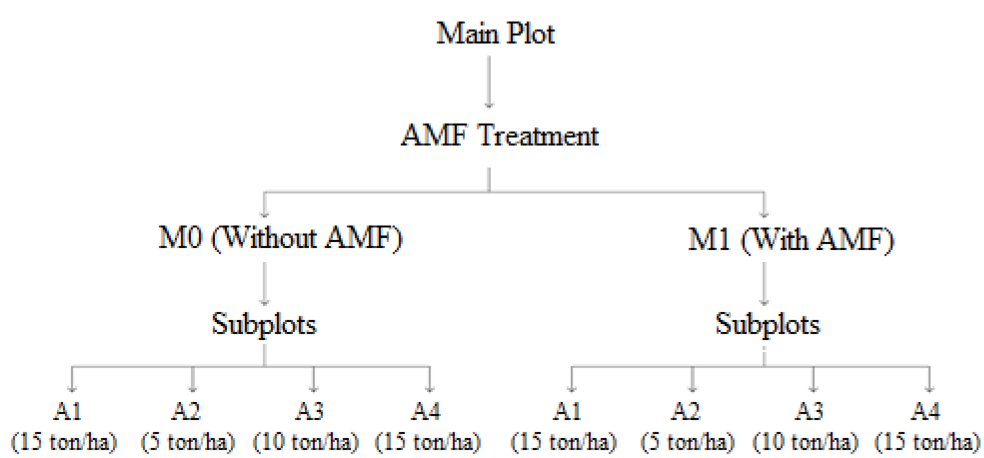

Figure 1. Experimental Design Flowchart

cultural lime was added, followed by a solution containing *Trichoderma* sp. (prepared by dissolving the contents of two test tubes in 500 ml of water) to accelerate the composting process, as well as a sugar solution made by dissolving 100 g of sugar in 1 liter of water. The resulting mixture was then tightly covered with a plastic tarpaulin to prevent the entry of external microorganisms and placed in a shaded area, protected from direct sunlight and rain, for 30 days. Meanwhile, for the production of corn stalk compost for treatment A1, chopped harvested corn stalks, poultry manure, and rice husk were mixed in a 1:1:1 ratio, each at 10 kg, until the mixture was homogeneous, followed by the addition of 5 g of agricultural lime and a sugar solution made by dissolving 50 g of sugar in 1 liter of water.

Land preparation began by creating raised beds measuring 100 cm x 300 cm with a planting distance of 20 cm x 20 cm, total number of plants in one plot is 75. The compost charcoal was applied one week before planting. Edamame soybean seeds were sown by dibbling at a depth of 1.5–2 cm. AMF application was done at the same time as planting. Thinning was performed at 10 days after sowing (DAS) if more than one plant was found per planting hole. NPK fertilizer was applied twice at a dose of 2.25 g/plant. The first fertilization was applied when the plants were 10 days after planting, and the second fertilization was applied when the plants were 26 days after planting, with each application receiving a half dose of 1.125 g per plant. Observations were made at 30 DAS for variables such as plant height, number of leaves, number of branches, dry weight of shoots and roots, shoot-to-root ratio, and N and P nutrient absorption. Variables for N and P uptake measured the total amount of nitrogen and phosphorus absorbed by the plants. The nutrient content of the whole plant was assessed at 30 days after sowing (DAS), and nutrient uptake was calculated by multiplying the dry weight of the plant by its respective N and P content. AMF-induced root infection was assessed on plant roots at 14 days after sowing (DAS) using a staining technique and observed under a microscope. The percentage of infected roots was calculated by dividing the number of infections observed in the root sections by the total number of root observations. The evaluation of N and P nutrient uptake as well as AMF root infection was conducted in the Plant Pathology Laboratory of the Faculty of Agriculture, Universitas Tanjungpura.

Harvest observations were made at 68 DAS for the number of pods per plant, fresh pod weight per plant, and fresh pod weight per plot. Data from the observations were analyzed using analysis of variance (ANOVA) to determine the effect of treatments on the observed variables. Variables that showed significant effects were further tested using the 5% Honestly Significant Difference (HSD) test to identify differences between treatment levels.

3. RESULTS AND DISCUSSION

The morphophysiological characteristics of edamame soybean plants showed a positive response to the treatments of Arbuscular Mycorrhizal Fungi (AMF) and bioactive compost charcoal in tidal swamp land ($P<0.05$). Observations of various variables such as plant height, number of leaves, shoot dry weight, root dry weight, shoot-to-root ratio, number of pods per plant, pod weight per plant, and pod weight per plot indicated that both treatments enhanced plant growth and yield.

3.1. Plant Height, Number of Leaves, and Number of Branches

The AMF treatment was able to increase the plant height and number of leaves in edamame soybeans. Treatment with AMF resulted in the highest plant height and number of leaves compared to the treatment without AMF (Table 1). This was due to AMF's ability to enhance nutrient and water uptake by plant roots. Research by Sasli & Abdurrahman (2024), showed that AMF inoculation increased the number of leaves in tomato plants compared to those without AMF inoculation. AMF improves the absorption of essential nutrients such as phosphorus, which plays a role in cell growth and elongation, as well as producing more leaves. According to Subardja (2016), AMF helps plants absorb nutrients, thereby increasing phosphorus concentration in soybean leaves, contributing to better growth. AMF can enhance the plant's ability to absorb both macro and micro nutrients, as well as increase the area for water and nutrient uptake from soil that was previously inaccessible to plant roots. Mycorrhizal plants exhibit better growth than non-mycorrhizal plants, especially in terms of phosphorus, nitrogen, and water absorption (Putri & Susiawan, 2020; Lubis *et al.*, 2015).

Although AMF inoculation significantly enhanced plant height and leaf number by improving nutrient and water uptake, it did not produce a significant change in the number of branches. One possible explanation is that branch formation is primarily governed by the plant's genetic factors and endogenous hormonal regulation particularly the balance between auxins and cytokinins which determine lateral bud outgrowth (Smith & Smith, 2011). While AMF colonization increases nutrient availability and overall vegetative growth, its indirect effects on the hormonal signals that trigger branch formation may be minimal, especially under conditions where nutrient stress is not severe (Augé, 2001). Consequently, the inherent genetic control over branching appears to override any subtle stimulatory influence that improved nutrient uptake might confer.

A dose of 15 tons/ha of bioactive compost charcoal resulted in the highest plant height and number of leaves, while a dose of 5 tons/ha of compost charcoal produced the lowest plant height and number of leaves (Table 1). The 15 tons/ha dose of bioactive compost charcoal produced the highest plant height, indicating that this dose was optimal for improving the physical, chemical, and biological properties of the soil. Improved soil structure allowed roots to spread more widely and absorb more nutrients and water, supporting overall plant growth (Widyantika & Prijono, 2019). Conversely, the 5 tons/ha dose resulted in the lowest plant height, indicating that this dose was not yet optimal.

Although AMF and bioactive compost charcoal were proven effective in increasing vegetative growth in terms of plant height and number of leaves, the number of branches showed relatively the same results across all treatment levels. This suggests that genetic factors have a greater influence on branch formation compared to external treatments like AMF. The number of branches is more influenced by genetic factors than by external factors such as AMF inoculation. Although AMF improved the overall condition of the plant, the number of branches remained unchanged due to genetic factors or because the plant had reached its maximum capacity for branch formation.

Table 1. Plant height, number of leaves, and number of branches with AMF and bioactive compost charcoal treatments

Arbuscular Mycorrhizal Fungi (AMF)	Plant Height (cm)	Number of Leaves (blades)	Number of Branches (branches)
Without AMF	26.58 a	15.11 a	2.81 a
AMF	28.17 b	19.39 b	2.64 a
p-value	0.04	0.05	0.51
HSD 5 %	1.49	4.26	0.90
Bioactive Compost Charcoal Dose (ton/ha)	**Plant Height (cm)**	**Number of Leaves (blades)**	**Number of Branches (branches)**
Corn stalk compost 15 ton/ha	26.94 ab	16.06 ab	2.56 a
Bioactive compost charcoal 5 ton/ha	25.72 a	15.44 a	2.56 a
Bioactive compost charcoal 10 ton/ha	27.67 b	17.78 bc	2.72 a
Bioactive compost charcoal 15 ton/ha	29.17 c	19.72 c	3.05 a
p-value	0.00	0.00	2.13
HSD 5 %	1.32	2.16	0.68

Note: Numbers followed by different letters indicate significant differences at the 5% HSD test level.

3.2. Dry Weight of Shoots, Dry Weight of Roots, and Shoot-to-Root Ratio

The dry weight of shoots and roots was measured at 30 days after sowing (DAS). The AMF treatment resulted in higher dry weights of shoots and roots compared to the no-AMF treatment (Table 2). This indicates that AMF not only enhances the vegetative size of the plants but also strengthens the roots of edamame soybeans to absorb more nutrients. AMF can reduce the shoot-to-root ratio due to the faster growth of roots compared to shoots, thus decreasing the proportion of shoots to roots. Mycorrhizae also provide protection against root pathogens and enhance the plant's resistance to adverse environmental conditions, such as drought. This contributes to better plant health and growth, ultimately increasing the dry weight of plant roots (Dewanti *et al*., 2018).

The 15 tons/ha bioactive compost charcoal treatment resulted in the highest average dry weight of shoots, followed by the 10 tons/ha treatment, while the 5 tons/ha treatment showed the lowest results. The highest average shoot-to-root ratio was recorded for the 5 tons/ha treatment (6.239), indicating that at this dose, the proportion of shoots to roots was higher. Compost charcoal has high porosity, increasing soil porosity and enabling the soil to retain more water and air, which is essential for root growth and plant health (Surjaningsih, 2023). Additionally, compost charcoal increases the availability of nutrients such as N, P, K, and Mg, which support plant growth. The increased availability of these nutrients accelerates plant growth and development, as well as enhances the dry weight of shoots and roots of edamame soybeans (Surjaningsih, 2023).

Table 2. Dry weight of shoots, dry weight of roots, and shoot-to-root ratio with AMF and compost charcoal treatments

Arbuscular Mycorrhizal Fungi (AMF)	**Dry Weight of Shoots (g)**	**Dry Weight of Roots (g)**	**Shoot-to-Root Ratio**
Without AMF	7.545 a	1.416 a	5.736 b
AMF	8.440 b	2.171 b	4.027 a
p-value	0.04	0.02	0.04
HSD 5 %	0.83	0.56	1.56
Bioactive Compost Charcoal Dose (ton/ha)	**Dry Weight of Shoots (g)**	**Dry Weight of Roots (g)**	**Shoot-to-Root Ratio**
Corn stalk compost 15 ton/ha	7.639 b	1.734 b	4.694 a
Bioactive compost charcoal 5 ton/ha	5.916 a	1.013 a	6.239 b
Bioactive compost charcoal 10 ton/ha	8.374 b	2.063 bc	4.159 a
Bioactive compost charcoal 15 ton/ha	10.043 c	2.362 c	4.435 a
p-value	0.00	0.00	0.00
HSD 5 %	1.48	0.42	1.56

Note: Numbers followed by different letters indicate significant differences at the 5% HSD test level.

3.3. Relative Growth Rate

The relative growth rate of edamame soybean plants was measured over four periods: 14–18 days after sowing (DAS), 18–22 DAS, 22–26 DAS, and 26–30 DAS. The results of the relative growth rate measured during these four observation periods showed similar growth rates for plants with AMF treatment and plants without AMF (Table 3). The relative growth rate measured over a 4-day period is an assessment of plant size changes within a relatively short time. AMF will enhance the growth of edamame soybean plants in the long term with gradual growth improvement, which may not always be visible within short intervals. If soil conditions and nutrient availability are already optimal, additional benefits from AMF might not be clearly visible in the short term (Kiuk *et al*., 2022).

Although compost charcoal improved other growth variables, the relative growth rate of edamame soybean plants remained similar across all levels of bioactive compost charcoal doses (Table 3). The relative growth rate, measured in a relatively short time frame (4 days per period), indicates that the effects of compost charcoal require more time to enhance plant growth, particularly for cumulative changes that are not immediately visible in the short term. On the other hand, charcoal, as the main component of compost charcoal, has varying effects depending on the soil type and environmental conditions. Some studies have shown that charcoal can improve plant yields, but the results are often varied and not always consistent across all growth parameters. As Zhu *et al*. (2018), mentioned, charcoal is better known for improving the physical and chemical properties of soil, such as increasing cation exchange capacity and water retention.

Table 3. Analysis of variance on number of branches and relative growth rate (RGR) of edamame soybean plants with AMF and compost charcoal treatments in tidal swamp land

Source of Variation	**F-value**	**F-value RGR**				**5% F-table**
	Number of Branches	**14–18 DAS**	**18–22 DAS**	**22–26 DAS**	**26–30 DAS**	
Main Plot						
Group (K)	0.65^{tn}	0.10 tn	2.32 tn	14.07 tn	0.06 tn	19.00
AMF (M)	0.63^{tn}	3.88 tn	2.05 tn	15.79 tn	0.09 tn	18.51
Subplot						
Compost charcoal (A)	2.14^{tn}	2.78 tn	0.24 tn	0.90 tn	2.20 tn	3.49
Interaction (M × A)	1.47^{tn}	0.45 tn	0.41 tn	0.65 tn	2.80 tn	3.49
Number of branches correction coefficient (a) = 18.87%; Coeffisien of variation (b) = 14.50%						
RGR correction coefficient (a) = 5.42%; Coeffisien of variation (b) = 4.80%						

Note: tn = no significant effect at the 5% significance level.

3.4. Number of Pods per Plant, Fresh Pod Weight per Plant, and Fresh Pod Weight per Plot

The harvest at 68 days after sowing (DAS) showed that the AMF treatment resulted in the highest number of pods per plant, fresh pod weight per plant, and fresh pod weight per plot compared to the plants without AMF treatment (Table 4). This indicates that AMF inoculation leads to increased phosphorus and nutrient absorption, which is important for pod formation. AMF helps plants absorb more nutrients, which in turn enhances pod production per plant. Arbuscular Mycorrhizal Fungi (AMF) can increase the plant's ability to absorb nutrients trapped in the soil, such as phosphorus (P), which is crucial for the growth and production of soybeans. AMF application increases nutrient availability, supporting flower development and pod formation (Ibrahim *et al*., 2024). AMF converts organic phosphorus into a more readily absorbable inorganic form, thereby increasing phosphorus availability for soybean plants (Rifani *et al*., 2023).

The treatment with 5 tons/ha bioactive compost charcoal resulted in the lowest number of pods per plant, while the treatment with 15 tons/ha bioactive compost charcoal was the best, although the 10 tons/ha bioactive compost charcoal dose could also replace it. The 5 tons/ha bioactive compost charcoal treatment showed the lowest pod weight per plant, while the 10 tons/ha bioactive compost charcoal treatment resulted in a pod weight per plant that was relatively the same as 15 tons/ha corn stalk compost. The 5 tons/ha bioactive compost charcoal treatment again showed the lowest fresh pod weight per plot. The 10 tons/ha bioactive compost charcoal treatment performed better in fresh pod weight per plot compared to the 15 tons/ha corn stalk compost. The 15 tons/ha bioactive compost charcoal treatment produced the highest pod weight per plant (Table 4). Overall, the 10 tons/ha bioactive compost charcoal treatment showed good potential as a substitute for higher doses, while the 15 tons/ha bioactive compost charcoal treatment remained the best option for maximum yield.

The application of compost charcoal also improves soil structure, enhances aeration, and improves drainage, supporting root growth and the absorption of water and nutrients. Additionally, compost charcoal increases the availability of nitrogen and phosphorus, which are essential for pod formation in leguminous plants (Vebiola *et al*., 2022). Charcoal also raises soil pH, creating a more favorable environment for nutrient absorption and pod formation (Priyadi *et al*., 2018), as well as enhancing soybean root growth, which supports nutrient absorption and increases pod weight (Wu *et al*., 2022).

Table 4. Number of pods and pod weight of edamame soybean with AMF and compost charcoal treatments

Arbuscular Mycorrhizal Fungi (AMF)	**Number of Pod (pods/plant)**	**Pod Weight (g/plant)**	**Pod Weight (kg/plot)**
Without AMF	33.56 a	79.33 a	1.313 a
AMF	37.33 b	85.83 b	1.456 b
p-value	0.02	0.02	0.03
HSD 5 %	2.59	4.35	0.12
Compost Charcoal Dose (ton/ha)	**Number of Pod (pods/plant)**	**Pod Weight (g/plant)**	**Pod Weight (kg/plot)**
Corn stalk compost 15 ton/ha	34.83 b	81.28 b	1.369 b
Bioactive compost charcoal 5 ton/ha	28.78 a	72.11 a	1.200 a
Bioactive compost charcoal 10 ton/ha	34.94 b	85.28 bc	1.425 b
Bioactive compost charcoal 15 ton/ha	43.22 c	91.67 c	1.545 c
p-value	0.00	0.00	0.00
HSD 5 %	3.66	8.34	0.11

Note: Numbers followed by different letters indicate significant differences at the 5% HSD test level.

3.5. Root Infection by AMF

Testing at 14 DAS showed that the treatment without FMA had very low mycorrhizal colonization rates (0–1.67%). The FMA treatment increased mycorrhizal colonization (ranging from 71.67% to 85.00%). The high infection levels in plants treated with FMA indicate that the infection was caused by the FMA treatment. FMA enhances nutrient uptake, including phosphorus, which is essential for plant growth, in line with Husna *et al*. (2021) statement that FMA plays an important role in improving nutrient and water absorption by plants.

The application of compost charcoal also affected the mycorrhizal colony levels in Edamame soybean roots. The higher the compost charcoal dose, the higher the percentage of mycorrhizal colonies in the Edamame roots. Compost charcoal can be used as a growing medium that supports plant growth because it contains essential mineral nutrients for plants and can improve the physical, chemical, and biological properties of the soil. Compost charcoal provides both macro and micro pores, improving air circulation and water retention, creating a better environment for FMA growth, thereby enhancing nutrient and water absorption by plants, which is particularly beneficial in less fertile soils (Husna *et al*., 2021).

Table 5. Mycorrhizal Colonization in Edamame Soybean Roots

Compost Charcoal Treatment	Mycorrhizal Colonization in Roots (%)	
	Without AMF	With AMF
Corn stalk compost 15 ton/ha	1.67	71.67
Bioactive compost charcoal 5 ton/ha	1.33	76.00
Bioactive compost charcoal 10 ton/ha	0.00	82.33
Bioactive compost charcoal 15 ton/ha	0.00	85.00

3.6. Nutrient Uptake of Plants

The data generated showed that FMA and biochar compost treatments significantly increased nitrogen and phosphorus uptake in Edamame soybean plants. The average N and P uptake for the FMA treatment was higher (1.17 g and 0.3 g) compared to the non-FMA treatment (1.06 g and 0.27 g). The addition of 15 tons/ha biochar compost showed the highest nutrient uptake concentration, supporting the fact that this treatment can optimally improve soil quality and nutrient availability. Both FMA and biochar compost treatments showed improvements in nitrogen and phosphorus nutrient uptake in Edamame soybean plants. This is because FMA expands the root surface area, enhancing nutrient absorption. Studies have shown that FMA inoculation can increase plant dry weight and biomass, which are good indicators of plant growth (Husna *et al*., 2021).

Treatments with FMA and biochar compost increased the average nitrogen and phosphorus uptake, contributing to the growth and yield of Edamame soybean plants. Further increases in biochar compost doses showed a positive effect in enhancing nutrient uptake. Biochar compost improves soil quality, increases water absorption capacity, and supports FMA growth, creating optimal conditions for plants. The increase in biochar compost doses had a more significant impact on nutrient uptake. The nitrogen content in biochar compost also supports photosynthesis and plant growth (Komarayati *et al*., 2016). FMA is an obligate mutualistic symbiosis between fungi and plant roots. FMA plays a key role in improving nutrient and water uptake by plants, expanding the root surface area, which enhances plant growth and production. FMA can extend the root surface through external and internal hyphal structures, improving the absorption of nutrients such as phosphorus. Phosphorus absorbed by FMA is essential for cell formation in root and shoot tissues, leading to increased biomass or dry weight of plants (Husna *et al*., 2021).

Table 6. Nitrogen (N) and phosphorus (P) uptake

Compost Charcoal Treatment	Nitrogen (N) Uptake (g)		Posphor (P) Uptake (g)	
	Without AMF	With AMF	Without AMF	With AMF
Corn stalk compost 15 ton/ha	1.23	1.06	0.32	0.27
Bioactive compost charcoal 5 ton/ha	0.88	0.97	0.20	0.24
Bioactive compost charcoal 10 ton/ha	1.27	1.08	0.33	0.26
Bioactive compost charcoal 15 ton/ha	0.87	1.58	0.22	0.45
Average	1.06	1.17	0.27	0.31

3.7. Correlation Between Variables

Correlation analysis showed a significant positive relationship between plant height, leaf number, pod number, pod weight, and phosphorus (P) uptake. The results of the correlation analysis between variables (Table 7) indicated a positive correlation between plant height and leaf number, plant height and pod number, plant height and pod weight, and plant height and P uptake. This suggests that better growth in plants is directly related to nutrient availability, especially phosphorus, which is crucial for pod production. Conversely, the number of branches and nitrogen (N) uptake showed a positive but non-significant correlation with other variables, indicating that although having more branches did not directly affect plant yield or nutrient uptake.

The correlation results between variables showed that plant height, leaf number, pod number, fresh pod weight, and P uptake had a significant relationship with the growth and production of Edamame plants. Plant height positively correlated with leaf number, pod number, fresh pod weight, and P uptake, indicating that taller plants had better vegetative growth and more effective phosphorus absorption. Leaf number was also positively correlated with pod number, fresh pod weight, and P uptake, as more leaves enhance photosynthesis and pod production. Pod number and fresh pod weight were positively correlated with P uptake, reflecting that nutrient availability supports better production.

Table 7. Results of Correlation Analysis Between Variables Observed on Edamame Soybean Plants (Coefficient Values)

Variable	Plant height	Number of leaves	Number of branches	Number of pods	Pod weight	Nitrogen absorption	Phosphorus absorption
Plant height		0.91*	0.37	0.98*	0.96*	0.57	0.92*
Number of leaves	0.91*		0.28	0.87*	0.84*	0.53	0.87*
Number of branches	0.37	0.24		0.37	0.47	0.05	0.59
Number of pods	0.98*	0.87*	0.37		0.96*	0.47	0.92*
Pod weight	0.96*	0.84*	0.47	0.96*		0.49	0.93*
Nitrogen absorption	0.57	0.58	0.05	0.47	0.49		0.49
Phosphorus absorption	0.92*	0.87*	0.59	0.92*	0.93*	0.49	

Note: * = Significant at the 0.05 significance level.

4. CONCLUSION

The use of FMA and bioactive compost charcoal improved the growth and yield of Edamame plants grown in tidal swamp land. Plants treated with FMA showed higher growth and pod yield compared to plants without FMA treatment. The use of a 5 ton/ha bioactive compost charcoal dose resulted in plant growth similar to that of 15 ton/ha corn stalk compost, while a 10 ton/ha bioactive compost charcoal dose yielded results similar to 15 ton/ha corn stalk compost. The 15 ton/ha bioactive compost charcoal treatment resulted in optimal plant growth and yield. The use of FMA and bioactive compost charcoal also increased the percentage of FMA infection in plant roots, with higher compost charcoal doses leading to a greater percentage of FMA infection. This increase in infection percentage positively affected phosphorus (P) absorption by the plants, resulting in optimal growth and yield. The application of 15 ton/ha bioactive compost charcoal can be recommended as an effective organic fertilizer to enhance edamame growth and yield in tidal swamp land.

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