Glosains: Jurnal Sains Global Indonesia
Volume 7, Issue 2, 468-475
e_ISSN: 2798-4311
https://glosains.staiku.ac.id
DOI: doi.org/10.59784/glosains.v7i2.701

Optimizing Nitrogen-Based Chemical Fertilizer Efficiency Through Microbial Organic Fertilizer (MOF) Integration for Sustainable Oryza sativa Productivity in Rainfed Lowland Fields

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Article Info :
Article history:
Received: March 14th, 2026
Revised: May 02nd, 2026
Accepted: May 08th, 2026

Keywords:
combination of fertilization; efficiency nitrogen-based chemical fertilizers; organic microbial fertilizer (MOF); oryza sativa

Abstract

Background: This study determines the best combination of nitrogen fertilizers and MOF (Microbial Organic Fertilizer) to sustainably increase rice productivity in rainfed lowland regions while minimizing N loss and improving soil health. Excessive application of nitrogen fertilizer contributes to soil degradation; however, MOF can help enhance nutrient uptake efficiency and reduce chemical dependency in rainfed agricultural areas due to its derivation from agricultural waste materials.
Objective: To identify the nitrogen fertilization and MOF combination that maximizes *Oryza sativa* yield in rainfed lowlands while reducing chemical fertilizer use. Specifically, this research aimed to determine the ideal combination ratio of NPK Phonska and mycorrhizae that yields the highest productivity while maintaining an adequate Nitrogen Use Efficiency (NUE).
Method: A Randomized Complete Block Design (RCBD) with 25 treatment combinations was conducted in Jember, East Java, Indonesia, as follows: NPK (0–100%) and MOF (0–100%) at three replications. Statistical analysis was performed using ANOVA and DMRT (5%).
Results: The combination of 100% NPK and 50–100% MOF showed a significant increase in yield, with the highest yield recorded at 100% NPK and 25% MOF (9,545 kg/ha). The 25% MOF and 75% NPK combination yielded 5,462.5 kg/ha, representing a 25% reduction in fertilizer application without a significant decrease in yield ($p < 0.05$).
Conclusion: The use of 25% MOF combined with 100% nitrogen fertilizer is beneficial for optimizing productivity, decreasing chemical fertilizer use, and promoting sustainable rainfed rice production.

To cite this article: Lestari, B. L., Karyanti, Salma, S., & Hariyanto, D. N. (2026). Optimizing Nitrogen-Based Chemical Fertilizer Efficiency Through Microbial Organic Fertilizer (MOF) Integration for Sustainable Oryza sativa Productivity in Rainfed Lowland Fields. *Glosains: Jurnal Sains Global Indonesia*, *7*(2), 468-475. https://doi.org/10.59784/glosains.v7i2.701

INTRODUCTION

Fertilization is one of the essential factors to increase the productivity of Oryza sativa. Nitrogen-based chemical fertilizers are a type of synthetic fertilizer that is widely used as a source of nutrients in Oryza sativa cultivation. Excessive use of nitrogen-based chemical fertilizers can lead to soil degradation and lower soil fertility levels. Nitrogen pollution can threaten biodiversity loss in soil and water, heavy metal toxicity, and production slowdown (Lan et al., 2020; Tyagi et al., 2022). Continuous damage to soil ecosystems results in a decrease in soil fertility and productivity (Abioye et al., 2024; Chaudhary et al., 2022).

Organic fertilizers improve the soil's physical properties, chemical content, and biological properties. Incorporating organic fertilizers with chemical fertilizers can reduce soil degradation. Organic fertilizers maintain soil aggregates, increase cation exchange capacity, and are efficient in nutrient use; thus, the soil fertility rate is increased. Microbial organic fertilizer (MOF) is a type of organic fertilizer derived from local resources, such as banana peels and pseudostems, Gliricidia leaves and leachate, and other agricultural waste residues, containing a variety of microorganisms that contribute to the nutrient cycle. This organic fertilizer significantly increases soil nitrogen and phosphorus, improving plant growth and yield (Laekemariam et al., 2024; Y. Liu et al., 2024). Yang et al. (2021) state that a configuration of 70% inorganic nitrogen (GM2) and 30% organic nitrogen can increase grain yields by 10.36% and 15.48%, respectively, in main rice and ratoon crops, compared to conventional chemical fertilizer (CF) treatment.

Combining NPK Phonska fertilizer with MOF has significantly increased rice plants' productivity in rainfed rice fields. Research shows that incorporating these fertilizers can increase plant productivity through increased nutrient absorption and efficiency of inorganic fertilizer use by plant roots. Applying microbial organic fertilizers can optimize the absorption and utilization of nutrients, thereby substantially improving plant growth and development while reducing the dose of inorganic fertilizers. Continuous damage to soil ecosystems can result in soil degradation and lower soil fertility, which must be avoided in sustainable agricultural systems. Therefore, the efficiency of nitrogen use and the reduction of environmental risks must be considered. For this reason, chemical fertilization must be accompanied by organic fertilizers. Adding liquid organic fertilizer derived from leachate combined with chemical fertilizers can increase plant growth (Hapsoh et al., 2023; Q. Liu et al., 2021).

The strategy of using chemical fertilizers combined with organic fertilizers in the correct ratio is essential to be developed so that soil fertility increases and environmental sustainability is maintained (Yang et al., 2021). Applying organic fertilizers increases soil fertility by improving the physical properties of soil, soil chemical content, and soil biological properties. Microbial organic fertilizers (MOFs) such as Bacillus sp. improve soil aggregates, so that nutrient availability increases and plants become more resistant to disease. The use of organic fertilizers improves the physical properties of the soil by increasing soil porosity, resulting in improved aeration and drainage, so that root growth and nutrient uptake are enhanced. Nutrient content in organic fertilizers is generally still low and more variable than that of synthetic chemical fertilizers, so they may not meet the nutritional needs of plants and cannot independently increase plant productivity (Karmakar et al., 2020). For this reason, plants need additional nutrients that can be directly utilized by adding chemical fertilizers; combining organic fertilizers and inorganic chemical fertilizers can be an alternative approach to increasing soil fertility and plant productivity.

The optimal combination of fertilizers to increase the productivity of rice plants is not widely known. From several studies, it has been proven that MOF can improve soil fertility and health. The combination of inorganic fertilizers and microbial organic fertilizers, as well as biochar and phosphate-solubilizing bacteria, can increase organic carbon, so this combination can be used as an alternative to increase nutrient absorption efficiency and reduce environmental pollution (Samreen et al., 2025; Yuan et al., 2025). Combining organic and inorganic fertilizers can improve rice yield and nitrogen use efficiency (NUE). A 20–50% chemical nitrogen fertilizer combined with organic fertilizer derived from food waste has been shown to maintain or even increase rice yield while increasing soil organic matter and microbial activity.

Applying organic fertilizers derived from food waste combined with chemical fertilizers can reduce the dose of chemical nitrogen by 25–50% (Li et al., 2022). Organic fertilizer applications can improve soil fertility through increased microbial biomass, soil organic carbon (SOC), and enzyme activity in the long term, making them ideal for environmentally friendly and sustainable agricultural systems (Fathi & Najafian, 2020). Combining chemical fertilizer with microbial organic fertilizer is very beneficial for increasing productivity and, at the same time, improving soil fertility. The ratio between the dosage of inorganic chemical fertilizers and organic fertilizers is critical because it affects the outcome caused by the optimal dosage of the fertilizer combination, which is not widely known. The optimal dose of the combination of NPK Phonska fertilizer with MOF remains a challenge for the development of rice cultivation in rainfed lowland fields.

Low soil fertility and lack of irrigation are significant challenges. The long-term use of organic fertilizers is expected to increase soil fertility through expanding the content of organic matter, carbon, and nitrogen-fixing bacteria such as Proteobacteria and Chloroflexi; on the other hand, the growth of fungi such as Talaromyces that interfere with plant growth can be inhibited due to the interaction of organic fertilizers (Hapsoh et al., 2023; Li et al., 2022; Y. Liu et al., 2021).

The use of microbial organic fertilizers can reduce dependence on chemical fertilizers, thereby reducing soil degradation and environmental pollution (Niu et al., 2024; Shao et al., 2023). Utilizing agricultural waste as organic fertilizer can promote the efficiency of inorganic chemical fertilizers, which can increase productivity without causing environmental damage (Lesik et al., 2019). When other beneficial nutrients are added to this fertilizer combination, organic fertilizers serve as a suitable alternative to chemical fertilizers that support plant growth and production while being safe for the environment.

Finally, the efficiency of NPK Phonska fertilizer can be achieved by adding organic fertilizer to rice fertilization management in rainfed lowland fields to increase plant productivity while simultaneously reducing the adverse effects of chemical fertilizer use and lowering soil degradation rates (Pahalvi et al., 2021). Fertilizer use efficiency is a measure of how effectively the applied fertilizer dosage enhances the absorption and utilization of nutrients within the soil ecosystem. Fertilizer efficiency can be achieved when the root ecosystem comprising soil porosity, aeration, water retention, and soil biology is well maintained and conducive to plant growth. Currently, the ratio of fertilizer combinations is not widely known, especially in the cultivation of rainfed rice crops; with the proper ratio, the efficiency of chemical fertilizer use through nutrient absorption in the available soil ecosystem can increase plant productivity while reducing the rate of soil degradation, thereby supporting sustainable agriculture.

This study aims to determine the optimal efficiency level and combination ratio of nitrogen-based chemical fertilizer dosage with MOF to increase rice plants' productivity in Indonesia's rainfed lowland fields. Specifically, this study tests whether locally derived MOF can reduce chemical nitrogen dependency by 25% without compromising Oryza sativa yield, addressing a critical knowledge gap in rainfed lowland fertilization management in Indonesia. Unlike previous studies focusing on either inorganic NPK or organic amendments separately, or using a single-factor RCBD, this study uniquely employs a factorial RCBD (5×5 = 25 treatment combinations) with locally sourced MOF derived from agricultural waste (Gliricidia, banana pseudostem, coconut coir, neem, cow urine, and leachate) to establish an optimal NPK:MOF ratio for rainfed rice in Indonesia. This contributes a novel, evidence-based framework for reducing chemical fertilizer dependency while maintaining or improving Oryza sativa yield under rainfed conditions.

METHOD

This research was conducted in Jember District, East Java, Indonesia (coordinates: 8°11′S, 113°42′E; altitude: ±89 m asl; annual rainfall: ±1,800 mm; soil type: clay-loam Inceptisol; soil pH: 5.8; organic matter: 1.9%). The materials used were Sintanur variety rice, NPK Phonska (recommended dose: 300 kg/ha, applied at 7 and 30 days after planting [DAP]), and Microbial Organic Fertilizer (MOF) made from Gliricidia leaves, banana pseudostem, coconut coir, neem, cow urine, leachate, coconut water, and brown sugar (recommended dose: 2,000 L/ha, applied at 7, 21, and 42 DAP; each experimental plot measured 4 m × 5 m = 20 m^2). The study employed a factorial Randomized Complete Block Design (RCBD) consisting of two factors and three replicates. The first factor was nitrogen-based chemical fertilizer, NPK Phonska (K), consisting of five levels, each applied according to the treatment, namely: K0 = Control (without NPK Phonska); K1 = NPK Phonska 25%; K2 = NPK Phonska 50%; K3 = NPK Phonska 75%; K4 = NPK Phonska 100%. The second factor was MOF (M), consisting of five levels, namely: M0 = Control (without MOF); M1 = MOF 25%; M2 = MOF 50%; M3 = MOF 75%; M4 = MOF 100%.

Tabel 1. The treatment of each factor was as follows:

M0K0	M0K1	M0K2	M0K3	M0K4
M1K0	M1K1	M1K2	M1K3	M1K4
M2K0	M2K1	M2K2	M2K3	M2K4
M3K0	M3K1	M3K2	M3K3	M3K4
M4K0	M4K1	M4K2	M4K3	M4K4

The observed research variables were:
(1) plant height at 40 HST (days after transplanting);
(2) number of tillers at 40 HST (days after transplanting);
(3) wet weight of grain (g);
(4) dry weight of grain (g);
(5) dry grain production per hectare (kg/ha).

Data analysis was conducted using Analysis of Variance (ANOVA at 5% and 1% significance levels), followed by Duncan's Multiple Range Test at 5% (DMRT 5%) for mean difference testing (Peters et al., 2003).

RESULTS AND DISCUSSION

Results

The results showed that the provision of MOF from 25%–100% was insignificant to the growth and production of *Oryza sativa* in rainfed lowland fields. The increase in MOF application did not have a significant effect on plant productivity. The production under the 100% MOF treatment (M4) only reached 5,142.90 kg ha^{-1} (Table 2).

Table 2. Effect of MOF on Productivity Oryza sativa in rainfed fields

Treatment	Plant height (cm)	Number of saplings	Number of panicles	Wet weight of grain /plot (kg)	Dry weight of grain/plot (kg)	Production /ha (kg)
M0	60,02 *a*	21,93 *a*	20,23 *a*	0.831 *a*	0.582 *a*	4157.32 *a*
M1	61,23 *a*	22,26 *a*	20,89 *a*	0.852 *a*	0.596 *a*	4257.89 *a*
M2	62,96 *a*	22,45 *a*	20,95 *a*	0.924 *a*	0.646 *a*	4618.43 *a*
M3	63,18 *a*	22,97 *a*	21,97 *ab*	0.983 *a*	0.688 *a*	4914.63 *a*
K4-M4	63,57 *a*	23,03 *a*	22,38 *ab*	1.029 *ab*	0.771 *a*	5142.90 *ab*

Note: the number 2 followed by the same letter shows an unreal difference in the Duncan 5% test.

The treatment of NPK Phonska showed that increasing the dose of chemical fertilizer could significantly improve plant growth and production; however, the dose of NPK Phonska at 100% (K4) had no discernible effect on plant height or total tiller number, so that the yield was only 7,134.95 kg per hectare (Table 3). NPK Phonska significantly ($p < 0.05$; $F = 148.3$) increased grain production across all levels compared to the K0 control. K4 (100% NPK) achieved the highest single-factor production of 7,134.95 kg/ha. K4 significantly increased the number of panicles (25.98) and dry grain weight (1.135 kg/plot) compared to K0 (DMRT 5%).

Table 3. Effect of NPK Phonska on productivity Oryza sativa in rainfed fields

Treatment	Plant height (cm)	Number of saplings	Number of panicles	Wet weight of grain /plot (kg)	Dry weight of grain/plot (kg)	Production/ha (kg)
K0	59,21 *a*	21,58 *a*	20,45 *a*	0.820 *a*	0.573 *a*	4098.71 *a*
K1	62,48 *b*	23,71 *b*	21,76 *ab*	1.045 *b*	0.752 *ab*	5226.23 *b*
K2	62,96 *bc*	24,13 *bc*	22,89 *bc*	1.193 *b*	0.895 *b*	5967.08 *c*
K3	63,78 *cd*	26,39 *c*	24,48 *cd*	1.367 *bc*	1.038 *c*	6832.76 *cd*
K4	64,26 *d*	28,65 *d*	25,98 *d*	1.427 *c*	1.135 *d*	7134.95 *d*

Note: the number 2 followed by the same letter shows an unreal difference in the Duncan 5% test.

This production differs significantly from that of NPK Phonska treatments combined with MOF (M2K4, M3K4, M4K4), where yields range from 8,028.5 to 9,545.0 kg per hectare. This productivity continues to increase as the dose of MOF added to NPK Phonska (M2K4, M3K4, M4K4) increases. The growth and production differ significantly from the results obtained with NPK Phonska fertilizer treatment alone. Plant height and the number of panicles increase with the addition of MOF to NPK Phonska. An increase in the dose of NPK Phonska accompanied by an increase in the dose of MOF can improve plant height and total tiller count; productivity increases to reach a yield of 9,545.00 kg per hectare (M4K4). However, this production is not significantly different from the treatment of 75% NPK Phonska fertilizer combined with 100% MOF (M3K4). The complete data are presented in Table 3.

Table 4. Effect of Interaction NPK Phonska and MOF on productivity Oryza sativa in rainfed fields

Treatment	Plant height (cm)	Number of saplings	Number of panicles	Wet weight of grain /plot (kg)	Dry weight of grain/plot (kg)	Production /ha (kg)
M0K0	59,38 a	20,15 a	18,83 a	0.743 a	0.590 a	4215.00 a
MOK1	62,34 ab	21,04 ab	20,97 ab	0.785 ab	0.619 a	4422.50 a
M0K2	65,46 ab	25,67 b	23,38 b	0.962 b	0.673 ab	4489.00 ab
M0K3	67,82 ab	30,18 bc	29,92 c	0.971 bc	0.680 b	4856.50 b
M0K4	71.37 bc	34,02 c	33,87 cd	1.086 c	0.760 b	**5430.00 c**
M1K0	59,61 a	19,54 a	19,39 a	0.747 a	0.592 a	4226.00 a
M1K1	62,74 ab	21,13 ab	21,78 ab	0.889 b	0.622 a	4444.50 b
M1K2	66,86 ab	25,86 b	25,67 bc	0.982 bc	0.680 b	4856.00 bc
M1K3	69,57 bc	31,27 c	30,89 cd	1.093 bc	0.765 b	5462.50 bc
M1K4	73.98 c	34,35 bc	34,98 d	1.133 c	0.793 bc	5663.50 cd
M2K0	60,27 a	19,65 a	20,35 ab	0.814 a	0.523 a	3733.50 a
M2K1	63,23 ab	21,33 ab	23,67 b	0.888 b	0.621 a	4438.00 b
M2K2	67,28 ab	26,26 b	27,89 bcd	0.973 bc	0.681 b	4866.00 bc
M2K3	72,08 bc	32,86 cd	33,78 cd	1.282 c	0.898 c	6411.50 d
M2K4	74.88 cd	34,53 cd	37,45 de	1.606 cd	1.124 cd	**8028.50 e**
M3K0	60,98 a	19,78 a	21,47 ab	0.827 a	0.593 a	4238.00 a
M3K1	63,85 ab	21,47 ab	24,89 b	0.916 bc	0.641 a	4580.05 ab
M3K2	69,62 bc	27,11 b	29,90 cd	0.952 bc	0.666 ab	4758.00 b
M3K3	75,18 cd	35,92 cd	38,78 d	1.979 bc	0.886 b	6897.00 d
M3K4	75.98 d	34,76 cd	39,89 de	1.608 cd	1.125 cd	**8039.00 e**
M4K0	61,07 a	19,86 a	21,89 ab	0.848 a	0.594 a	**4240.50 a**
M4K1	63,74 ab	21,98 ab	25,78 bc	0.889 ab	0.622 a	4445.00 a
M4K2	72,86 bc	28,25 b	30,23 cd	0.975 b	0.682 b	4872.50 bc
M4K3	74,68 cd	34,85 d	39,34 de	1.576 cd	1.103 cd	**7880.50 de**
M4K4	76,25 d	34,93 d	42,76 e	1.909 d	1.336 d	**9545.00 e**

Note: the number 2 followed by the same letter shows an unreal difference in the Duncan 5% test.

Discussion

The results show that the provision of MOF from 25% to 100% was insignificant to the growth and production of Oryza sativa in rainfed land. MOF 100% (M4) production only reached 5,142.90 kg per hectare (Table 1). The lack of influence suggests that the level of nutrients contained in MOF is insufficient for plants, so it cannot effectively increase the growth and production of rice plants. This shows that organic fertilizers cannot match the productivity of chemical fertilizers (Lesik et al., 2019). The treatment of NPK Phonska showed that increasing the dose of chemical fertilizer could significantly ($P < 0.005$) increase plant growth and production; the dose of NPK Phonska at 100% (K4) had no discernible effect on plant height or total tiller number, so that the production was only 7,134.95 kg per hectare (Table 2).

This significant increase in production is accompanied by soil degradation, which over time will decrease soil fertility and cause soil damage (Pahalvi et al., 2021). This production differs markedly from NPK Phonska applied with MOF (M2K4, M3K4, M4K4), where the yield reaches 8,028.5–9,545.0 kg per hectare. Adding 50–100% of the recommended dose of MOF to 100% NPK chemical fertilizer yields the highest production; this shows that organic fertilization is needed in rice cultivation on rainfed land. Adding organic fertilizers increases soil porosity, cation exchange capacity, and plant nutrient absorption, resulting in increased production.

Microbes contained in organic fertilizers play a role in carbon balance during composting; this increase in productivity can be used as an indicator of increasing soil fertility levels and for better management of agricultural production. Yuan et al. also concluded that the use of chemical fertilizers supplemented with straw biochar increases organic carbon, the effect of which is an increase in corn productivity (Yuan et al., 2025).

To determine the optimal dosage of NPK Phonska chemical fertilizer combined with MOF in increasing rice productivity, a comprehensive strategy must consider the balance between organic and chemical fertilizers, soil health, nutrient use efficiency (NUE), and environmental sustainability. The combination of NPK Phonska with MOF significantly increased grain production. The combination of the two fertilizers can increase NUE and provide a nutrient supply by releasing nutrients precisely and slowly. From the results of the F-test, the application of MOF liquid organic fertilizer affected the number of panicles per hill. However, the number of panicles produced in each treatment was not significantly different, which indicates that MOF has the same effect as nitrogen-based chemical fertilizers.

Organic fertilizers, including microbial fertilizers, significantly improve the diversity and structure of soil microbial communities. Organic fertilizers increase the abundance of beneficial microbes such as Firmicutes, Bacillus, and Sphingomonas while reducing harmful bacteria such as Nocardioides and Solidubrobacter (Bhunia et al., 2021). Microbial organic fertilizers (MOF) contain nutrients that can increase total nitrogen, available phosphate, and potassium in the soil (Niu et al., 2024). Microbial organic fertilizers (MOF) derived from local resources such as banana peels and cassava contain various microorganisms that play a role in the nutrient cycling process, allowing MOF to increase plant growth and production.

This study showed that adding 50–100% MOF to 100% NPK Phonska chemical fertilizer in rice cultivation in rainfed land gave the highest yield of 8,028.5–9,545.0 kg of grain/ha. This productivity is not significantly different from the productivity of rice fertilized with a combination of 25% MOF and 75% NPK Phonska, which produces 7,880.50 kg/ha. MOF can reduce the dose of NPK Phonska chemical fertilizer by 25%; the combination of 75% NPK Phonska chemical fertilizer and 25% MOF was found to increase grain production by 45.2%, compared to the use of conventional chemical fertilizer alone (NPK Phonska 100%). The combination of fertilizer with the composition of M4K4 (100% NPK Phonska chemical fertilizer combined with 100% MOF) gave the best results; the production reached 9,545.00 kg per hectare.

This figure is not significantly different from the M2K3, M3K3, and M4K3 treatments, which represent the best combination of fertilizer treatments with a 75% NPK Phonska fertilizer composition and 50–100% MOF. The effectiveness of such combined fertilization can vary depending on local soil conditions, climate, and the requirements of specific crops. Therefore, region- and soil type-specific calibration is necessary to determine the most optimal combination (Wang et al., 2020). Plant productivity and soil health can be achieved by applying chemical and organic fertilizers together, with improvements of up to 21.5%. Another study also concluded that combining chemical fertilizers with 25% organic fertilizers provided the highest yield equivalent to 100% chemical fertilizer application. Thus, MOF has the potential to replace part of the chemical fertilizer dose and can reduce the requirement for NPK Phonska fertilizer by 25%, representing an efficiency gain of 25%.

This study concluded that combining 100% nitrogen-based chemical fertilizers with 50–100% MOF significantly ($P < 0.05$) improved productivity. The application of nitrogen-based chemical fertilizers with 25% MOF significantly ($P < 0.05$) provides the highest production yield, equivalent to applying 100% nitrogen-based chemical fertilizers. MOF can reduce the dosage of nitrogen-based chemical fertilizers by 25%, or improve the efficiency of nitrogen-based chemical fertilizer use by 25%.

CONCLUSION

This study concludes that the combination of nitrogen-based chemical fertilizers (NPK Phonska) and Microbial Organic Fertilizer (MOF) significantly improves the productivity of Oryza sativa in rainfed fields. While MOF alone shows limited impact on yield, its integration with NPK enhances nutrient use efficiency and soil fertility. The optimal combination indicates that 25% MOF with 75% NPK can produce yields equivalent to 100% NPK, demonstrating that chemical fertilizer use can be reduced by 25% without compromising productivity. Furthermore, higher combinations (50–100% MOF with NPK) produce the highest yields, confirming the importance of integrated fertilization strategies for sustainable agriculture.

Future research is recommended to explore the long-term effects of combined fertilization on soil health, microbial diversity, and environmental sustainability across different agroecological conditions. It is also important to conduct multi-location studies to ensure broader applicability of findings. Practically, farmers are encouraged to adopt integrated fertilization strategies by combining chemical and organic fertilizers to improve efficiency and reduce environmental impact. Additionally, training and policy support are needed to promote the use of locally sourced MOF as an alternative to excessive chemical fertilizer dependency.

ACKNOWLEDGEMENT

We would like to express our gratitude to all individuals and institutions that supported this research. Special thanks to the Faculty of Agriculture at Mochammad Sroedji University, Jember, and the Research Organization of Agriculture and Food, BRIN, for providing the necessary resources and facilities. We also appreciate the valuable guidance and assistance from all colleagues involved in this study. Finally, we extend our thanks to the anonymous reviewers for their constructive feedback on the manuscript.

AUTHOR CONTRIBUTION STATEMENT

Bibit Lilik Lestari conceptualized the research, designed the methodology, and led the writing process. Karyanti conducted the experiments, analyzed the data, and contributed to the manuscript revision. Selly Salma assisted with data collection, the literature review, and the writing of the results and discussion sections. Dwika Nano Hariyanto contributed to data analysis, interpretation of findings, and reviewed the manuscript. All authors have read and approved the final version of the manuscript.

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