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The synergistic effects of vermicompost and mycorrhiza on the growth and yield of glutinous maize (*Zea mays ceratina* L) and soil fertility

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Abstract: Indonesia has experienced a decline in corn production, so it is necessary to take steps to increase production. Strategic steps that can be taken include utilizing vermicompost and mycorrhiza. The research aimed to analyze the synergistic effects of vermicompost and mycorrhiza on the growth and yield of glutinous maize, as well as their impact on soil fertility. The research was conducted as a factorial experiment using a Randomized Block Design with three replications. The first factor examined was the dose of vermicompost, with amounts set at 0, 10, 20, 30, and 40 t ha^{-1}. The second factor was the dose of mycorrhiza, using 0, 0.35, 0.70, and 1.05 t ha^{-1}. The observed variables included plant height, stem diameter, number of leaves, leaf area, the timing of male and female flower appear, number of cob, cob length, cob diameter, cob weight, the number of seeds per cob, and the N total, P_2O_5 total, K_2O total as well as the number of mycorrhiza spores. The results indicated that applying 40 t ha^{-1} of vermicompost in combination with 1.05 t ha^{-1} of mycorrhiza led to significant increases in several growth and yield parameters. Specifically, stem diameter increased by 71.4%, leaf area by 28.1%, cob length by 62.2%, cob diameter by 76.8%, and cob weight by 110.5%. Additionally, the soil's phosphorus pentoxide (P_2O_5) content increased by 54.2 ppm, and the number of mycorrhiza spores rose by 35.7 ppm.

Keywords: vermicompost, mycorrhiza, organic fertilizer, maize.

Introduction

Maize is one of the most widely grown cereal crops in the world, and this includes Indonesia. In 2021, global maize production was over 1,200 million tons (Djalovic *et al.*, 2024). However, in Indonesia, maize production in 2023 dropped to 14.46 million tons from 16.53 million tons in 2022 (Central Bureau of Statistics, 2023). This decrease has led the government to take steps to increase production through both intensification and extensification. These actions aim to support the agricultural ecosystem and improve national food security. The government also wants to meet export market demands, especially as other maize-exporting countries are imposing export limits, which have driven up global maize prices. In 2022, the international maize price reached USD 348 per ton (Moegiarso, 2022).

Many studies aim to improve maize production by focusing on two methods: using vermicompost and mycorrhiza. Vermicompost is a natural organic fertilizer (Aritonang and Sidauruk, 2020). It is rich in nutrients and helps improve the soil's physical, chemical, and biological qualities (Nahar *et al.*, 2021). This type of fertilizer also increases the soil's ability to hold water (Mahmoud and Gad, 2020). Mycorrhiza is a type of fungus that helps plants take in nutrients. It forms networks of threads, called hyphae, in the soil (Fall *et al.*, 2022). This process boosts the plants' absorption of nitrogen, phosphorus, and potassium (Anderson *et al.*, 2018).

Aslam and Ahmad (2020) found that using a mix of vermicompost and inorganic fertilizers (like nitrogen and phosphorus) significantly boosts maize growth and yield. Abera *et al.* (2019) showed that vermicompost can improve maize seed production. Kevin *et al.* (2021) reported that vermicompost speeds up the appearance of male flowers, helps absorb nitrogen, and increases maize seed yields. Thakur *et al.* (2021) noted that vermicompost can raise plant biomass by 7.7% and increase maize seed yields by 18.35%. Purnawanto and Ahadiyat (2022) added that vermicompost not only raises maize yields but also improves the protein content in maize seeds.

Regarding mycorrhiza use in maize plants, Suherman *et al.* (2023) found that applying 0.7 t ha^{-1} can boost the length, diameter, and weight of maize cobs. Cahyani *et al.* (2023) reported that mycorrhiza promotes maize plant growth and phosphorus absorption. Hazra *et al.* (2022) confirmed that mycorrhiza enhances growth and increases phosphorus availability in soil. Rustikawati *et al.* (2022) indicated that using up to 1.05 t ha^{-1} of mycorrhiza can significantly boost the stem diameter and root weight of maize plants.

These studies suggest that both vermicompost and mycorrhiza are effective organic fertilizers that enhance maize growth and production. However, there has not yet been an investigation into their combined use to further improve maize growth and yield. Benaffari *et al.* (2022) stated that adding both vermicompost and mycorrhiza can enhance plant growth by improving photosynthesis and nutrient absorption. This combination increases dissolved sugars, protein levels, and antioxidant activity in leaves and roots. Therefore, it is important to study the effects of vermicompost and mycorrhiza on maize production in Indonesia.

Results

Plant height, stem diameter, number of leaves, leaf area, and the time flowers appear

The use of vermicompost and mycorrhizae did not have a significant effect on the height of corn (*Zea mays* L.), although there was a noticeable trend towards an increase in the treatment that combined 20 t ha^{-1} of vermicompost with 0.7 t ha^{-1} of mycorrhiza. The response in stem diameter was markedly different, with the control group (0 t ha^{-1} of vermicompost, 0 t ha^{-1} of mycorrhiza) showing the smallest stem diameter at 20.2 mm, while the treatment involving 20 t ha^{-1} of vermicompost and 1.05 t ha^{-1} of mycorrhiza resulted in the largest stem diameter at 23.8 mm, yielding a 17.8% increase compared to the control. There were no significant differences in the number of leaves per plant among the treatments. However, a notable variation in leaf area was observed. The treatment with 20 t ha^{-1} of vermicompost without mycorrhiza (3179.8 cm^2) and with 1.05 t ha^{-1} of mycorrhiza (3133.1 cm^2) produced significantly larger leaf areas compared to the control (2464.4 cm^2). The application of 20 t ha^{-1} of vermicompost resulted in a 27–29% increase in leaf area when compared to no vermicompost application. In addition, the application of vermicompost and mycorrhizae did not significantly affect the timing of male and female flower emergence (Table 2).

Number, length, diameter, weight of cobs, and number of seeds per cob

Regarding crop yield components, there were no significant differences in the number of cobs per plant among the treatments. Conversely, cob length displayed a significant increase. The combination of 40 t ha^{-1} of vermicompost and 1.05 t ha^{-1} of mycorrhiza produced a cob length of 30.0 cm, which differed significantly from the control (18.8 cm), marking a 59.6% increase. The cob diameter also showed a significant increase, rising from 36.6 mm in the control to 64.7 mm in the treatment with 40 t ha^{-1} of vermicompost and 1.05 t ha^{-1} of mycorrhiza, reflecting a 76.8% increase. Cob weight more than doubled, increasing from 273.7 g in the control to 576.0 g in the most effective treatment, indicating an increase of 110.5%. Similarly, the number of seeds per cob rose notably, from 146.0 seeds in the control to 467.9 seeds per cob in the treatment of 40 t ha^{-1} of vermicompost and 1.05 t ha^{-1} of mycorrhiza, representing a 220.5% increase (Table 3).

Nitrogen, phosphorus, potassium content, and mycorrhiza population

The evaluation of the chemical and biological properties of the soil revealed that the application of vermicompost and mycorrhizae did not have a significant effect on the total nitrogen content in the soil. Nonetheless, there was a considerable increase in phosphate (P_2O_5) availability. The treatment of 40 t ha^{-1} of vermicompost combined with 1.05 t ha^{-1} of mycorrhiza per plant resulted in a P_2O_5 value of 62.2 ppm, compared to just 8.0 ppm in the control, indicating a 54.2 ppm increase. The total potassium (K_2O) content also experienced a significant rise, from 0.057% in the control to 0.093% in the most effective treatment, marking an increase of 63.2%. Additionally, there was a substantial increase in the population of mycorrhiza spores. The treatment of 40 t ha^{-1} of vermicompost with 1.05 t ha^{-1} of mycorrhiza led to a spore population of 44.7 spores per 20 g of soil, which was nearly a 400% increase relative to the control (9.0 spores per 20 g of soil) (Table 4). These results imply that the combined application of high doses of vermicompost and mycorrhiza inoculation enhanced nutrient availability and soil biological activity, thereby contributing to improved growth and yield of maize plants.

Discussion

The results of this study indicate that vermicompost application significantly increases the availability of macronutrients in the soil, such as nitrogen, phosphorus, and potassium, which have a positive impact on plant growth, especially in increasing stem diameter. This finding is in line with the report of Dreslova (2023), which states that vermicompost functions as the main source of nutrients in supporting plant vegetative growth. In addition, the provision of mycorrhiza fungal inoculum contributes to improving the efficiency of nutrient absorption, especially phosphorus and micronutrients, through a symbiotic relationship with plant roots. These results support the findings of Bolou-Bi *et al.* (2023) and Sarathambal *et al.* (2024), which emphasize the importance of the role of mycorrhizae in increasing the availability of essential nutrients for plants.

The combination of vermicompost and mycorrhiza fungi produced a stronger synergistic effect than a single application, as reflected in the greater increase in stem diameter. This synergy is most likely due to the dual role of vermicompost as a source of nutrients and a stimulant of mycorrhiza activity, as stated by Tütüncü (2024). In addition, the presence of growth hormones such as auxins and cytokinins in vermicompost (Al-Rawi and Alkobaisy, 2023; Toor *et al.*, 2024), as well as the production of phytohormones by mycorrhiza fungi (Benaffari *et al.*, 2022), contributes to the regulation of cell division and elongation processes, which physiologically support stem diameter growth. Overall, these results indicate that the integration of vermicompost and mycorrhiza fungi is an effective strategy to enhance plant vegetative growth, especially in the context of increasing stem diameter. The combination of vermicompost and mycorrhiza significantly increases the availability and absorption of key nutrients, such as phosphorus, nitrogen, and potassium, which are known to play an important role in leaf development (Atakli *et al.*, 2022). This finding is in line with previous studies showing that mycorrhiza increases the surface area of plant roots, thereby increasing the capacity for nutrient absorption (Bolou-Bi *et al.*, 2023; Xue *et al.*, 2022). The combination of vermicompost and mycorrhiza also has implications for increasing the rate of photosynthesis and stomatal conductance of plants, which leads to increased biomass accumulation (Sarathambal *et al.*, 2024). The role of vermicompost in increasing photosynthetic activity is thought to be related to the presence of plant growth regulator compounds such as humic acid and hormone-like substances that can stimulate plant metabolism. Overall, the interaction between vermicompost and mycorrhiza offers an effective approach to increasing plant leaf growth through a multifactorial mechanism involving increased nutrient uptake, soil improvement, and stimulation of plant physiological processes. The results of this study indicate that the simultaneous use of vermicompost and mycorrhiza has a significant effect on increasing corn cob growth parameters, including length, diameter, weight, and number of seeds. This increase can be attributed to improved soil conditions and increased availability of essential nutrients such as nitrogen, phosphorus, and potassium.

Table 1. Preliminary chemical and biological properties of soil and vermicompost (before planting).

Sampel	N (%)	P_2O_5 (%)	K_2O (%)	Mycorrhiza spore (in 20 g of soil)
Vermicompost	2.37	0.67	3.06	-
Soil	0.18	0.27	0.10	8
Mycorrhiza	-	-	-	19

Table 2. Effect of vermicompost and mycorrhiza on maize growth components.

Vermicompost Dose (t ha^{-1})	Mycorrhiza Dose (t ha^{-1})	Plant Height (cm)	Stem Diameter (mm)	Number of Leaves	Leaf Area (cm^2)	Time Male Flowers Appear*	Time Female Flowers Appear*
0	0	50.6^{a}	20.2^{b}	9.5^{a}	2464.4^{d}	40.7^{a}	48.9^{a}
	0.35	49.8^{a}	21.8^{ba}	9.4^{a}	2800.0^{dcba}	40.0^{a}	46.8^{a}
	0.70	50.9^{a}	22.1^{ba}	10.3^{a}	3076.1^{ba}	40.8^{a}	47.9^{a}
	1.05	50.4^{a}	22.1^{ba}	10.1^{a}	3023.8^{cba}	40.9^{a}	48.3^{a}
10	0	49.2^{a}	22.6^{ba}	9.9^{a}	2905.9^{cba}	40.6^{a}	47.5^{a}
	0.35	51.1^{a}	22.5^{ba}	9.9^{a}	2824.8^{dcba}	40.1^{a}	46.6^{a}
	0.70	51.2^{a}	22.8^{ba}	9.9^{a}	2670.6^{dcb}	40.9^{a}	47.1^{a}
	1.05	52.6^{a}	22.0^{ba}	9.2^{a}	3015.0^{cba}	39.8^{a}	46.9^{a}
20	0	52.2^{a}	22.6^{ba}	10.4^{a}	3179.8^{a}	42.1^{a}	48.7^{a}
	0.35	51.0^{a}	21.7^{ba}	10.3^{a}	3133.1^{a}	40.5^{a}	46.4^{a}
	0.70	56.2^{a}	22.1^{ba}	10.1^{a}	2848.4^{dcba}	39.1^{a}	48.6^{a}
	1.05	53.0^{a}	23.8^{a}	10.2^{a}	2621.0^{dc}	41.6^{a}	47.9^{a}
30	0	54.2^{a}	23.2^{ba}	9.9^{a}	2668.0^{dcb}	41.4^{a}	48.9^{a}
	0.35	54.3^{a}	21.8^{ba}	10.1^{a}	2854.0^{dcba}	40.3^{a}	47.1^{a}
	0.70	53.8^{a}	21.7^{ba}	9.8^{a}	2853.3^{dcba}	39.6^{a}	47.1^{a}
	1.05	54.2^{a}	22.7^{ba}	10.0^{a}	2881.2^{dcba}	39.0^{a}	46.2^{a}
40	0	54.8^{a}	23.0^{ba}	10.2^{a}	2860.2^{dcba}	42.1^{a}	49.2^{a}
	0.35	52.1^{a}	21.9^{ba}	9.7^{a}	2896.5^{dcba}	41.6^{a}	47.7^{a}
	0.70	50.9^{a}	23.2^{ba}	10.3^{a}	3011.5^{cba}	39.2^{a}	47.9^{a}
	1.05	52.4^{a}	23.7^{a}	10.4^{a}	3156.2^{a}	42.1^{a}	48.2^{a}

Means followed by the same letter do not differ from each other according to the Duncan Multiple Range Test at 5% probability. *days after planting.

Table 3. Effect of vermicompost and mycorrhiza on maize yield components.

Vermicompost Dose (t ha^{-1})	Mycorrhiza Dose (t ha^{-1})	Number of Cobs	Length of Cobs (cm)	Diameter of Cobs (mm)	Weight of Cobs (g)	Number of Seeds per Cob
0	0	1.3^{a}	18.8^{b}	36.6^{b}	273.7^{d}	146.0^{b}
	0.35	2.4^{a}	19.1^{b}	39.4^{ba}	291.6^{d}	151.0^{b}
	0.70	2.4^{a}	19.6^{b}	39.7^{ba}	410.0^{dcba}	159.9^{b}
	1.05	2.5^{a}	21.4^{ba}	39.5^{ba}	541.1^{ba}	174.4^{b}
10	0	1.6^{a}	19.3^{b}	44.5^{ba}	297.7^{dc}	181.0^{b}
	0.35	1.8^{a}	19.3^{b}	45.9^{ba}	384.0^{dcba}	188.0^{b}
	0.70	2.0^{a}	20.3^{b}	46.1^{ba}	414.8^{dcba}	198.0^{b}
	1.05	2.1^{a}	21.0^{ba}	48.8^{ba}	421.8^{dcba}	198.6^{b}
20	0	1.6^{a}	20.3^{b}	41.7^{ba}	299.3^{dc}	202.4^{b}
	0.35	1.8^{a}	20.6^{b}	40.2^{ba}	402.2^{dcba}	215.1^{b}
	0.70	2.3^{a}	21.1^{ba}	48.3^{ba}	436.5^{dcba}	219.3^{b}
	1.05	2.3^{a}	23.0^{ba}	40.9^{ba}	544.1^{ba}	220.1^{b}
30	0	1.7^{a}	19.1^{b}	43.5^{ba}	331.3^{dcb}	238.8^{ba}
	0.35	1.7^{a}	21.3^{ba}	41.4^{ba}	359.3^{dcba}	241.5^{ba}
	0.70	2.4^{a}	21.6^{ba}	46.7^{ba}	418.6^{dcba}	243.9^{ba}
	1.05	2.4^{a}	22.1^{ba}	43.6^{ba}	500.5^{dcba}	265.8^{ba}
40	0	1.8^{a}	20.8^{ba}	37.1^{b}	312.1^{dcb}	266.2^{ba}
	0.35	1.9^{a}	20.9^{ba}	39.6^{ba}	414.4^{dcba}	276.1^{ba}
	0.70	2.6^{a}	22.2^{ba}	37.2^{b}	528.1^{cba}	317.6^{ba}
	1.05	2.9^{a}	30.0^{a}	64.7^{a}	576.0^{a}	467.9^{a}

Means followed by the same letter do not differ from each other according to the Duncan Multiple Range Test at 5% probability.

Table 4. Effect of vermicompost and mycorrhiza on the chemical and biological properties of the soil.

Vermicompost Dose (t ha^{-1})	Mycorrhiza Dose (t ha^{-1})	N total (%)	P_2O_5 available (ppm)	K_2O total (%)	Mycorrhiza Population*
0	0	0.18^{a}	8.00^{f}	0.057^{gf}	9.0^{d}
	0.35	0.17^{a}	10.10^{f}	0.057^{gf}	23.0^{c}
	0.70	0.18^{a}	9.80^{f}	0.053^{g}	35.3^{b}
	1.05	0.25^{a}	10.60^{f}	0.060^{gfe}	45.0^{a}
10	0	0.22^{a}	14.30^{fed}	0.060^{gfe}	7.3^{d}
	0.35	0.19^{a}	12.80^{fe}	0.063^{fed}	24.0^{c}
	0.70	0.20^{a}	13.90^{fed}	0.060^{gfe}	34.0^{b}
	1.05	0.22^{a}	15.50^{fed}	0.067^{ed}	43.0^{a}
20	0	0.19^{a}	17.80^{fedc}	0.077^{cb}	13.0^{d}
	0.35	0.22^{a}	29.40^{edcb}	0.077^{cb}	23.7^{c}
	0.70	0.26^{a}	22.40^{fedcb}	0.070^{dc}	32.3^{b}
	1.05	0.23^{a}	26.30^{fedcb}	0.077^{cb}	43.3^{a}
30	0	0.22^{a}	18.00^{fedc}	0.070^{dc}	7.7^{d}
	0.35	0.28^{a}	22.50^{fedcb}	0.080^{b}	21.3^{c}
	0.70	0.21^{a}	22.00^{fedcb}	0.077^{cb}	35.0^{b}
	1.05	0.19^{a}	32.20^{dcb}	0.080^{b}	43.7^{a}
40	0	0.24^{a}	35.40^{cb}	0.077^{cb}	9.0^{d}
	0.35	0.19^{a}	38.30^{b}	0.083^{b}	24.7^{c}
	0.70	0.27^{a}	39.00^{b}	0.080^{b}	34.0^{b}
	1.05	0.23^{a}	62.20^{a}	0.093^{a}	44.7^{a}

Means followed by the same letter do not differ from each other according to the Duncan Multiple Range Test at 5% probability. *Spore number in 20 g of soil.

The application of vermicompost not only improves soil structure and increases water retention, but also increases soil microbial activity, which cumulatively contributes to better root growth and higher nutrient uptake (Syarifinnur *et al.*, 2022; Younas *et al.*, 2021).

In addition to improving soil conditions, vermicompost also plays a role in increasing the efficiency of plant photosynthesis. The increase in chlorophyll content and electron transport rate observed in plants receiving vermicompost (Younas *et al.*, 2021) has direct implications for increasing reproductive biomass, including cob length and seed weight. Mycorrhiza fungi also play an important role through the formation of external hyphal networks that increase the ability of plant roots to absorb phosphorus and other micronutrients, which are vital in the process of seed formation and filling (Karami *et al.*, 2018; Mobasser *et al.*, 2012). The combined application of vermicompost and mycorrhizae provides a synergistic effect, resulting in greater increases in grain yield and cob weight compared to single treatments, as reported by Atakli *et al.* (2022).

Application of vermicompost and mycorrhiza significantly increased the content of phosphorus (P) and potassium (K) in the soil. This increase was mainly due to the synergistic effect between improving soil conditions and increasing microbiological activities that support mineralization and mobilization of nutrients. Vermicompost improves soil structure, enriches organic matter content, and increases the population of microorganisms, including phosphate-solubilizing bacteria and potassium-solubilizing microbes, which accelerate the release of P and K from bound forms to available forms (Bellitürk *et al.*, 2017; Hussain *et al.*, 2018).

Increasing the dose of vermicompost correlated with an increase in P and K content, supporting previous findings that vermicompost is effective in increasing nutrient availability in the soil (Bellitürk *et al.*, 2017). In addition, the decrease in soil pH due to vermicompost application is thought to accelerate the dissolution of phosphate and potassium compounds that were previously unavailable (Hussain *et al.*, 2018). Mycorrhiza fungi contribute through the secretion of organic acids and phosphatase enzymes that dissolve unavailable P and K, expand the root exploration zone through the hyphal network, and increase nutrient uptake by plants. Increased mycorrhiza colonization, supported by soil conditions resulting from vermicompost application, also strengthens the increase in P and K availability in the rhizosphere zone. The combination of vermicompost and mycorrhizae also plays a role in stabilizing nutrient ions in the soil, reducing losses due to immobilization and leaching, thus maintaining the availability of P and K in the long term. Thus, the integrated use of vermicompost and mycorrhizae is a sustainable strategy to increase soil fertility and fertilizer efficiency.

Materials and Methods

Field experiment

The research was conducted in Karangsoka Village, Kembaran District, Banyumas Regency, with Andisol. The initial content of nitrogen, phosphorus, potassium, and mycorrhizal spores in Andisol (before planting) is listed in Table 1. The research was a factorial experiment arranged based on a Randomized Block Design with three replications, and each treatment consisted of five sample plants. The first factor was the dose of vermicompost, consisting of 0, 10, 20, 30, and 40 t ha^{-1}. The second factor, the dose of mycorrhiza, consisted of 0, 0.35, 0.70, and 1.05 t ha^{-1}.

Conducting of study and experimental design

Composite soil samples were taken randomly at a depth of 0-20 cm. Furthermore, the soil was air-dried and sieved with a size of 2 mm. After that, the sieved soil was put into polybags, as much as 15 kgs, and added with vermicompost and mycorrhiza according to the treatment, then mixed evenly. Preliminary chemical and biological properties of vermicompost and mycorrhiza are listed in Table 1. The planting medium, in the form of a mixture of soil, vermicompost, and, was then watered to field capacity. Corn seeds were planted with a planting depth of about 5 cm, and each planting hole was filled with two seeds and then covered with soil. After growing, thinning was carried out by leaving one healthy plant per planting hole. Nitrogen fertilizer of 0.092 t ha^{-1} was given at the ages of 7 and 30 days after planting, each ½ dose. Potassium fertilizer of 0.06 t ha^{-1} was given at the age of 7 days after planting. While phosphorus fertilizer of 0.036 t ha^{-1} was given one week before planting. Nitrogen and potassium fertilizers were buried into the soil to a depth of 7-10 cm at a distance of about 15 cm from the plant, while phosphorus fertilizer was mixed evenly.

Data collecting

Observations included a) morphological characteristics of corn, including plant height, stem diameter, number of leaves, leaf area, and the emergence of male and female flowers; b) components of yield, observed at the end of the experiment including cob length, cob diameter, cob weight, and number of seeds per cob. Harvesting was carried out when the plants reached physiological maturity, namely when the age was ± 90 days after planting, with the criteria that the husks were dry and hard.

This study evaluated the concentrations of nitrogen (N), phosphorus (P), and potassium (K) in soils cultivated with corn. The abundance of mycorrhiza spores was also quantified. Furthermore, corn growth and yield parameters were assessed. Data were analyzed using analysis of variance (ANOVA) at a 5% significance level. When significant differences were detected, means were further compared using Duncan's Multiple Range Test (DMRT) at a 5% significance level.

Conclusion

The provision of vermicompost as much as 40 t ha^{-1} accompanied by mycorrhiza 1.05 t ha^{-1}, can increase the stem diameter, leaf area, cob length, cob diameter, and cob weight by 71.4%, 28.1%, 62.2%, 76.8% and 110.5% respectively. The soil P_2O_5 content also increased by 54.2 ppm, while the number of mycorrhiza spores increased by 35.7 ppm. The results of this experiment indicate that vermicompost mixed with mycorrhiza should be used to increase corn production while maintaining sustainable agriculture.

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