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Application of Fly Ash-Based Soil Amendments to Improve The Growth and Yield of Lowland Rice (*Oryza Sativa. L*)

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Abstract

The quality of organic soil amendments can be enhanced by incorporating mineral materials such as fly ash, zeolite, and dolomite in appropriate formulations. This study aimed to evaluate the quality of soil amendments formulated from various organic matter sources combined with fly ash and to assess their effects on the growth and yield of lowland rice (*Oryza sativa* L.). The experiment was conducted under greenhouse conditions from April to December 2024 using a randomized complete block design (RCBD) with three replications. The tested soil amendment formulations were based on fly ash (F), palm oil mill effluent (POME; LC), rice straw compost (JP), cattle manure compost (PK), and *Tithonia diversifolia* compost (TT). The observed parameters included soil amendment characteristics (pH, organic C, total N, total P, total K, and total Si) and rice growth and yield variables. The results demonstrated that increases in rice yield were positively correlated with the silica content of the soil amendments. Soil amendments formulated from rice straw compost, cattle manure compost, and *Tithonia diversifolia* compost in combination with fly ash complied with the technical standards specified in SNI 7763:2024 and the Indonesian Minister of Agriculture Regulation No. 261/KPTS/SR.310/M/4/2019. The highest rice yield was obtained from treatment FKF4, consisting of cattle manure compost amended with fly ash at 75% of the compost dry weight and applied at a rate of 10 t ha^{-1}. To improve both the quality of soil amendments and lowland rice productivity, compost should be blended with fly ash at proportions exceeding 50% of the compost dry weight.

Keywords: Compost, Manure, Rice Straw, Rice Yield, Silica, *Tithonia diversifolia*

1. Introduction

Over the past four decades, the Green Revolution program in Indonesia has successfully increased lowland rice productivity, culminating in national rice self-sufficiency in 1984. One of the key contributing factors was the adoption of high-yielding rice varieties that were highly responsive to fertilization, accompanied by the intensive application of inorganic fertilizers in every planting season. To accelerate the planting cycle, rice straw was commonly burned or removed from paddy fields. This intensification program has resulted in a continuous decline in soil organic matter content and an increasing accumulation of phosphorus (P) and potassium (K) in paddy soils (Ermadani et al., 2018; Hermansah, 2023; Kasno et al., 2013; Maftu'ah and Nursyamsi, 2015; Mulyani et al., 2012; Sitepu et al., 2017).

The depletion of soil organic matter has resulted in declining environmental quality and increased nutrient losses (Lal, 2004). Most paddy fields are currently experiencing soil degradation, characterized by low organic carbon content (<2%) and excessive accumulation of phosphorus (P) and potassium (K) nutrients (Lenin et al., 2018).. In intensively cultivated paddy fields, in addition to low organic matter content, deficiencies of beneficial silicon (Si), nutrient imbalances, and micronutrient deficiencies are frequently observed (Babu et al., 2016; Hermansah et al., 2009; Husnain et al., 2012). Nutrient imbalance mainly results from the continuous application of fertilizers at irrational rates. Such conditions have contributed to the stagnation of productivity improvement in lowland rice cultivation.

The stagnation of rice productivity in West Sumatra

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has been evident since 2010, with a declining trend observed over the last five years. The average rice productivity in 2017 reached 52.47 quintals ha^{-1}. However, from 2018 to 2021, productivity showed a decreasing trend each year, declining to 47.37, 47.58, 46.92, and 48.36 quintals ha^{-1}, respectively (BPS, 2022). In 2025, the productivity of lowland rice in West Sumatra was only 48.67 quintals ha^{-1} (BPS, 2026), with increasingly limited yield improvement. This condition indicates the occurrence of a productivity plateau *(leveling off)* in lowland rice production in West Sumatra Province, one of the major rice-producing regions in Indonesia.

One approach to restoring degraded land is through the application of organic materials (Saidy, 2018). The application of organic matter can improve soil health and soil quality (Hermansah, 2023; Lenin and Siska, 2018; Rani et al., 2023). Potential in situ sources of organic matter include rice straw, manure, and *Tithonia diversifolia* (Hermansah, 2023). Rice straw generally has high C/N, C/P, and C/S ratios; therefore, it should be processed into compost or biochar before application (Sismiati et al., 2018). The application of rice straw compost has been reported to increase the availability of phosphorus (P) and potassium (K) and to improve lowland rice yield (Lenin et al., 2021). Organic materials formulated with inorganic soil amendments offer advantages in improving soil quality (Dariah et al., 2015). The rehabilitation of degraded paddy fields aims to increase soil organic carbon content, improve nutrient balance, and enhance the availability of macro, micro, and silicon nutrients (Yuhardi and Yasin, 2021).

A potential source of silicon (Si) nutrients is currently available in the form of fly ash generated by coal-fired power plants. Fly ash is alkaline in nature, with a pH ranging from 8 to 12 (Noviardi, 2012), and contains essential macro elements such as phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), as well as micronutrients including iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), boron (B), and silicon (Si) (Lenin et al., 2026; Noviardi, 2012; Singh, 2012; Wardani et al., 2012). The silica content of fly ash generally ranges from 40–63% SiO_2 , while other major constituents include CaO (2–10%), MgO (1.2–2.5%), Na_2O (0.17%), K_2O (0.33–1.14%), and P_2O_5 (0.1–0.25%) (Damayanti, 2018)

The application of fly ash provides essential nutrients for plant growth, including Ca, Mg, K, P, Fe, Cu, Zn, and Mn (Adriano et al., 1980; Adriano and Weber, 2001; Damayanti, 2018), and increases the availability of silicon in the soil. A portion of the applied Si is adsorbed onto soil exchange sites, whereas another fraction dissolves in the soil solution as plant-available silica. The application of silicate materials has been reported to enhance phosphorus availability for plants (Prasetyo et al., 2019). Fly ash application increases the concentration of monosilicic acid in the soil solution, thereby transforming insoluble P into available forms and releasing fixed phosphorus (Jala, 2005; Yukamgo and Yuwono, 2007). The silicate ion (SiO_4^{4-}) possesses higher electronegativity than phosphate ions (PO_4^{3-}), enabling silicate to replace adsorbed phosphate ions on soil colloids. In addition, silicon can reduce phosphorus leaching by approximately 40–90% through P binding mechanisms (Matichenkov and Calvert, 2002).

Silicon application has also been shown to improve the availability of essential nutrients such as N, P, K, Ca, Mg, S, and Zn, reduce the toxicity of Fe, Mn, and Al, minimize biotic and abiotic stresses in plants, and ultimately enhance rice yield (Rao and Susmitha, 2017).. Furthermore, silicon influences the uptake of major nutrients, particularly N, P, and K, which are essential for sustaining plant growth and productivity (Wong and Su, 1997).

Fly ash contains nearly all essential plant nutrients commonly present in soil, except for nitrogen (N) and organic carbon (Damayanti, 2018). The application of fly ash to paddy soils has been reported to enhance nutrient uptake and increase crop yield (Lenin and Yulianti, 2021; Prasetyo et al., 2019). In addition, fly ash has been shown to stimulate soil microbial activity, improve soil physical and chemical properties, and enhance plant productivity (Li et al., 2024).

To improve the effectiveness of soil amendments, organic materials are often combined with inorganic ameliorants such as dolomite, humic acid, rock phosphate (Lenin et al., 2021; Subiksa and Husnain, 2019) harzburgite (Lenin, 2006), and biochar (Nurida and Rachman, 2012). However, to the best of our knowledge, no soil amendment formulated with fly ash has yet been reported.

Compared with other soil ameliorants, fly ash offers several advantages, including its abundant availability, alkaline pH, high silica content, and the presence of essential macro- and micronutrients required for plant growth (Damayanti, 2018).

An appropriate formulation of organic materials combined with fly ash is expected to provide a more effective approach for improving soil quality, accelerating nutrient balance restoration, enhancing fertilizer use efficiency, and sustainably increasing lowland rice yield. Therefore, this study aimed to evaluate the quality of fly ash-based soil amendments formulated from various organic matter sources and to assess their effects on the growth and yield of lowland rice.

2. Material and Methods

This study was carried out in the greenhouse of the Indonesian Center for Agricultural Modernization Implementation, West Sumatra (ICAMI West Sumatra), situated at an elevation of 997 m above sea level and located at 0°56′42.43″ S, 100°37′25.05″ E (−0.945119, 100.623626), from April to December 2024.

The materials used in this study included rice straw, cattle manure, *Tithonia diversifolia*, palm oil mill effluent, fly ash, plastic sacks, decomposer inoculants, label paper, rice seeds, polybags, 20-L plastic buckets, inorganic fertilizers (Urea, TSP, and KCl), and pesticides.

2.1. Evaluation of the Quality of Fly Ash-Based Soil Amendments

The soil amendment formulations evaluated in this study were based on fly ash (F) combined with palm oil mill effluent (LC), rice straw (JP), cattle manure (PK), and *Tithonia diversifolia* (TT). A total of 20 fly ash-based soil amendment formulations were tested, consisting of five formulations derived from palm oil mill effluent (LCF1, LCF2, LCF3, LCF4, and LCF5), five formulations derived from rice straw (JPF1, JPF2, JPF3, JPF4, and JPF5), five formulations derived from cattle manure (PKF1, PKF2, PKF3, PKF4, and PKF5), and five formulations derived from *Tithonia diversifolia* (TTF1, TTF2, TTF3, TTF4, and TTF5).

Organic materials, including rice straw, cattle manure, and *Tithonia diversifolia*, were collected from farmers' fields in Cupak Village, Gunung Talang District, Solok Regency. Palm oil mill effluent was obtained from a palm oil processing factory in Dharmasraya Regency, while fly ash was collected from the waste disposal unit of PLN Indonesia Power Ombilin Power Plant, Sawahlunto.

The organic materials were composted using Agrodeko decomposer, a biodecomposer based on *Trichoderma sp* and *Lentinus* fungal strains enriched with nitrogen-fixing bacteria. In particular, the palm oil mill effluent was fermented with Agrodeko for three weeks prior to use.

Composite samples were collected from each formulation for laboratory analysis. The observed variables included pH, organic C, macronutrient contents (N, P, and K), and silicon (Si) content. Soil and fertilizer analyses were conducted in accordance with the technical guidelines for chemical analysis of soil, plant, fertilizer, and water issued by the Soil Research Institute (Sulaeman et al., 2005). The analyzed variables, analytical methods, and extractants used in the study are presented in Table 1. The systematic sequence of the research procedures is presented in Figure 1.

2.2. Evaluation of the Effects of Soil Amendment Application on the Growth and Yield of Lowland Rice

The study was conducted in the greenhouse of ICAMI West Sumatra. Soil for the pot experiment was collected from a major rice-producing area in Solok Regency. The soil was air-dried indoors under shaded conditions to avoid direct sunlight exposure and then cleaned of root residues, stones, plastic debris, and gravel. The air-dried soil was crushed and sieved through a 2-mm mesh sieve. Subsequently, 10 kg of soil was placed into each plastic pot and thoroughly mixed with the soil amendments according to the respective treatments at an application rate equivalent to 10 t ha^{-1}. The treated soil was then flooded and incubated for 21 days, maintaining a water level of approximately 2–3 cm above the soil surface in each pot.

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A total of 10 kg of soil was placed into each plastic pot and thoroughly mixed with the soil amendments according to the respective treatments at an application rate equivalent to 10 t ha^{-1}. The treated soil was subsequently flooded and incubated for 21 days, while maintaining a water level of approximately 2–3 cm above the soil surface in each pot.

The experiment was arranged in a Randomized Block Design with three replications. The treatments consisted of 20 soil amendment formulations, including five formulations derived from rice straw compost (JPF1, JPF2, JPF3, JPF4, and JPF5), five formulations derived from cattle manure compost (AMF1, AMF2, AMF3, AMF4, and AMF5), five formulations derived from *Tithonia diversifolia* compost (TTF1, TTF2, TTF3, TTF4, and TTF5), and five formulations derived from palm oil mill effluent (LCF1, LCF2, LCF3, LCF4, and LCF5).

The experiment used the locally improved upland rice variety Seganggam Panuah. Seeds were initially sown in seedling trays and transplanted 15 days after sowing, with one seedling planted per pot. The plants were fertilized at rates equivalent to 90 kg N, 45 kg P_2O_5, and 60 kg K_2O ha^{-1}. The amount of fertilizer applied to each pot was calculated using the following equation:

$$P = \frac{A}{B} x C$$

where:
(P)=fertilizer dose per pot
(A)=weight of soil in the pot
(B)= weight of soil in 1 ha at a depth of 20 cm (2,000,000 kg)
(C) = fertilizer rate per hectare.

As basal fertilization, the entire dose of TSP and one-third of the K fertilizer dose were applied at planting. Urea fertilizer was applied in three split applications, namely at 10, 30, and 45 days after transplanting (DAT). The remaining K fertilizer, equivalent to two-thirds of the total dose, was applied simultaneously with the second N application at 30 DAT. Weed control was carried out manually, while pest and disease management was conducted through a single application each of insecticide and fungicide during the growing season.

The observed variables included plant growth parameters (plant height and number of tillers), yield components, and grain yield. Plant height and tiller number were measured during the rapid vegetative stage (45 DAT), late vegetative stage (60 DAT), early generative stage (90 DAT), and late generative stage/harvest stage (103 DAT). Plant height was measured from the soil surface to the tip of the tallest leaf or the highest part of the plant. Tiller number was determined based on the total number of tillers per hill, whereas the number of productive tillers was calculated based on the number of tillers producing panicles in each hill.

Table 1. Analytical Methods Used for Determining the Chemical Properties of Soil Amendments in the Laboratory.

No.	Chemical Properties	Analytical Method
1	pH (H_2O)	pH meter
2	Organic Carbon	Walkley and Black method
3	Total N	Kjeldahl method
4	Total P	25% HCl extraction
5	Total K	25% HCl extraction
6	Total Si	Gravimetric method

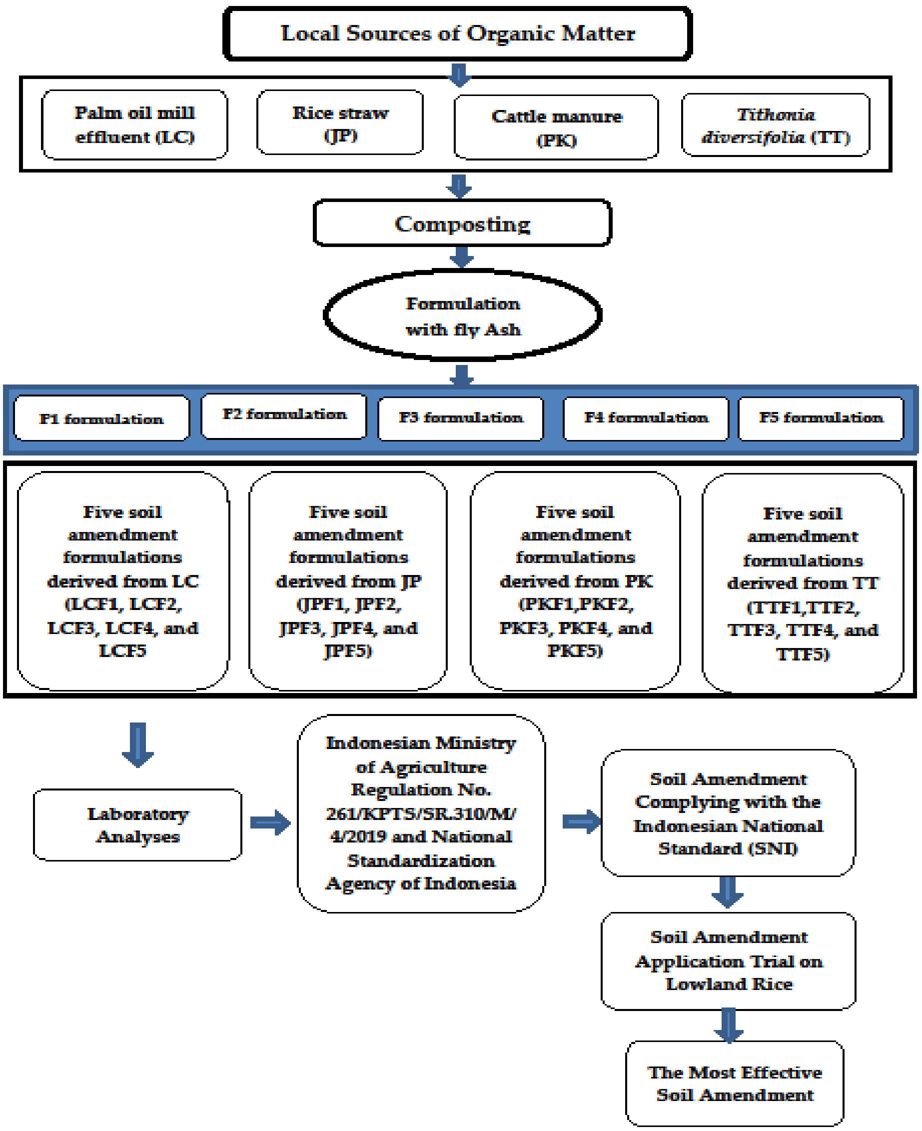

Figure 1. Flowchart of the experimental procedure for evaluating the effects of fly ash-based soil amendments on the growth and yield of lowland rice (*Oryza sativa* L.)

The yield components observed included panicle length, number of grains per panicle, number of filled grains per panicle, number of unfilled grains per panicle, and 1000-grain weight. Panicle length was measured from the base of the panicle to the tip of the longest panicle in each hill. The total number of grains per panicle was counted for each panicle in every pot, while unfilled grains were separated and counted to determine the percentage of empty grains.

The 1000-grain weight was determined after threshing by selecting 1000 filled grains. Grain moisture content was measured using a grain moisture tester (Serra Tester), after which the grains were weighed and standardized to 14% moisture content. Rice yield was measured on a per-pot basis. The harvested rice was threshed, unfilled grains were separated, and grain weight and moisture content were determined before conversion to 14% moisture content using the following formula:

$$\text{Ya} = \frac{100\% - Cb}{100\% - 14\ \%} x\ Yb$$

Where:
(Ya) = grain weight at 14% moisture content
(Cb) = grain moisture content at harvest
(Yb) = grain weight at harvest

Analysis of variance (ANOVA) and significance testing among treatments were conducted according to the procedures described by (Gomez and Gomez, 1983). Differences among treatment means were further evaluated using the Least Significant Difference (LSD) test at the 99% and 95% confidence levels.. The research data were analyzed using STATISTICA Version 8.0 software (StatSoft Inc., Tulsa, OK, USA).

3. Results and Discussion

3.1. Chemical Characteristics of Fly Ash

The fly ash used in this study, a coal combustion by-product obtained from PLN Indonesia Power Ombilin Power Plant, exhibited alkaline properties with a pH of 8.14. It contained both macro- and micronutrients essential for plant growth, including Si, Ca, Mg, K, P, Fe, Cu, Zn, Mn, and boron (B) (Table 2).

Table 2. Chemical characteristics of the fly ash used in this study in comparison with SNI 9387:2025 standards

No.	Parameter	Unit	Value	Fly Ash Soil Amendment (SNI 9387:2025 Grade A)	Fly Ash Soil Amendment (SNI 9387:2025 Grade B)
1	pH	–	8.14*)	6–12	6–12
2	C	%	0.31*)	declared	declared
3	Total N	%	0.01	–	–
4	SiO_2	%	43.95	≥ 20	–
5	Al_2O_3	%	19.49	Max. 30	Max. 30
6	Fe_2O_3	%	12.48	Max. 20	Max. 20
7	CaO	%	3.28	–	–
8	MgO	%	2.46	–	–
9	Total CaO + MgO	%	5.74	≥ 6	1 to < 6
10	K_2O	%	0.12*)	declared	declared
11	Na_2O	%	0.17	declared	declared
12	P_2O_5	%	0.023*)	declared	declared
13	Cu	mg/L	0.0053	declared	declared
14	Zn	mg/L	0.0084	declared	declared
15	B	mg/L	9.3370	declared	declared
16	Pb	mg/L	0.0264	Max. 500	Max. 500
17	Cd	mg/L	0.0002	Max. 100	Max. 100
18	Hg	mg/L	0.0001	Max. 1	Max. 1
19	As	mg/L	0.1767	Max. 25	Max. 25

Source: PT Surveyor Indonesia and *) ICAMI West Sumatera Laboratory.

The silica content reached 43.93% SiO_2. The application of fly ash in appropriate proportions and formulations, combined with various locally available organic materials, is expected to improve the quality of the resulting soil amendment. Its high silica content indicates strong potential as a source of silicon nutrient for agricultural purposes (Basu et al., 2009; Noviardi, 2012; Puslitbangtekmikra, 2021). According to National Standardization Agency of Indonesia SNI 9387:2025, the fly ash used in this study was classified as Grade A soil amendment material. Therefore, the utilization of fly ash is expected to provide complementary effects when combined with various organic matter sources, while simultaneously enhancing the silica content of paddy soils.

3.2. Chemical Characteristics of Soil Amendments Formulated with Fly Ash

The soil amendments evaluated in this study exhibited alkaline properties, with pH values ranging from 9 to 10. The application of these soil amendments is therefore expected to increase soil pH, particularly in acidic soils. The organic carbon (C-organic) content was strongly influenced by the type and source of organic materials used in the formulations. The C-organic content of soil amendments derived from palm oil mill effluent (POME) ranged from 0.09% to 0.78%, which was considerably lower than that of soil amendments formulated from rice straw, manure, and *Tithonia diversifolia* (Table 3).

The C-organic contents of all tested soil amendments met the technical requirements for soil amendments, except for the POME-based formulations. According to Indonesian Ministry of Agriculture Regulation No. 261/KPTS/SR.310/M/4/2019 and National Standardization Agency of Indonesia SNI 773:2024, the minimum required C-organic content for soil amendments is 15% (Lenin et al., 2026). The highest total N content (1.56%) was observed in the soil amendment treatment (TTF1). A similar result was reported by (Gusnidar et al., 2019), who found that composted *Tithonia diversifolia* combined with rice straw contained 1.55% total N with a C/N ratio of 17.49. To further improve the quality of soil amendments and their effects on soil quality, *Tithonia diversifolia* a can be combined with other amendment materials, such as biochar, as reported by (Yuhardi and Yasin, 2021). The addition of fly ash is also expected to enhance the quality of the soil amendment material.

Table 3. Organic C, N, P, K, and Si contents, as well as C/N and C/P ratios, of fly ash-based soil amendments

Soil Amendments	pH	Organic-C (%)	Total-N (%)	Total-P (%)	Total-K (%)	SiO_2 (%)	C/N ratio	C/P ratio
LCF1	9	0,09	0,07	0,02	0,35	0,9	1,3	4,5
LCF2	9	0,23	0,15	0,02	0,35	10,32	1,5	11,5
LCF3	9	0,25	0,05	0,02	0,27	21,53	5,0	12,5
LCF4	9	0,3	0,17	0,02	0,29	33,64	1,8	15,0
LCF5	9	0,78	0,19	0,63	0,27	44,85	4,1	1,2
JPF1	10	19,98	1,07	0,58	5,54	13,37	18,7	34,4
JPF2	10	18,72	0,97	0,38	3,49	20,06	19,3	49,3
JPF3	9	16,19	1,26	0,37	3,03	40,11	12,8	43,8
JPF4	9	14,59	1,05	0,26	2,59	53,48	13,9	56,1
JPF5	10	8,98	0,51	0,32	1,76	66,85	17,6	28,1
PKF1	9	21,47	1,1	1,3	4,98	7,86	19,5	16,5
PKF2	9	17,48	0,92	0,99	3,29	14,67	19,0	17,7
PKF3	9	11,69	0,86	0,56	2,35	28,81	13,6	20,9
PKF4	9	9,13	0,51	0,72	1,47	40,86	17,9	12,7
PKF5	9	7,29	0,52	0,76	1,76	52,39	14,0	9,6
TTF1	9	22,02	1,56	1,3	9,1	8,72	14,1	16,9
TTF2	9	18,8	1,03	0,73	5,84	15,25	18,3	25,8
TTF3	9	17,73	0,67	0,55	4,32	28,87	26,5	32,2
TTF4	9	12,28	0,9	0,34	3,62	41,4	13,6	36,1
TTF5	9	9,67	0,78	1,05	2,01	54,47	12,4	9,2

Note: The analyses were conducted at the ICAMI West Sumatra Laboratory. Soil amendment samples were analyzed after a 15-day incubation period for all observed parameters. Each treatment consisted of three replicates.

The highest P nutrient content (1.30%) was observed in the PKF1 and TTF1 soil amendment treatments. The highest total K content (9.1%) was recorded in the TTF1 soil amendment, while the highest silica content (66.85% SiO_2) was found in the JPF5 soil amendment. In general, increasing the proportion of fly ash in the soil amendments reduced the contents of organic C, total N, total P, and total K. In contrast, a higher proportion of fly ash in the soil amendments increased the silica content.

The reduction in organic C content, as well as in N, P, and K nutrient content, was likely closely associated with the decreasing proportion of compost and the increasing proportion of fly ash in the soil amendments. Fly ash contains nearly all the elements commonly present in soil, except for organic carbon and nitrogen (Damayanti, 2018). The fly ash used in this study contained only 0.01% N, 0.023% P_2O_5 , and 0.12% K_2O, and therefore did not contribute significantly to the enhancement of N, P, and K nutrient contents. Previous studies reported that fly ash application had no significant effect on increasing soil organic C content and tended to reduce total N content; however, it increased available P by 25.65–50.95% and doubled the availability of silica (Lenin et al., 2026).

The C/N and C/P ratios are important indicators for determining the quality of organic fertilizers and soil amendments, as reported by (Sismiati et al., 2018). The addition of fly ash influenced both the C/N and C/P ratios. In the LC soil amendments, the C/N ratio was very low, ranging from 1.3 to 5.0. This low C/N ratio was attributed to the very low organic C content of the LC amendments, which ranged from 0.09% to 0.78%.

In the JP soil amendments, the lowest C/N ratio (12.8) was observed in the JPF3 treatment. Similarly, in the PK soil amendments, the lowest C/N ratio (13.6) was recorded in the PKF3 treatment. Meanwhile, in the TT soil amendments, the lowest C/N ratio (12.4) was obtained in the TTF5 treatment.

Based on the C/N ratio values, all soil amendments evaluated in this study met the technical requirements stipulated in the Indonesian Ministry of Agriculture Regulation No. 261/KPTS/SR.310/M/4/2019 and SNI 7763:2024, which specify a C/N ratio of less than 20. These values indicate that all soil amendments are suitable for soil application and have undergone sufficient mineralization.

The ability of organic materials to release nutrients depends largely on their C/N ratio. A lower C/N ratio facilitates nutrient release, whereas a higher C/N ratio tends to hinder nutrient availability. Organic materials with a low C/N ratio decompose more rapidly, while those with a high C/N ratio decompose more slowly, as reported by (Gusnidar and Prasetyo, 2008) and by (Setiawati et al., 2018).

The C/P ratio is also an important indicator in determining the quality of organic materials. The mineralization of organic matter proceeds more effectively when the organic material has a high P content, as reflected in the C/P ratio (Setiawati et al., 2018). The correlation between the percentage of fly ash by weight in the soil amendment materials and the C/P ratio followed a quadratic pattern (Figure 2). A strong correlation was observed between the proportion of fly ash in the soil amendments and the C/P ratio. Increasing the fly ash proportion up to 50% increased the C/P ratio, whereas further increases tended to decrease the C/P ratio, indicating an improvement in the quality of the soil amendments.

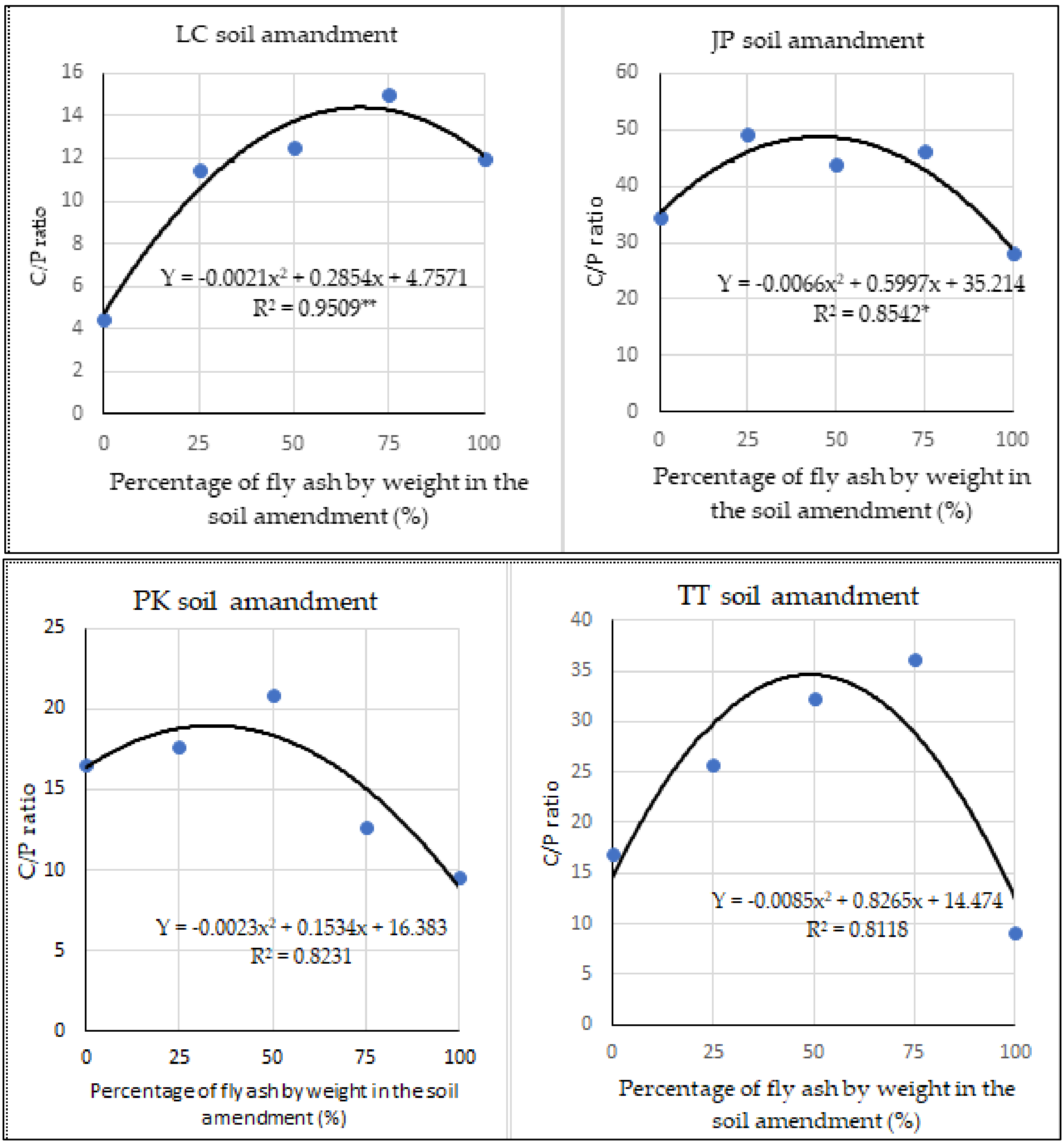

Figure 2. Relationship between the percentage of fly ash by weight in the soil amendment and the C/P ratio

The soil amendments produced in this study underwent P mineralization, thereby increasing P availability for plant uptake. According to (Atmojo, 2003), mineralization and the release of P into the soil occur when the C/P ratio is low (<200). In contrast, a high C/P ratio (>300) may lead to P immobilization or P loss.

3.3. Effect of fly ash-based soil amendment application on rice plant growth.

The application of fly ash-based soil amendments significantly affected plant height. During the rapid vegetative growth stage (45 DAT), plants exhibited greater height under the TT soil amendment treatments. The tallest plants (85.67 cm) were observed in the TTF4 treatment. At 75 DAT, the highest plant height (107.67 cm) was recorded in the TTF1 treatment, which was not significantly different from the PKF1, PKF2, PKF3, PKF4, and PKF5 treatments (Table 4).

Table 4. Effect of soil amendment application on plant height.

Soils amendment	Plant height (cm)		
	45 DAT	60 DAT	90 DAT
LCF1	77.00 ± 1.30 bc	99.67 ± 1.46 abc	120.33 ± 1.85 bcd
LCF2	67.67 ± 1.76 d	91.33 ± 2.42 c	115.67 ± 2.18 d
LCF3	70.33 ± 1.20 cd	96.33 ± 4.85 abc	115.33 ± 0.34 d
LCF4	72.33 ± 2.53 bcd	95.33 ± 2.34 bc	116.67 ± 5.21 cd
LCF5	72.00 ± 0.60 bcd	97.67 ± 1.77 abc	115.00 ± 1.53 d
JPF1	71.67 ± 2.73 bcd	91.67 ± 3.32 c	119.67 ± 1.53 bcd
JPF2	71.00 ± 2.09 bcd	98.00 ± 2.13 abc	124.33 ± 3.28 abcd
JPF3	78.33 ± 1.20 abc	102.00 ± 2.65 abc	128.00 ± 4.51 abc
JPF4	74.33 ± 1.20 bcd	99.67 ± 0.45 abc	130.67 ± 6.23 ab
JPF5	75.00 ± 2.95 bcd	96.67 ± 4.91 abc	123.33 ± 1.76 abcd
PKF1	73.33 ± 2.42 bcd	97.67 ± 4.93 abc	119.67 ± 5.18 bcd
PKF2	79.00 ± 7.59 ab	100.33 ±2.91abc	130.67 ± 6.89 ab
PKF3	74.67 ± 3.72 bcd	99.33 ± 7.43 abc	126.00 ± 7.65 abcd
PKF4	78.00 ± 2.09 abc	105.67 ± 4.68 ab	133.33 ± 3.85 a
PKF5	74.00 ± 1.49 bcd	97.33 ± 1.80 abc	120.33 ± 0.67 bcd
TTF1	77.67 ± 2.32 abc	107.67 ± 4.34 a	128.00 ± 6.67 abc
TTF2	78.33 ± 2.85 abc	91.33 ± 4.81 c	123.33 ± 0.34 abcd
TTF3	85.67 ± 4.68 a	98.00 ± 2.00 abc	121.67 ± 2.33 abcd
TTF4	74.33 ± 1.32 bcd	96.00 ± 1.15 bc	122.67 ± 4.18 abcd
TTF5	78.33 ± 1.46 abc	91.67 ± 8.77 c	128.67 ± 2.33 ab
CV (%)	6.65	7.16	5.86

Values within the same column followed by the same lowercase letter are not significantly different at the 5% LSD level.

The enhanced growth observed during the early vegetative stage under the TT soil amendment treatments was likely closely related to the more rapid nutrient availability compared with the other soil amendment treatments. One of the main advantages of *Tithonia diversifolia* over other organic materials is its relatively rapid decomposition rate, higher nutrient content, and faster effect on plant growth, as reported by (Aryani et al., 2019). Fresh Tithonia contains approximately 16.90% lignin and 52.99% cellulose. Its low lignin and high cellulose contents facilitate rapid decomposition and faster nutrient release, particularly nitrogen. The N and K contents in *Tithonia diversifolia* can reach 3.43% and 4.16%, respectively, as reported by (Gusnidar and Prasetyo, 2008). Nitrogen and potassium are required by plants in greater amounts than most other nutrients. Nitrogen plays an important role in enhancing photosynthesis, serving as a constituent of amino acids and proteins, and promoting vegetative growth, as explained by (Mu and Chen, 2021).

As plant age increased, plant growth under the TT soil amendment treatments tended to slow down. The addition of fly ash to the PK and JP soil amendments significantly affected plant height. In contrast, adding fly ash to the TT soil amendments did not significantly affect plant height at 90 DAT. Plants grown under the LC soil amendment treatments were shorter than those grown under the JP, PK, and TT soil amendments.

A study by (Mutaqin et al., 2022) reported that the application of palm oil mill effluent (POME) had no significant effect on soil N content, either in the form of N–NO_3^- or N–NH_4^+. This condition was likely responsible for the lower plant growth rate, particularly in plant height, observed under the LC soil amendment treatments compared with the other soil amendment treatments.

The application of fly ash-based soil amendments significantly affected tiller number. At 45 DAT, the highest average number of tillers (26.67) was observed in the PKF2 treatment, which was not significantly different from those in the JPF1, JPF2, JPF3, JPF4, PKF4, PKF5, TTF3, and TTF5 treatments (Table 5).

At 60 DAT, the highest average number of tillers

(44.33 tillers) was recorded in the PKF2 and TTF1 treatments. The number of tillers in all tested soil amendment treatments continued to increase until 90 DAT. The highest number of tillers at this stage was observed in the PKF4 treatment; however, it was not significantly different from the other treatments, except for LCF1 and LCF2.

In general, the application of soil amendments combined with fly ash showed a more favorable effect on rice tiller formation. A study by (Lenin et al., 2026) reported that the application of fly ash combined with manure increased total P, available P, total K, and available K contents, as well as enhanced exchangeable base cations and soil cation exchange capacity (CEC). According to (Maulidan and Putra, 2024), phosphorus (P) is an essential nutrient for plants because it acts as a limiting factor affecting plant growth and productivity. In rice plants, P plays an important role in promoting root growth and development, as well as tiller formation.

Table 5. Effect of soil amendment application on the number of rice tillers.

Soil amandment	Number of rice tillers (tillers clump^{-1})		
	45 DAT	60 DAT	90 DAT
LCF1	19.33 ± 3.06 g	28.67 ± 3.18 cd	36.00 ± 3.06 b
LCF2	19.67 ± 2.91 fg	30.00 ± 3.46 bcd	37.67 ± 4.41 b
LCF3	20.33 ± 2.91 efg	32.33 ± 3.18 bcd	42.00 ± 4.00 ab
LCF4	22.33 ± 2.40 cdefg	28.67 ± 1.46 cd	39.67 ± 5.90 ab
LCF5	20.33 ± 0.67 efg	24.67 ± 2.65 d	41.00 ± 3.51 ab
JPF1	27.33 ± 2.03 abc	38.00 ± 2.52 ab	47.00 ± 2.00 ab
JPF2	26.00 ± 0.58 abcd	33.00 ± 1.15 bcd	43.00 ± 3.06 ab
JPF3	26.00 ± 1.00 abcd	35.67 ± 2.41 abc	45.67 ± 1.34 ab
JPF4	24.33 ± 0.29 abcdefg	34.33 ± 1.85 bc	38.67 ± 2.03 ab
JPF5	22.33 ± 1.34 cdefg	33.33 ± 1.76 bcd	46.00 ± 1.15 ab
PKF1	20.67 ± 3.18 defg	32.00 ± 4.73 bcd	40.00 ± 5.69 ab
PKF2	29.67 ± 1.76 a	44.33 ± 4.34 a	48.00 ± 4.51 ab
PKF3	23.67 ± 2.85 bcdefg	35.00 ± 1.53 bc	42.33 ± 5.21 ab
PKF4	28.67 ± 3.53 ab	37.33 ± 3.72 abc	52.00 ± 2.09 a
PKF5	25.33 ± 1.46 abcde	37.00 ± 0.58 abc	45.33 ± 2.03 ab
TTF1	23.67 ± 0.67 bcdefg	44.33 ± 2.33 a	43.67 ± 1.20 ab
TTF2	22.67 ± 2.33 cdefg	35.33 ± 5.24 abc	42.00 ± 7.95 ab
TTF3	25.00 ± 0.58 abcdef	33.00 ± 1.15 bcd	45.33 ± 2.34ab
TTF4	22.67 ±1.67 cdefg	30.33 ± 1.67 bcd	49.33 ± 7.23 ab
TTF5	24.66 ± 2.73 abcdefg	24.67 ± 6.37 d	41.00 ± 2.67 ab
CV (%)	14.39	16.34	19.92

Values within the same column followed by the same lowercase letter are not significantly different at the 5% LSD level.

3.4. Effect of soil amendment application on rice yield components and lowland rice yield.

The application of soil amendments significantly affected all yield components and lowland rice yield parameters. The average number of productive tillers at harvest (103 DAT) did not differ substantially from that recorded at 90 DAT. The highest average number of productive tillers (52.00 tillers clump^{-1}) was obtained in the PKF4 treatment, which differed significantly from the LCF1 and LCF2 treatments (Table 6).

The highest panicle length and number of grains per panicle were observed in the LCF2 soil amendment treatment, while the lowest percentage of unfilled grains was recorded in the LCF3 and PKF4 treatments. The highest grain weight (25 g 1000 grains^{-1}) was obtained in the PKF4 treatment.

The PKF4 soil amendment produced superior yield component values compared with the other soil amendments, as indicated by the highest number of productive tillers, the lowest percentage of unfilled grains, and the highest 1000-grain weight. Therefore, the combination of manure compost and fly ash at an appropriate ratio contributed positively to improving lowland rice yield.

3.5. Effect of soil amendment application on lowland rice yield.

The application of soil amendments significantly affected rice yield. Among the ten treatments evaluated, all produced significantly higher yields than the others. The highest average yield (108.33 g pot^{-1}) was obtained with the PKF4 soil amendment treatment, followed by JPF5 and PKF5. However, these yields were not significantly different from those obtained under the JPF3, PKF3, TTF3, TTF4, TTF5, LCF5, and JPF4 treatments.

The order of effectiveness of the ten selected ameliorant treatments in increasing lowland rice yield was as follows: PKF4 > JPF5 > PKF5 > JPF3 > PKF3 = TTF3 > TTF4 = TTF5 > LCF5 = JPF4 (Table 6). In the LC and TT soil amendment treatments, fly ash addition did not significantly affect rice yield. In contrast, in the JP and PK soil amendment treatments, increasing the proportion of fly ash significantly enhanced yield. A consistent trend was observed in which higher proportions of fly ash in the soil amendments led to increased lowland rice productivity.

Table 6. Effect of several combinations of local organic materials and fly ash on lowland rice yield components.

Soil amendment	Yield components.					Grain yield (g pot^{-1}).
	Productive tillers (tillers clump^{-1}).	Panicle length (cm).	Number of grains panicle^{-1}	Unfilled grains (%).	1000-grain weight (g).	
LCF1	36.00 ± 3.06 b	22.67 ± 1,45 ab	133.00 ± 26,07 bcd	26.00 ± 6,99 abc	24.33 ±0,77 abc	91.67 ±4,41 bcde
LCF2	37.67 ± 4.41 b	24.67 ± 2,10 a	179.67 ± 26,53 a	22.67 ± 5,19 abc	23.33 ± 0,72 abcd	91.67 ± 4,41 bcde
LCF3	42.00 ± 4.00 ab	22.67 ± 0,09 ab	138.67 ± 7,78 abcd	16.67 ± 1,91 c	24.67 ±0,36 ab	85.00 ± 2,89 de
LCF4	39.67 ± 5.90 ab	21.33 ± 0,30 ab	110.67 ± 2,08 cd	24.33 ± 5,27 abc	23.67 ±0,64 abcd	88.33 ± 1,67 cde
LCF5	41.00 ± 3.51 ab	22.01 ± 1,06 ab	156.00 ± 12,70 ab	22.33 ± 4,09 abc	24.33 ± 1,08 abc	93.33 ± 3,33 abcde
JPF1	47.00 ± 2.00 ab	20.67 ± 0,54 b	111.67 ± 11,60 cd	24.67 ± 8,29 abc	23.67 ± 0,84 abcd	86.67 ± 14,53 de
JPF2	43.00 ± 3.06 ab	22.33 ± 1,20 ab	139.67 ± 33,08 abcd	31.33 ± 5,38 abc	22.67 ± 0,54 bcd	81.67 ± 4,41 e
JPF3	45.67 ± 1.34 ab	21.67 ± 1,34 ab	119.33 ± 15,10 bcd	24.67 ± 6,94 abc	22.67 ± 0,55 bcd	100.00 ± 7,64 abcd
JPF4	38.67 ± 2.03 ab	20.67 ± 1,28 b	118.00 ± 22,85 bcd	24.33 ± 9,34 abc	23.67 ± 0,29 abcd	93.33 ± 1,67 abcde
JPF5	46.00 ± 1.15 ab	22.33 ± 0,43 ab	98.00 ± 10,41 d	19.67 ± 2,92 bc	24.67± 1,14 ab	105.00 ± 7,64 ab
PKF1	40.00 ± 5.69 ab	21.00 ± 1,04 b	101.33 ± 13,16 cd	37.67 ± 19,64 ab	22.00 ± 0,65 d	90.00 ± 5,77 bcde
PKF2	48.00 ± 4.51 ab	19.67 ± 1,86 b	142.33 ± 14,90 abc	40.33 ± 18,66 a	23.00 ± 0,50 abcd	91.67 ± 7,26 bcde
PKF3	42.33 ± 5.21 ab	21.67 ± 1,69 ab	126.00 ± 20,48 bcd	20.67 ± 5,76 abc	22.67± 1,53 bcd	98.33 ± 10,93 abcd
PKF4	52.00 ± 2.09 a	22.67 ± 0,85 ab	122.00 ± 14,40 bcd	15.00 ± 1,77.c	25.00 ± 1,04 a	108.33 ± 4,41 a
PKF5	45.33 ± 2.03 ab	21.67 ± 1,67 ab	125.67 ± 19,75 bcd	21.00 ± 4,03 abc	24.00 ± 0,72abcd	103.33 ± 3,33 abc
TTF1	43.67 ± 1.20 ab	21.33 ± 1,05 ab	116.00 ± 9,03 bcd	18.67 ± 1,24 bc	23.67 ± 0,49 abcd	96.67 ± 12,02 abcde
TTF2	42.00 ± 7.95 ab	22.33 ± 0,68 ab	130.67 ± 12,76 bcd	24.00 ± 1,70 abc	22.33 ± 0,29 cd	91.67 ± 3,33 bcde
TTF3	45.33 ± 2.34ab	22.33 ± 1,10 ab	129.00 ± 14,28 bcd	22.33 ± 1,32 abc	23.00 ± 0,47 abcd	98.33 ± 4,41 abcd
TTF4	49.33 ± 7.23 ab	22.00 ± 0,12 ab	105.33 ± 17,09 cd	21.00 ± 1,67abc	23.33 ± 0,27 abcd	96.67 ± 3,33 abcde
TTF5	40.33 ± 3.34 ab	21.33 ± 0,32 ab	133.00 ± 17,16 bcd	24.00 ± 3,58 abc	22.33 ± 0,66 cd	96.67 ± 3,33 abcde
CV (%)	19.92	9.61	20.43	21,23	5.52	9.96

Values within the same column followed by the same lowercase letter are not significantly different at the 5% LSD level.

The fly ash used in this study contained 43.95% silica, indicating its strong potential as a source of silicon nutrient for agricultural applications (Puslitbangtekmikra, 2021).The application of fly ash to agricultural land can improve silicon availability, thereby enhancing crop productivity (Basu et al., 2009; Noviardi, 2012; Puslitbangtekmikra, 2021). The application of fly ash to peat soils can enhance rice growth and grain yield, which are closely associated with improvements in soil pH and the increased availability of Si, Ca, and Mg (Lutfiyani et al., 2025; Slag et al., 2024).

The silica nutrient content in the soil amendments was positively correlated with lowland rice yield. Higher silica concentrations in the amendment materials were associated with greater rice productivity (Figure 3). The application of fly ash contributed essential nutrients for plant growth, including Ca, Mg, K, P, Fe, Cu, Zn, and Mn, while also increasing silicon availability.

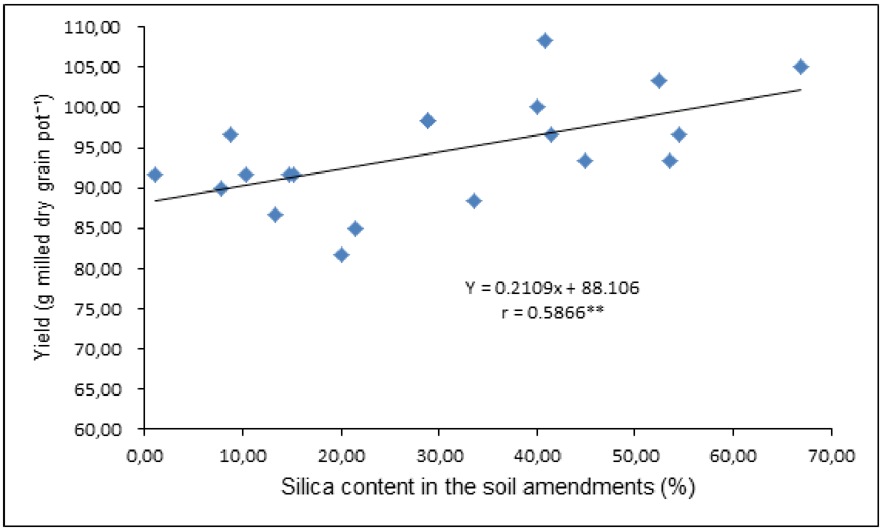

Figure 3. Relationship between the silica content of soil amendments applied to paddy soil and lowland rice yield.

Silicon plays a crucial role in promoting vigorous plant growth and enhancing resistance to fungal diseases in rice (Gong et al., 2022). In addition, silicon suppresses plant pathogens by depositing in various plant tissues and modulating and inducing specific defense-related genes (Sathe et al., 2021). Rice is considered a silicon accumulator and actively accumulates Si in its tissues at concentrations of 5% or higher (Sugiyanta et al., 2018).

According to the findings of Lenin et al., the combination of fly ash and manure was effective in increasing silicon availability through the dissolution of organic acids. The combined application of fly ash and manure increased available Si by 250.4%, doubled the Si concentration in plant tissues, and enhanced lowland rice yield by 126.4%. The growth performance of plants under the LCF4, JPF4, PKF4, and TTF4 treatments is presented in Figure 4, whereas a comparison of plant growth between PKF1 and PKF4 is shown in Figure 5.

Visual observations indicated that the PKF4 treatment produced more productive tillers than the other treatments. In addition, the panicles appeared denser and better filled, and plant height was more optimal compared with the other treatment groups. A comparison between PKF1 and PKF5 further demonstrated superior growth under PKF5, as evidenced by a higher number of productive tillers, longer panicles, a greater number of filled grains, and a lower proportion of unfilled grain.

Figure 4. Representative growth performance of lowland rice (*Oryza sativa* L.) under the LCF4 (LC-75), PKF4 (PK-75), JPF4 (JP-75), and TTF4 (TT-75) treatments

Figure 5. Representative growth performance of lowland rice (*Oryza sativa* L.) under the PKF1 (PK-0) and PKF4 (PK-75) treatments.

4. Conclusion

The fly ash-based JP, PK, and TT soil amendments complied with the technical specifications established under SNI 7763:2024 and the Regulation of the Minister of Agriculture of the Republic of Indonesia No. 261/KPTS/SR.310/M/4/2019. A total of ten soil amendment treatments produced higher yields compared with the other treatments. The highest average yield (108.33 g pot^{-1}) was obtained with the PKF4 treatment, followed by JPF5 and PKF5. The order of effectiveness of the ten selected ameliorant treatments in increasing lowland rice yield was as follows: PKF4 > JPF5 > PKF5 > JPF3 > PKF3 = TTF3 > TTF4 = TTF5 > LCF5 = JPF4. Superior yield components, including the highest number of productive tillers, the lowest percentage of unfilled grains, and the greatest 1000-grain weight also supported the highest yield obtained under the PKF4 treatment. A positive correlation was observed between the silica content of the soil amendments and lowland rice yield. Higher silica contents in the soil amendments were associated with greater rice productivity.

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