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Effectiveness of organic fertilizer on root performance and nutrient uptake of soybean in agroforestry system

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ABSTRACT

The global population is projected to reach 9.7 billion by 2050, leading to a 70% increase in food demand, including soybean as a significant protein source. Climate change exacerbates soybean productivity with environmental stress, which can reduce yields by up to 13.5%. Pine-based agroforestry systems with organic fertilizer application offer a sustainable solution through improved soil quality and biodiversity. This study aims to evaluate the effectiveness of four types of fertilizers, namely, inorganic fertilizer, natural dye waste (Indigofera tinctoria), corn cob waste, and peanut green manure in supporting the cultivation of soybean variety Dena 1 in agroforestry systems. The research was conducted at Alas Bromo, Karanganyar, Central Java, using a randomized complete block design (RCBD) with 20 experimental units. Parameters observed included the number of leaves, plant leaf area, leaf area index, specific leaf area, root length, root dry weight, number of root nodules, root crown ratio, and nitrogen, phosphate, and potassium uptake. ANOVA and DMRT further test analyzed data. The results showed that groundnut green manure (P4) gave the best contribution, such as increasing the number of leaves (19.40 strands), specific leaf area (82.76 cm^2/g), root lenght (16.64 cm), and nutrient uptake (N = 12.45 mg, K = 5.02 mg). This study concludes that peanut green manure is most effective in supporting soybean growth. Good soybean growth can support sustainable soybean productivity in pine-based agroforestry systems.

Keywords: agroforestry, nitrogen uptake, phosphorus uptake, *Pinus merkusii*, potassium uptake.

INTRODUCTION

The dynamic interaction between population growth, changing consumption patterns and climate change presents diverse challenges to global food security. As the global population increases, so does the demand for food, putting pressure on agricultural systems. The increase in global population, projected to reach around 9.7 billion by 2050, is a major driver of food demand. This surge requires a substantial increase in food production, estimated to be up to 70% higher than current levels (Pradhan, 2024). Soybean (*Glycine max*) is one source that plays an important role in global food security due to its high protein content and versatility in food products. However, several challenges threaten soybean productivity. Climate change can exacerbate existing stresses in soybean crops, such as drought and flooding, hindering growth and development (Foyer et al., 2018). Research shows that climate change is impacting soybean productivity in Northern Ghana. The study found that climate change can reduce productivity by 3% to 13.5% (MacCarthy et al., 2022). In addition, climate change can alter pest and disease dynamics, further complicating management strategies for soybean farmers (Liu et al., 2020).

Agroforestry systems that integrate trees and cultivated plants into farming systems offer sustainable solutions to many challenges faced in agriculture, including those related to soybean production. The presence of trees and shrubs in these systems can increase soil organic matter through the addition of leaf litter and root biomass, which enhances nutrient cycling and microbial activity (Ramadhani, 2024; Ramirez et al., 2022). In addition, studies have shown that agroforestry systems can increase soil nitrogen levels, which are critical for soybean growth, thus promoting higher yields (Nasielski et al., 2015; Sgarbossa et al., 2018). Trees also play an important role in regulating the water cycle by increasing infiltration and reducing runoff, which helps maintain soil moisture levels essential for soybean cultivation (Caron et al., 2018; Siarudin et al., 2021). Agroforestry systems increase biodiversity by creating habitats for various species, including beneficial insects and microorganisms that can improve plant health (Bin et al., 2020; Castle et al., 2021). Increased biodiversity in agroforestry systems can result in more resilient ecosystems, making them more resistant to pests and diseases (Qiang et al., 2022; Sgarbossa et al., 2018).

Pine is one of the trees that contribute to agroforestry systems. Pine trees can significantly affect the microclimate in agroforestry systems. Pine trees provide shade, which can help moderate soil temperatures and reduce evaporation rates, thus maintaining soil moisture levels that are important for plant growth (Fitch et al., 2022; Turley et al., 2017). Pine trees can also increase habitat for various beneficial organisms, including pollinators and natural pest predators, which can improve overall ecosystem health and productivity (Akdoğan, 2024; Hódar et al., 2018). Pine trees contribute to soil health by improving soil structure through their root system. Pine tree roots help bind soil particles together, reducing erosion and increasing soil stability (Komonen et al., 2015; Muster et al., 2022). In addition, the decomposition of pine needles adds organic matter to the soil, which improves soil fertility and increases water storage capacity (Diers et al., 2021; Kirby et al., 2016). Research shows that soils under pine trees often have higher levels of nutrients, such as nitrogen and phosphorus, which are critical for the growth of companion crops like soybeans (Diers et al., 2021; Ray and Landau, 2019).

The application of agroforestry systems in soybean cultivation can support productivity, but it is limited by low light intensity and soil fertility, which need to be improved. Organic fertilizers, such as compost made from agricultural waste, significantly improve soil fertility and structure. Budiastuti et al. showed that soybeans responded positively to various organic fertilizers in a pine stand-based agroforestry system, increasing growth and yield (Budiastuti et al., 2023). Adding organic matter from compost helps increase soil organic carbon levels, improving soil structure, enhancing water retention and increasing nutrient availability (Sudharta et al., 2022). In addition, the decomposition of organic matter contributes to forming soil aggregates, which are essential for maintaining soil health and preventing erosion (Setyaningrum, 2023). Although organic fertilizers have been widely researched, there is still a gap in information regarding their effectiveness on root performance and nutrient uptake of soybeans under agroforestry systems with pine trees. This study aims to evaluate the effectiveness of four types of fertilizers, including inorganic fertilizer, natural dye waste, corn cob waste, and peanut green manure, on the leaf morphology, root performance, and nutrient uptake of soybean variety Dena 1 in a pine-based agroforestry system while supporting the development of sustainable agricultural practices.

MATERIALS AND METHODS

This research was conducted in a forest area focusing on the Alas Bromo area, located on Jalan Derpoyudo, Pelet, Gedong, Karanganyar, Central Java. The research location is at an altitude of 254 meters above sea level. Various equipment was used in this study, including a lux meter, spectrophotometer, atomic absorption spectrophotometry, measuring instruments, cultivation devices, and other laboratory equipment. The materials used included soybean seeds of the Dena 1 variety, inorganic fertilizer, fertilizer made from waste extracted from natural dyes (*Indigofera tinctoria*), fertilizer made from corn cob waste, and green manure from peanut plants.

This research is experimental with a randomized complete block design (RCBD). This experiment tested one treatment factor, namely various types of fertilizers. The types of fertilizers used consisted of four kinds, namely, inorganic fertilizer (P1), natural dye extraction waste fertilizer (P2), corn cob waste fertilizer (P3), and groundnut green fertilizer (P4). Each treatment was repeated five times, resulting in 20 experimental units. Each experimental unit consisted of 54 plants planted in a 3 × 1.5 meter plot with a 30 × 20 cm spacing. Variables observed in this study included number of leaves, plant leaf area, leaf area index, specific leaf area, root length, root dry weight, number of root nodules, root-crown ratio, and uptake of nitrogen, phosphate, and potassium. The data obtained were analyzed using analysis of variance (ANOVA) and continued with Duncan's Multiple Range Test (DMRT) to determine differences between treatments.

RESULT AND DISCUSSION

Leaf morphology

Leaves play an important role in the growth and yield of soybean plants, primarily through their function in photosynthesis. The number of leaves directly affects the plant's ability to capture sunlight and convert it into energy, which is essential for growth and development. The application of various types of organic fertilizers is responded to well by soybeans, as indicated by the number of leaves that are more than the inorganic fertilizer treatment. Applying organic fertilizers can increase the number of leaves by 21% compared to inorganic fertilizers. Groundnut green fertilizer provides the highest increase of 22%. This is because organic fertilizers have a variety of nutrients needed for soybean growth, including leaf formation. Nutrient availability, especially nitrogen, is another important factor affecting leaf formation and photosynthesis. Nitrogen deficiency can reduce chlorophyll content and impair photosynthetic function, reducing plant growth potential (Bao et al., 2021; Zhang, 2024). Studies have shown that adequate nitrogen levels increase the activity of nitrogen-assimilating enzymes in leaves, which is essential for effective photosynthesis and nutrient distribution within the plant (Yuan et al., 2022; Zhang, 2024). In addition, applying mineral fertilizers and foliar nutrients has significantly increased leaf area and photosynthetic productivity, thereby increasing soybean yields (Bondarenko et al., 2022; Tsyhanska, 2024).

Measuring leaf area in soybeans can provide information on plant growth and development and can be used to study soybean responses to environmental conditions and fertilizer treatments. The results showed that applying several types of fertilizers did not significantly affect soybean leaf area (Table 1). The highest leaf area at harvest was obtained in corn cob fertilization, which was 124.81 cm^2. The smallest leaf area was obtained by applying inorganic fertilizer with a leaf area of 81.25 cm^2. This can occur because plants have not adequately utilized some fertilizers' nutrients. Plants with low light intensity cannot maximize the processing of water and nutrients into photosynthates, so the leaf area of each treatment is relatively the same (Yang et al., 2018). In line with (Liu et al., 2017; Susanto and Sundari, 2010), 50% light intensity reduced soybean leaf area.

Light intensity also plays an important role in leaf development and photosynthesis. Soybean plants grown under optimal light conditions tend to have higher leaf area and better photosynthetic performance than those grown in shaded environments (Fan et al., 2018). Studies have shown that intercropping systems, such as maize-soybean intercropping, can affect light availability, thereby affecting leaf growth and photosynthetic efficiency (Fan et al., 2018; Wu et al., 2021). Under shaded conditions, soybean plants can exhibit reduced leaf number and chlorophyll content, reducing biomass and yield (Fan et al., 2018; Yuan et al., 2022). Conversely, strategic management of light exposure can increase leaf greenness and photosynthetic rate, contributing to better growth outcomes (Raza et al., 2019, 2021).

Leaf area index (LAI) is important in understanding plant growth and productivity, especially photosynthesis. Defined as the ratio of total leaf area to the plant's land area, LAI indicates leaf density in a given area. It is important to assess the photosynthetic capacity of vegetation. Higher LAI usually correlates with increased light interception, which enhances photosynthesis and biomass accumulation (Ariza-Carricondo et al., 2019; Dezső et al., 2020; Endiviana et al., 2022). The results showed that the treatment of several types of fertilizers did not significantly affect the leaf area index of soybean (Table 1). The highest leaf area index was obtained from corn cob fertilization, which was 0.21. The smallest leaf area index resulted from inorganic fertilization, which was 0.14. The application of several types of fertilizers has not been able to increase the leaf area index of soybeans in the agroforestry system. However, the application of organic fertilizers can increase the leaf area index than the application of inorganic fertilizers.

Nutrient availability, especially nitrogen, can affect leaf expansion and overall LAI. Nitrogen-stressed plants can exhibit longer internodes and increased leaf surface area. However, this is often at the expense of root growth, which can ultimately affect overall plant health and productivity (Odiyi, 2023). However, shading can reduce leaf area and photosynthetic rates, as observed in maize-soybean intercropping systems studies (Cheng et al., 2022; Yao et al., 2017). The ability of soybean cultivars to adapt to varying light conditions by regulating canopy structure and leaf area distribution is critical for maintaining photosynthetic efficiency and yield under competitive conditions (Cheng et al., 2022; Yao et al., 2017). In addition, applying organic fertilizers can be supported to compensate for these problems. Organic fertilizer can increase the photosynthetic efficiency of soybeans by up to 45.25% compared to those without organic fertilizer. Efficient photosynthesis can cause the soybean leaf area index to increase.

Specific leaf area (SLA) is an important metric in understanding soybean plant growth and productivity, especially in agroforestry systems. SLA is defined as the ratio of leaf area to leaf dry mass, which shows how efficiently plants utilize light for photosynthesis compared to biomass investment in leaf production. The results showed that applying several fertilizers did not significantly affect specific leaf areas (Table 1). Peanut green fertilizer treatment produced the highest specific leaf area with 82.76 cm^2/g. Inorganic fertilizer gave the lowest specific leaf area of 67.68 cm^2/g. The interaction between tree species and soybean crops can cause soil nutrient availability variations, further impacting SLA. For example, leaf litter decomposition from trees can improve soil fertility, promoting better soybean-growing conditions and potentially increasing SLA (Purnomo et al., 2022). However, if nutrient availability is limited, as observed in some mahogany systems, soybean plants may show reduced SLA due to suboptimal growth conditions (Widono, 2024).

Root morphology

Roots have an equally important role at the top of the plant. The roots absorb water and nutrients from the soil and support the plant to keep it upright. The length of the roots shows the area of the absorption field, so the longer the roots, the more optimal the absorption of water and nutrients by soybeans. The results showed that applying several types of fertilizers had the same effect on the length of soybean roots (Table 2). Root length with peanut green fertilizer treatment gave the highest root length of 16.64 cm. The shortest roots resulted from inorganic fertilizer, which was 15.88 cm. Several types of fertilizers have not been provided to stimulate root growth. Low light-intensity conditions in agroforestry systems inhibit root growth and increase the shallowness of soybean root distribution (Wang et al., 2020).

Root dry weight refers to the dry weight of the roots after drying. The drying process is carried out so that the water content in the roots evaporates and leaves the organic matter produced by the plant. A high root dry weight indicates that the distribution of photosynthates to the roots is sufficient. Photosynthates that are widely distributed to the roots will support root formation so that it can widen the absorption area. The wider absorption field will help the roots supply water and nutrients for the continuity of the photosynthesis process (Cui et al., 2016). The results showed that applying several fertilizers produced significant differences (Table 2). Root dry weight in treating I. tinctoria extraction waste fertilizer and peanut green manure gave the highest results with a weight of 0.07 grams. The inorganic fertilizer treatment produced the lowest root dry

Table 1. Morphology of soybean leaves in agroforestry systems

Treatment	Number of leaves	Plant leaf area (cm^2)	Leaf area index	Specific leaf area (cm^2/g)
P1	15.80a	81.25	0.14	67.68
P2	19.20b	91.95	0.15	80.26
P3	18.80b	124.81	0.21	82.02
P4	19.40b	109.60	0.18	82.76

Note: P1: (Inorganic fertilizer); P2: (Natural dye extraction waste fertilizer); P3: (Corn cob fertilizer); P4: (Groundnut green fertilizer); numbers followed by the same letter in the same column are not significant based on DMRT ($\alpha = 0.05$).

Table 2. Soybean root morphology in agroforestry systems

Treatment	Root length (cm)	Root dry weight (g)	Number of root nodules	Root-crown ratio
P1	15.88	0.062a	2.00a	0.082
P2	16.40	0.070b	3.60b	0.080
P3	16.26	0.068b	3.80b	0.084
P4	16.64	0.070b	4.60b	0.082

Note: P1: (Inorganic fertilizer); P2: (Natural dye extraction waste fertilizer); P3: (Corn cob fertilizer); P4: (Groundnut green fertilizer); numbers followed by the same letter in the same column are not significant based on DMRT ($\alpha = 0.05$).

weight at 0.062 grams. The application of organic fertilizer successfully supports root growth compared to inorganic fertilizer. Based on these results, the organic fertilizer treatment produced a higher root dry weight. Higher root dry weight is caused by more photosynthate distribution. Sufficient nitrogen in peanut green manure and I. tinctoria extraction waste fertilizer succeeded in providing the highest root dry weight value. Sufficient nitrogen can support soybean root growth (Santana et al., 2020).

Soybean is one of the legume plants known for its ability to form root nodules. Root nodules have many rhizobial bacteria, such as *Bradyrhizobium, Rhizobium, Sinorhizobium,* and *Mesorhizobium*. These bacteria live in symbiosis with soybean roots and help in nitrogen fixation, which converts nitrogen from the air into compounds that plants can use. The number of root nodules in soybean plants can vary depending on various factors, including the population of Rhizobium bacteria, the presence of inhibitory bacteria, soil conditions, and environmental conditions. The results showed that applying several types of fertilizers significantly affected the number of root nodules (Table 2). The highest number of root nodules was produced by the application of peanut green manure, which was 4.60 units. Groundnut green manure can produce the highest number of root nodules because the groundnut stover contains Rhizobium bacteria. The application of peanut green fertilizer also adds the number of Rhizobium bacteria because peanuts are symbiotic with Rhizobium (Wang et al., 2022). Applying inorganic fertilizer produces the least number of root nodules, namely 2.00 units. This is due to urea fertilizer's nitrogen content, which is too high, inhibiting Rhizobium activity. Long-term use of inorganic fertilizers impacts reducing root nodules because soil biological nitrogen fixation is inhibited by excessive nitrogen fertilization (Wei et al., 2023).

Observation of the crown-root ratio is one of the methods used to measure the relationship between root production and crown production (top of the plant) of soybeans. This method provides information on the allocation of resources between the lower and upper parts of the soybean. The crown-root ratio can provide clues about the efficient use of plant resources, plant health, and plant response to the environment or treatment (Ordóñez et al., 2020). The results showed that treating several types of fertilizers did not significantly affect the soybean crown-root ratio (Table 2). The most significant soybean crown-root ratio resulted from the corn cob fertilizer treatment 0.084. The treatment of *I. tinctoria* extraction waste fertilizer gave the smallest crown root ratio of 0.080. This study's ratio of crown roots shows that photosynthate is focused on the crown area because the root area is sufficient for water and nutrients. Roots with enough water and nutrients do not need to grow broader or deeper because they are already available in the soil surface area (Xiong et al., 2021).

Nutrient uptake

Nitrogen uptake in plants, especially soybeans, is critical for their growth and development. As a legume crop, soybeans have a unique ability to fix atmospheric nitrogen through a symbiotic relationship with rhizobia, which enhances nitrogen uptake ability. This biological nitrogen fixation (BNF) allows soybeans to utilize atmospheric nitrogen. At the same time, it also absorbs inorganic nitrogen compounds such as nitrate (NO3-) and ammonium (NH4+) from the soil, which are essential for synthesizing proteins, nucleic acids, and chlorophyll needed for plant growth (Ohyama et al., 2017; Pereira et al., 2023; Sun, 2024).

The results showed that the application of several types of fertilizers had a significant effect on the value of soybean nitrogen uptake. The application of peanut green fertilizer gave the highest nitrogen uptake of 12.45 mg. Inorganic fertilizer gave the most minor nitrogen uptake compared to other fertilizer treatments at 7.57 mg. The application of several types of organic fertilizers succeeded in increasing soybean nitrogen uptake. This is because organic fertilizers have various elements plants need, especially nitrogen elements. The highest nitrogen uptake was produced by peanut green manure. Groundnut green manure contains high nitrogen so that it can meet the needs of soybeans. Organic fertilizers can increase soybean nutrient uptake and improve soil quality (Hua et al., 2020). Groundnut green manure also carries rhizobia bacteria. These bacteria form a symbiotic mutualism with soybeans and can fix atmospheric nitrogen into a form of nitrogen that soybeans can use (Han et al., 2020).

Phosphate uptake in soybeans refers to the plant's ability to take up and use phosphate nutrients from the soil. Phosphate is one of the essential nutrients for soybean growth and development. Soybeans require adequate amounts of phosphate to support healthy root formation, good flowering, and optimal seed development. Soybean roots have tiny root hairs that function as absorption surfaces. These root hairs play a role in absorbing water and nutrients from the soil, including phosphate. The large surface of root hairs allows soybeans to absorb phosphate efficiently. The results showed that applying several types of fertilizer did not significantly affect the phosphate uptake value of soybeans. The corn cob fertilizer treatment of 2.72 mg produced the highest phosphate uptake. The inorganic fertilizer treatment gave the most minor phosphate uptake of 2.14 mg.

The application of several types of fertilizers has not been able to increase the phosphate uptake of soybeans. The low light intensity can cause this, so the phosphate absorption process is inhibited (Zhou et al., 2019). Root length that was not significantly different in all treatments caused less effective phosphorus absorption. The spatial distribution of phosphorus in the soil can affect its availability to soybean plants. Barbosa et al. highlighted that phosphorus can migrate to deeper soil layers, potentially making it less accessible to plant roots (Barbosa et al., 2018). This spatial variability may lead to a situation where, even with phosphate fertilization, the plant may not adequately absorb the nutrient due to poor root access to phosphorus. The application of corn cob fertilizer gets the highest phosphate uptake results because corn cobs have more phosphate content than other organic fertilizers, thus increasing the availability of phosphate in the soil.

Potassium uptake in soybean is an important process for its growth and development, as potassium (K) plays an important role in various physiological functions, including enzyme activation, osmoregulation, and photosynthesis. However, research shows that applying different potassium fertilizers does not significantly increase potassium uptake in soybeans under certain conditions. The application of peanut green manure gave the highest potassium uptake of 5.02 mg. Applying inorganic fertilizer gave the most minor potassium uptake of 4.31 mg. Light conditions affect the potassium uptake of soybeans (Ahammed et al., 2022). Low light intensity causes non-optimal photosynthesis (Yang et al., 2018). Non-optimal photosynthesis causes low soybean potassium uptake. The interaction between potassium and other nutrients, such as nitrogen and phosphorus, also affects potassium uptake by soybeans (Dotaniya et al., 2016). In addition, some soybean varieties may have different sensitivities to potassium availability in the soil.

A study by Batista et al. showed that while potassium application at planting could affect plant height, it did not significantly affect overall potassium uptake or yield in soybean plants compared to the control group (Batista et al., 2020). This finding suggests that the timing and method of potassium application may not be as important as previously thought, especially in soils with sufficient potassium levels. Similarly, Oliveira et al. reported that although potassium fertilization generally increases yield components, the specific effects on potassium uptake may vary depending on cultivar and environmental conditions (Oliveira et al., 2022) (Table 3).

CONCLUSIONS

This study showed that groundnut green manure (P4) supported soybean growth and nutrient uptake efficiency in pine-based agroforestry systems. Groundnut green manure (P4) increased the number of leaves (19.40 strands), specific leaf area (82.76 cm^2/g), root length (16.64 cm) and number of nodules (4.60 pieces), and produced the highest nitrogen and potassium uptake of 12.45 mg and 5.02 mg, respectively. Corn cob fertilizer (P3) was also effective in increasing leaf

Table 3. Soybean nutrient uptake in agroforestry systems

Treatment	Nitrogen uptake (mg)	Phosphorus uptake (mg)	Potassium uptake (mg)
P1	7.57a	2.14	4.31
P2	11.18b	2.59	4.53
P3	10.77b	2.72	4.51
P4	12.45b	2.53	5.02

Note: P1: (Inorganic fertilizer); P2: (Natural dye extraction waste fertilizer); P3: (Corn cob fertilizer); P4: (Groundnut green fertilizer); numbers followed by the same letter in the same column are not significant based on DMRT ($\alpha = 0.05$).

area (124.81 cm^2) and phosphorus uptake (2.72 mg). Otherwise, inorganic fertilizer (P1) showed the lowest results, confirming its limitations in the agroforestry system. These results prove that groundnut green manure and other organic fertilizers significantly increase soybean productivity and contribute to the sustainability of pine-based agroforestry. Thus, the research objective of evaluating the effectiveness of organic fertilizers on leaf morphology, root performance, and nutrient uptake of soybeans was successfully achieved.

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