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Soil Quality Enhancement and Growth Response of Rice (*Oryza sativa* L., Var. PMJ-01) to Liquid Organic Fertilizer Application in a Greenhouse System

Peningkatan Kualitas Tanah dan Respon Pertumbuhan Tanaman Padi (Oryza sativa L. ,Var. PMJ-01) terhadap Aplikasi Pupuk Organik Cair dalam Sistem Rumah Kaca

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ABSTRACT

In the context of supporting the national food security program, increasing rice productivity should be directed toward the use of environmentally friendly fertilizers that can reduce dependence on synthetic chemical inputs. This study aimed to evaluate the effectiveness of liquid organic fertilizer (LOF) on vegetative growth, yield performance, and soil quality of rice variety PMJ-01. The research was conducted in a greenhouse located in Jotosanur, Lamongan, using 13 treatment combinations of LOF 3 ppm concentration and application frequency. The observed parameters included plant height, panicle length, 1000-grain weight, yield per clump, as well as soil quality indicators measured by pH, nitrogen (N), phosphorus (P), and potassium (K) content. The results showed that treatments P2 and P4 produced the best vegetative growth in terms of plant height, while treatments P2, P6, and P10 resulted in the longest panicles. The highest 1000-grain weight was obtained in treatments P2 and P11, whereas yield per clump significantly increased under treatments P2 and P11. Application of LOF 7 ppm also improved soil quality, particularly by increasing soil pH, although the levels of macronutrients (N, P, K) remained below the Indonesian National Standard (SNI). Thus, LOF has the potential to be an alternative to chemical fertilizers in rice cultivation. Therefore, developing LOF formulations with additional macronutrients is necessary to support increased productivity and sustainability of rice farming systems.

Key words: soil quality, growth response, *Oryza sativa*, liquid organic fertilizer, greenhouse

ABSTRAK

Dalam rangka mendukung program ketahanan pangan nasional, peningkatan produktivitas padi perlu diarahkan pada penggunaan pupuk ramah lingkungan yang mampu mengurangi ketergantungan terhadap pupuk kimia sintetis. Penelitian ini bertujuan untuk mengevaluasi efektivitas pupuk organik cair (LOF) terhadap pertumbuhan vegetatif, hasil panen, dan kualitas tanah pada padi varietas PMJ-01. Penelitian dilaksanakan di greenhouse Jotosanur, Lamongan, dengan menggunakan 13 kombinasi perlakuan konsentrasi dan frekuensi aplikasi LOF. Parameter yang diamati meliputi tinggi tanaman, panjang malai, bobot 1000 butir, hasil panen per rumpun, serta kualitas tanah yang diukur melalui pH, kandungan nitrogen (N), fosfor (P), dan kalium (K). Hasil penelitian menunjukkan bahwa perlakuan P2 dan P4 memberikan pertumbuhan vegetatif terbaik pada parameter tinggi

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tanaman, sedangkan perlakuan P2, P6, dan P10 menghasilkan panjang malai tertinggi. Bobot 1000 butir tertinggi diperoleh pada perlakuan P2 dan P11, sementara hasil panen per rumpun meningkat secara signifikan pada perlakuan P2 dan P11. Pemberian LOF juga terbukti memperbaiki kualitas tanah, khususnya meningkatkan nilai pH, meskipun kandungan unsur hara makro (N, P, K) masih berada di bawah standar SNI. Dengan demikian, LOF berpotensi menjadi alternatif penggunaan pupuk kimia dalam budidaya padi. Oleh karena itu, diperlukan pengembangan formulasi LOF dengan penambahan unsur hara makro guna mendukung peningkatan produktivitas dan keberlanjutan sistem pertanian padi.

Kata kunci: kualitas tanah, pertumbuhan, Oryza sativa, pupuk organic cair, greenhouse

INTRODUCTION

Rice (*Oryza sativa L.*) remains one of the most important staple crops worldwide, serving as the primary source of calories for more than half of the global population (Birla et al., 2017). In Indonesia, rice holds a particularly strategic role, contributing over 95% of national carbohydrate intake and directly shaping food security and socio-economic stability (Amandaria et al., 2025). According to Statistics Indonesia, national per capita rice consumption currently reaches 92.9 kg/year, with projections indicating a rise to 95.5 kg/year by 2029 in line with population growth and increased food demand (Abeysekara & Rathnayake, 2024). Despite its central importance, rice productivity in Indonesia has stagnated over the past decade (Mariyono, 2018). The Ministry of Agriculture reported an average productivity of only 5.1 tons/ha in 2022, a figure that lags behind other major rice-producing countries such as Vietnam and China (Connor et al., 2023). This stagnation presents a critical challenge to national food security (Widiana et al., 2022).

One of the primary causes of this stagnation is the deterioration of soil fertility, largely driven by the prolonged and excessive use of synthetic chemical fertilizers (Pahalvi et al., 2021). Continuous reliance on chemical inputs has resulted in declining soil organic matter, nutrient imbalances, and disruption of soil microbial communities (Hossain et al., 2022). Such degradation not only limits the capacity of soils to sustain rice production but also poses long-term threats to ecosystem health and agricultural sustainability (N. Kumar et al., 2022). Consequently, there is an urgent need to shift toward environmentally sound and sustainable fertilization strategies that restore soil health while maintaining or enhancing crop productivity.

Liquid organic fertilizer (LOF) represents a promising bio-organic amendment capable of addressing these challenges. LOF provides essential macro- and micronutrients in a readily available form, enhances soil structure, and stimulates microbial activity that supports nutrient cycling (Riddech et al., 2025). Previous studies have highlighted its potential; for example, Gusta et al. (2020) demonstrated that livestock waste-based LOF increased rice plant height and tiller numbers by up to 18% compared to non-treated controls (V. Kumar et al., 2023). Moreover, integrated LOF 7 ppm application has been reported to reduce the requirement for inorganic fertilizers by up to 40% without compromising yield (Wang et al., 2025). Despite these promising findings, systematic evaluations of LOF performance across diverse rice varieties and under controlled environments remain limited, leaving a critical knowledge gap regarding its broader applicability and optimization.

Jotosanur Village in Lamongan Regency, East Java, provides a unique case for such investigations through the Integrated Food Greenhouse (Pangan Terpadu - PANDU) program, initiated

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by KODIM 0812 Lamongan. The greenhouse system offers precise control over irrigation, temperature, and humidity, enabling rigorous testing of fertilization treatments under semi-controlled conditions. Such an environment is ideal for examining the effectiveness of LOF formulations on high-performing rice varieties, particularly *Padi Malai Jumbo 01* (as known as PMJ 01) variety. This variety is recognized for its high yield potential, resistance to blast disease, and relatively short growth cycle (95–100 days after sowing). However, applied studies on the interaction between LOF 7 ppm application and PMJ 01 performance remain scarce, particularly in greenhouse-based production systems that simulate future-oriented precision agriculture.

This study was therefore designed to fill this research gap by addressing two key questions: (1) How do varying concentrations of liquid organic fertilizer influence the vegetative growth and agronomic performance of rice variety PMJ 01 under controlled greenhouse conditions? (2) How does liquid organic fertilizer application affect soil quality and nutrient composition, and what are its implications for sustainable rice production systems?

By integrating plant growth performance with soil quality assessments, this research aims to provide evidence-based insights into the potential of LOF additions & treatments as a sustainable fertilization strategy for rice cultivation. The findings are expected to contribute to the development of bio-organic fertilization models that enhance productivity while ensuring long-term soil health and environmental sustainability.

MATERIALS AND METHODS

The research stages describe the development process of LOF for the PMJ-01 rice variety. The process began with a comprehensive literature review and field survey, followed by the collection of preliminary data related to soil and environmental conditions. Based on these data, the LOF formulation was developed and subsequently tested on rice plants under greenhouse conditions. The experimental results were statistically analyzed during the data analysis stage and further validated to ensure accuracy and applicability. The final stage involved the downstream implementation of the LOF product for broader application within sustainable agricultural systems.

Research Site and Experimental Conditions

The present study was carried out under controlled greenhouse conditions at the Integrated Food Greenhouse (PANDU), KODIM 0812, located in Jotosanur Village, Tikung District, Lamongan Regency, East Java, Indonesia (7°09’40.961” S; 112°24’27.605” E) (Figure 1). This facility was strategically chosen for its capacity to provide a highly controlled environment, essential for isolating the effects of experimental treatments.

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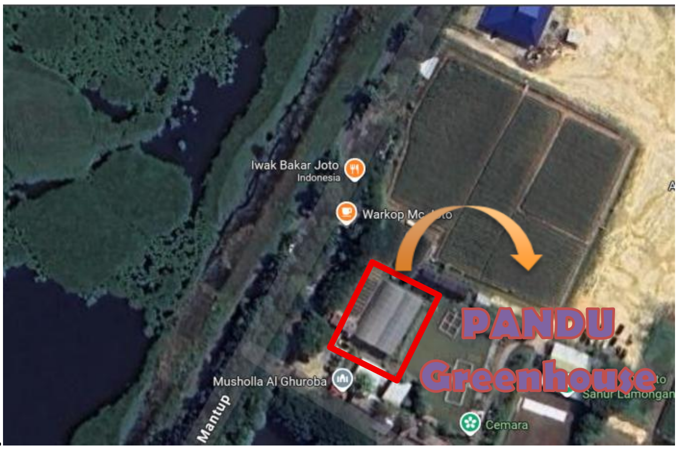

Figure 1. Study location

The greenhouse is designed to allow precise management of critical environmental variables, including temperature, relative humidity, light intensity, and irrigation frequency, which are known to significantly influence plant growth and physiological responses. By maintaining these conditions within optimal ranges, the greenhouse minimizes external variability caused by seasonal fluctuations, precipitation, and other climatic factors, thereby enhancing the reproducibility and reliability of the study outcomes. Additionally, the site benefits from well-established infrastructure for nutrient and water management, including automated irrigation systems and drainage facilities, which ensure uniform delivery of water and fertilizers to experimental plots. The greenhouse also permits efficient monitoring of plant health and pest incidence, enabling timely interventions without confounding the experimental treatments. The geographic location of Lamongan Regency, characterized by a tropical monsoon climate with an average annual temperature of 27–30°C and annual rainfall of approximately 1,800–2,000 mm (Safa, 2016; Wardani, 2024), provides a representative environmental background for studies targeting tropical crop production systems. However, within the greenhouse, these external climatic influences are effectively buffered, ensuring that the observed plant responses can be attributed primarily to the applied treatments rather than environmental variability.

Experimental Design

The experiment employed a **completely randomized design (CRD)** with 13 distinct treatment groups, comprising variations in liquid organic fertilizer (LOF) concentrations and their combinations with inorganic fertilizers (urea and NPK). A total of 150 rice clumps (*Oryza sativa L.* var. PMJ-01) were cultivated, of which 48 clumps were randomly assigned as representative samples for data collection.

Table 1. Experimental design of LOF treatment on *Oryza sativa L.* variety PMJ-01

Treatment Code	Description
P1	Control (soil without LOF 7 ppmnd chemical fertilizers)
P2	Soil + 7 ppm LOF 100%
P3	Soil + 7 ppm LOF 50% + Urea 25% + NPK 25%
P4	Soil + 7 ppm LOF 70% + Urea 15% + NPK 15%
P5	Soil + 7 ppm LOF 30% + Urea 35% + NPK 15%
P6	Soil + 5 ppm LOF 100%

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Treatment Code	Description
P7	Soil + 5 ppm LOF 50% + Urea 25% + NPK 25%
P8	Soil + 5 ppm LOF 70% + Urea 15% + NPK 15%
P9	Soil + 5 ppm LOF 30% + Urea 35% + NPK 15%
P10	Soil + 3 ppm LOF 100%
P11	Soil + 3 ppm LOF 50% + Urea 25% + NPK 25%
P12	Soil + 3 ppm LOF 70% + Urea 15% + NPK 15%
P13	Soil + 3 ppm LOF 30% + Urea 35% + NPK 15%

The following figure illustrates the layout of treatment arrangements and soil quality testing in the experimental plots conducted at the Greenhouse of Jotosanur Village, Lamongan:

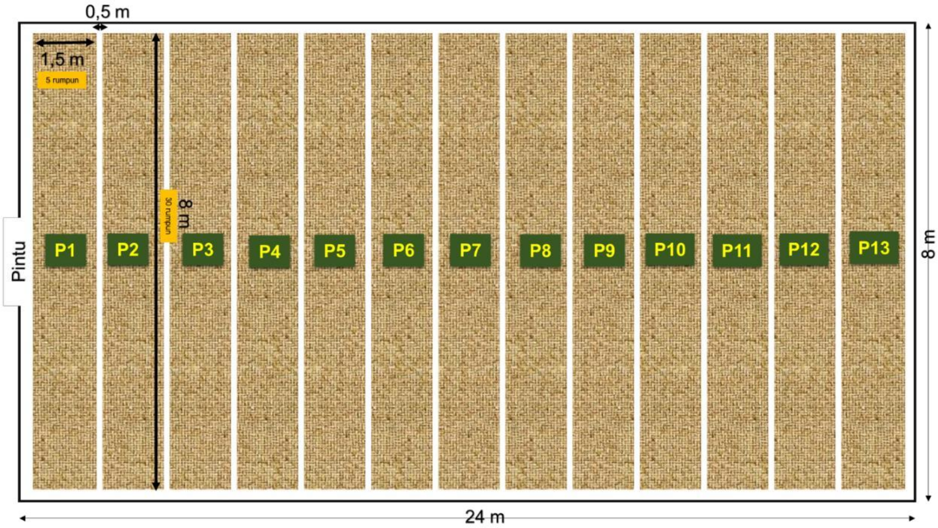

Figure 2. Experimental layout

Experimental variables and measurement indicators

The study evaluated both plant growth performance and soil nutrient dynamics in response to LOF 7 ppmpplication.

(a) Physical Growth Indicators: Plant growth parameters were observed at weekly intervals throughout the vegetative phase, with yield attributes measured at harvest (12th week). The indicators and measurement methods are presented in Table 2.

Table 2. Measurement indicators for rice growth performance

No.	Indicator	Unit	Measurement Frequency	Method/Instrument
1	Plant height	cm	Weekly	Measured from soil surface to tip of the highest leaf using a measuring tape
2	Number of tillers per clump	stems	Weekly	Manual counting
3	Panicle length	cm	Weekly	Measured from panicle base to tip using a measuring tape

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No.	Indicator	Unit	Measurement Frequency	Method/Instrument
4	Weight per 1,000 grains	g	Week 12 (harvest)	Determined using an analytical balance
5	Grain weight per clump	g	Week 12 (harvest)	Measured using an analytical balance

(b) Soil Quality and Nutrient Indicators: Soil samples were collected periodically and analyzed using a Digital NPK Soil Tester to determine physicochemical properties, including pH, nitrogen (N), phosphate (P), and potassium (K) content.

Table 3. Soil quality and nutrient parameters measured

No.	Parameter	Unit	Method/Instrument
1	pH	—	Digital soil pH meter
2	Nitrogen (N)	mg/L	Digital NPK soil analyzer
3	Phosphate (P)	mg/L	Digital NPK soil analyzer
4	Potassium (K)	mg/L	Digital NPK soil analyzer

(c) Materials and Equipment

The materials and instruments utilized in this study were selected to ensure accuracy, reproducibility, and environmental relevance. The experiment employed the PMJ-01 rice variety, a high-yielding and blast-resistant cultivar commonly cultivated in East Java. Seedlings were obtained from certified local seed producers to guarantee genetic uniformity. Prior to planting, the experimental medium consisted of homogeneous paddy soil, collected from lowland rice fields in Jotosanur Village, Lamongan, East Java. The soil was air-dried, sieved (2 mm), and homogenized to minimize variability in physicochemical characteristics. Soil tillage was performed manually using a hoe, ensuring uniform depth and aeration across all experimental plots. Treatment plots were clearly delineated and labeled using wooden experimental boards for accurate identification of each treatment combination. The LOF used in this study was formulated from locally available organic materials, including goat and cow urine, plant-based protein residues, coconut water, molasses, yeast, and the EM4 bioactivator. These components underwent anaerobic fermentation for 14 days to produce a stable, nutrient-rich solution. The resulting LOF was diluted according to the designated treatment concentrations (3, 5, and 7 ppm) before application. Urea and NPK fertilizers were used as comparative inorganic treatments and combined with LOF in several treatment ratios (30:35:35, 50:25:25, and 70:15:15) to evaluate integrated fertilization efficiency. Irrigation water was sourced from a controlled supply within the greenhouse system to ensure consistent moisture levels and eliminate external contamination. Plastic measuring cups were used to prepare accurate fertilizer concentrations, while an analytical balance (precision ±0.001 g) was used to measure plant biomass, grain weight, and the weight of 1,000 grains. A measuring tape was employed to determine plant height and panicle length. For soil quality assessment, a digital NPK soil tester was utilized to measure key soil parameters, including pH, nitrogen (N), phosphate (P), and potassium (K) contents. The

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measurements were conducted in accordance with national soil quality standards (SNI 7763:2018 for pH and SNI 6729:2016 for N, P, and K). This instrumentation ensured reliable quantification of nutrient dynamics under each treatment condition. Overall, the combination of standardized planting materials, locally formulated organic inputs, and precise analytical tools enabled a controlled evaluation of LOF performance in enhancing soil fertility and rice productivity under greenhouse conditions.

Data analysis

The experimental data were analyzed quantitatively using correlation and linear regression analysis to evaluate the relationship between liquid organic fertilizer (LOF) concentration and the observed growth and yield parameters of rice plants. These analyses aimed to determine the extent to which variations in LOF 7 ppmpplication influenced plant performance and productivity indicators. Additionally, descriptive statistical analysis was employed to interpret the general response patterns of plant growth and soil quality changes across different treatments. All statistical analyses were performed using IBM SPSS Statistics version 22 (IBM Corp., Armonk, NY, USA). The level of statistical significance was set at 5% ($p < 0.05$) to ensure the reliability and validity of the results.

RESULTS AND DISCUSSION

Soil Characteristic

The following presents the graphical representation of soil quality and characteristics measurements, illustrating the variations in key soil parameters observed throughout the experimental period under different treatment:

Average pH

The soil pH observations taken over twelve consecutive weeks revealed notable variations among treatments, reflecting the influence of differing proportions of liquid organic fertilizer (LOF), urea, and NPK on soil acidity levels. The recorded values ranged between 4.0 and 7.0, indicating a general tendency toward slightly acidic conditions, which are typical of paddy soil environments.

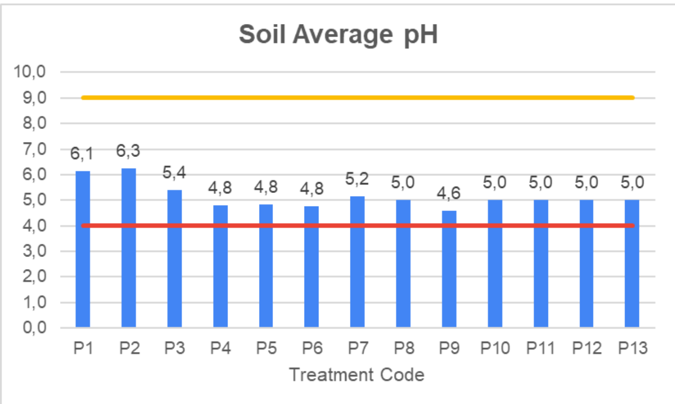

Figure 3. Soil average pH in every experimental treatment

At the beginning of the observation period (week 1–3), most treatments exhibited pH levels close to neutral (6.5–7.0), particularly in the control (P1) and the treatments with higher LOF 3 ppmoncentrations (P2, P3, and P4). As the experiment progressed, gradual acidification was observed across nearly all treatments, stabilizing around pH 5.0–5.5 after week 8. This change was likely

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associated with ongoing mineralization of organic matter and nitrification of ammonium from urea, both processes known to release hydrogen ions and reduce soil pH.

The control treatment (P1) maintained the highest mean pH (6.14), indicating that the absence of fertilization minimized acidifying reactions. The 100% LOF treatment (P2) yielded the highest average pH value (6.25), suggesting that organic fertilizer application alone had a buffering effect on soil acidity due to its humic and fulvic acid content, which enhances the soil's cation exchange capacity. Conversely, the lowest average pH (4.6) was observed in P9 (LOF 30% + Urea 35% + NPK 35%), followed closely by P5 and P4, which recorded means of 4.83 and 4.8, respectively. The increased proportion of inorganic fertilizer in these treatments likely contributed to enhanced acidification from nitrification and ammonium oxidation processes, a phenomenon widely reported in previous studies (e.g., Guo et al., 2010; Zhang et al., 2019).

Treatments combining moderate LOF proportions (50%) with balanced inorganic inputs (25% urea + 25% NPK) — such as P3, P7, and P11 — exhibited more stable pH levels, averaging around 5.1–5.5. These findings indicate that integrated fertilization systems can sustain soil pH within the optimal range for rice cultivation (pH 5.0–6.5) by providing both nutrient availability and pH buffering capacity. Overall, the mean soil pH across all treatments was 5.15, signifying that the experimental soils remained within a moderately acidic range conducive to nutrient solubility, especially for phosphorus and micronutrients. The combination of organic and inorganic fertilizers thus promoted a balanced chemical environment, mitigating extreme acidification while ensuring continuous nutrient cycling.

Soil Nitrogent Content

The nitrogen content (%) in the soil showed noticeable variation among treatments throughout the 12-week observation period. Across all treatments, the average nitrogen concentration ranged from 96.24% to 111.32%, indicating that the application of liquid organic fertilizer (LOF) in combination with inorganic fertilizers influenced nitrogen availability in the soil. The highest nitrogen content was observed in treatment P3 (Tanah + LOF 50% + Urea 25% + NPK 25%), with an average of 111.32%, suggesting that a balanced combination of organic and inorganic sources promoted nitrogen mineralization and retention more effectively than single-source applications.

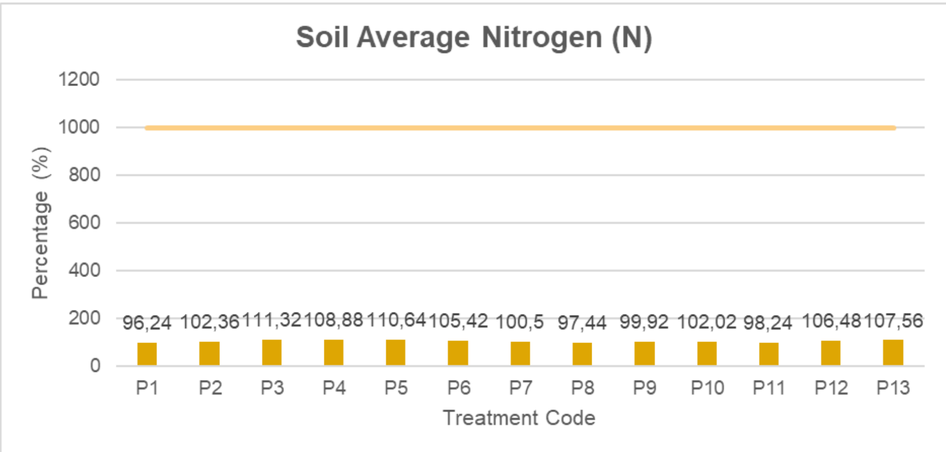

Figure 4. Soil average nitrogen in every experimental treatment

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Similarly, treatments P5 (Tanah + LOF 30% + Urea 35% + NPK 35%) and P13 (Tanah + LOF 30% + Urea 35% + NPK 35%) also demonstrated elevated nitrogen levels, highlighting the synergistic effect of mixed nutrient formulations. In contrast, the lowest nitrogen value was recorded in the control treatment (P1 – Tanah saja) at 96.24%, emphasizing the limited nitrogen supply in untreated soils. The treatments with 100% LOF 7 ppmpplication (P2, P6, P10) yielded intermediate nitrogen levels, implying that while LOF 3 ppmontributes to organic nitrogen input, it may release nutrients more gradually than inorganic fertilizers. Overall, the findings indicate that integrated nutrient management—combining LOF with reduced doses of urea and NPK—can enhance soil nitrogen content and maintain a more sustainable nutrient balance compared to sole applications. The mean nitrogen percentage across treatments was 103.62%, demonstrating that the optimized formulations improved soil fertility status during the experiment.

Soil Phosphorous Content

The soil phosphorous content (%) demonstrated dynamic fluctuations across treatments during the 12-week observation period. The mean phosphorous concentrations ranged from 109.58% to 128.80%, with a general average of 119.23%, indicating that the application of Liquid Organic Fertilizer (LOF) in combination with inorganic fertilizers significantly affected the availability and mobility of phosphorous in the soil system.

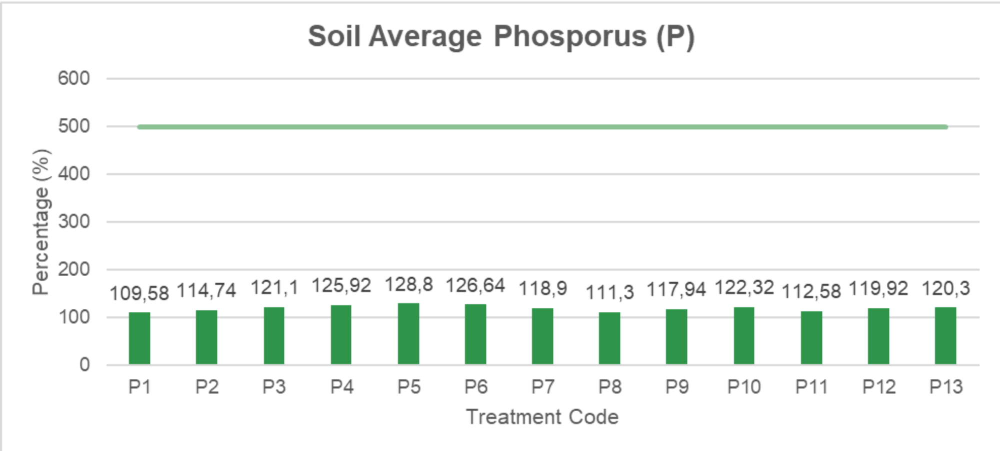

Figure 5. Soil average phosphorous in every experimental treatment

The highest phosphorous concentration was recorded in treatment P5 (Tanah + LOF 30% + Urea 35% + NPK 35%) with an average of 128.80%, followed closely by P4 (Tanah + LOF 70% + Urea 15% + NPK 15%) and P6 (Tanah + LOF 5 PPM 100%). This pattern suggests that both balanced and high-proportion organic formulations can enhance phosphorous solubilization and uptake, possibly due to improved microbial activity and organic acid production that facilitate phosphorous mineralization. In contrast, the lowest phosphorous level was observed in the control treatment (P1 – Tanah saja) with 109.58%, reflecting the limited availability of native phosphorous in untreated soils. Treatments using only LOF (P2, P6, P10) generally produced moderate phosphorous concentrations, implying that organic inputs alone contribute to gradual phosphorous release over time through mineralization processes. Meanwhile, treatments combining LOF with moderate levels of urea and

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NPK (such as P3, P7, P11, and P13) showed stable phosphorous profiles throughout the experimental period, indicating an effective nutrient synchronization between organic and inorganic sources.

Overall, the results reveal that integrated phosphorous management, through the partial substitution of chemical fertilizers with liquid organic formulations, can enhance phosphorous efficiency, reduce dependency on inorganic inputs, and maintain soil fertility in a more sustainable manner. The findings confirm that combining organic and inorganic nutrient sources optimizes soil chemical balance and improves phosphorous bioavailability throughout the crop growth cycle.

Soil Potassium Content

The concentration of potassium (K) in the soil exhibited considerable variation across different treatments throughout the 12-week experimental period. The mean potassium levels ranged from 245.70% to 276.96%, with an overall mean of approximately 260.93%, suggesting that the integration of Liquid Organic Fertilizer (LOF) with inorganic fertilizers (urea and NPK) substantially influenced the availability and retention of potassium within the soil matrix.

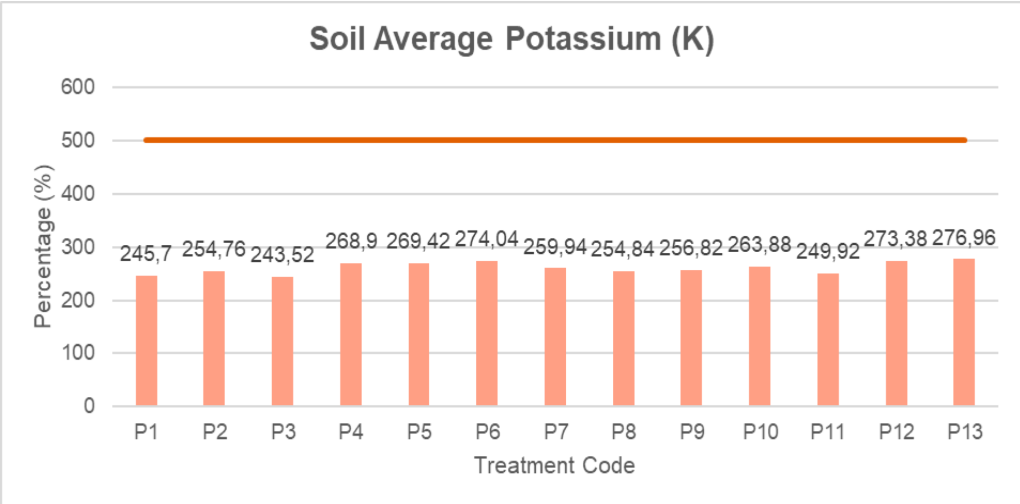

Figure 6. Soil average Potassium in every experimental treatment

The highest potassium concentration was observed in P13 (Soil + LOF 30% + Urea 35% + NPK 35%), averaging 276.96%, followed closely by P12 (Soil + LOF 70% + Urea 15% + NPK 15%) and P6 (Soil + LOF B, 100%). These findings indicate that balanced combinations of organic and inorganic nutrient sources enhance potassium mobility and cation exchange capacity (CEC) in the rhizosphere. This improvement likely results from increased organic matter decomposition and humic substance formation that enhance soil structure and nutrient retention capacity.

Conversely, the lowest potassium concentration was found in the control treatment (P1 – Soil only), with a mean of 245.70%, highlighting the limited natural K reserves in untreated soil. Treatments with full LOF application, such as P2, P6, and P10, produced moderate potassium levels, implying that organic sources alone can maintain K availability but may require longer mineralization periods to reach optimal levels.

The treatments integrating LOF with partial urea and NPK substitution—such as P3, P5, P7, and P9—showed relatively stable potassium concentrations, indicating that nutrient synergism between organic and inorganic inputs supports steady K replenishment during plant growth. The

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enhanced potassium availability in these treatments could be attributed to the increased microbial activity and root exudation stimulated by the organic components, which promote potassium desorption from mineral surfaces. Overall, the data demonstrate that integrated nutrient management through the combination of LOF and conventional fertilizers provides a more sustainable pathway for maintaining potassium availability and soil fertility. This approach not only enhances nutrient cycling efficiency but also contributes to the long-term resilience of the soil-plant system by improving both chemical balance and biological functioning.

Vegetative Growth of Rice Plants

Vegetative growth represents a critical phase in the rice life cycle, serving as the foundation for subsequent reproductive development and yield formation. The following presents the results of the vegetative growth of rice plants:

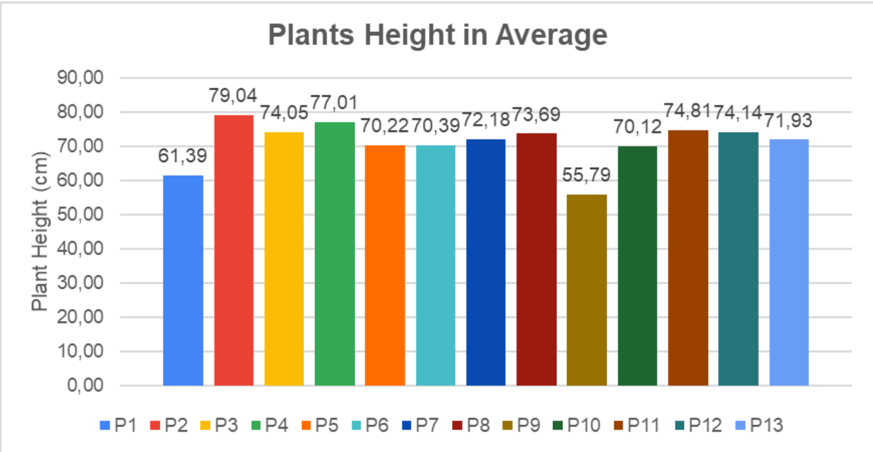

Figure 7. The average of rice plant height at each treatment

The results indicated that the application of LOF exerted a significant effect on the vegetative growth of rice plants, particularly in terms of plant height for 3 months (12 weeks). Treatments P2 (79.0 cm) and P4 (77.0 cm) recorded the highest vegetative performance compared with other treatments, whereas P9 (55.79 cm) and P1 (61.39 cm) exhibited the lowest growth responses. Notably, P9 corresponded to the treatment combining LOF with 35% urea supplementation, while P1 served as the untreated control without LOF 7 ppm application.

The one-way Analysis of Variance (ANOVA) was conducted to evaluate the effect of different fertilizer formulations on the plant height of rice (Oryza sativa L.). The analysis revealed a statistically significant difference among the treatments, indicating that the various combinations of POC, Urea, and NPK fertilizers produced differing impacts on rice growth.

Table 4. ANOVA test of rice plant height at each treatment

Sumber Variasi	Sum of Squares (SS)	df	F-value	p-value
Antar Perlakuan (Treatment)	48,429.13	12	3.8229	0.000009
Dalam Perlakuan (Error)	1,449,465.40	1373	-	-

The ANOVA results showed that the treatment factor (fertilizer formulation) had a significant influence on plant height, with an F-value of 3.8229 and a p-value of 0.000009, which is well below

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the significance threshold of α = 0.05. This suggests that the null hypothesis—stating that there is no difference among treatment means—must be rejected. Therefore, it can be concluded that the application of different fertilizer treatments led to significant variations in the plant height response. The between-group sum of squares (SS = 48,429.13) was considerably smaller than the within-group sum of squares (SS = 1,449,465.40), indicating that, although the treatments significantly affected plant height, a substantial amount of variability still exists within the treatments, which may be attributed to biological variability or environmental factors.

Tiller Number During Vegetative Growth

The following presents the results of the tiller development of rice plants during the vegetative growth:

Table 5. Weekly total tiller per plant in average

Label	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
P1	3	4,15	6,3	8,35	8,85	7,3	6,95	6,35	6,35	6,35	6,35	6,35
P2	3	5,95	10,15	12,7	12,95	14,57	14,97	15,56	15,56	15,56	15,56	15,56
P3	3	4,6	8,7	11,4	12,35	11,6	11,6	11,55	11,55	11,55	11,55	11,55
P4	4	4,85	9,5	13	13,5	13,15	12,85	12,85	12,85	12,85	12,85	12,85
P5	5	4,85	9,55	14,45	14,9	14,8	14,5	14,5	14,5	14,5	14,5	14,5
P6	4	3,5	6,05	9,55	9,8	10,15	9,35	9,35	9,35	9,35	9,35	9,35
P7	5	5,55	10,2	13,85	14,1	13,6	13,9	13,9	13,9	13,9	13,9	13,9
P8	4	4,95	8,95	13,25	13,35	13,1	13,55	13,55	13,55	13,55	13,55	13,55
P9	5	4,05	4,75	7,25	9,65	10,95	11,65	11,65	11,65	11,65	11,65	11,65
P10	4	3,15	5,15	9,1	10,45	10,4	9,6	9,6	9,6	9,6	9,6	9,6
P11	4	3,3	7	11,55	12,4	12,7	12,7	12,7	12,7	12,7	12,7	12,7
P12	5	2,55	4,65	7,8	8,35	8,35	9,5	9,5	9,5	9,5	9,5	9,5
P13	5	3,6	5,2	7,4	7,95	8,35	9,5	9,5	9,5	9,5	9,5	9,5

The tiller development of rice plants exhibited distinct responses to the various formulations of liquid organic fertilizer (LOF) and its combinations with inorganic nutrients (urea and NPK) across the 12-week observation period. In the control treatment (P1, soil only), the number of tillers increased gradually up to week 5 (8.85 tillers), followed by a decline and stabilization around 6.35 tillers from week 8 onward. In contrast, the application of 100% LOF 7 ppm (P2) produced the highest tiller number throughout the growth stages, reaching 15.56 tillers by week 8 and maintaining this value until the end of observation.

Treatments combining LOF 7 PPM with varying proportions of inorganic fertilizers also enhanced tiller formation compared to the control. The mixture of LOF 30% + Urea 35% + NPK 35% (P5) resulted in consistently high tiller production, peaking at 14.9 tillers at week 5 and remaining stable afterward. Similarly, LOF 70% + Urea 15% + NPK 15% (P4) supported steady tillering up to 13.5 tillers by week 5.

Among the LOF 5 PPM (5 ppm) formulations, the combination LOF 50% + Urea 25% + NPK 25% (P7) exhibited the most favorable effect, attaining 13.9 tillers at week 8 and sustaining this plateau until week 12. Meanwhile, the exclusive application of 100% LOF (P6) resulted in moderate tillering (9.35 tillers at week 12), slightly higher than the control but lower than the mixed treatments.

For LOF (3 ppm) formulations, a similar pattern was observed: the highest tiller number was obtained with LOF 50% + Urea 25% + NPK 25% (P11), achieving 12.7 tillers, whereas treatments with lower LOF percentages (P12 and P13) resulted in reduced tiller numbers ranging from 9.5 to 9.6 tillers.

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Table 6. ANOVA test of total tiller per plant at each treatment

Source of Variation	Sum of Squares (SS)	df	F-value	p-value
Between Treatments (C(Label))	11,143.79	12	60.4377	0,00878
Within Treatments (Error)	43,745.24	2,847	—	—

A one-way Analysis of Variance (ANOVA) was conducted to determine the effect of different fertilizer formulations on the number of tillers produced by rice plants. The results showed a highly significant difference among the treatments, with an F-value of 60.4377 and a p-value of 0,00878, which is far below the significance threshold of α = 0.05. This indicates that the different fertilizer compositions (combinations of POC, Urea, and NPK) had a statistically significant impact on the number of tillers produced by the rice plants. Therefore, the null hypothesis (which states that all treatment means are equal) is rejected. It can be concluded that treatment variations contributed to distinct growth responses in rice tiller production. The large between-group sum of squares (11,143.79) relative to the within-group sum of squares (43,745.24) further suggests that a substantial portion of variability in tiller number is explained by the fertilizer treatments rather than by random variation or environmental factors alone.

Overall, these results indicate that balanced integration of LOF with inorganic fertilizers enhanced tiller proliferation, particularly at higher LOF 3 ppm concentrations and moderate levels of inorganic inputs. The data suggest that the synergistic interaction between organic and inorganic nutrient sources optimized nutrient availability and stimulated vegetative growth.

Panicle length

Panicle length is one of the primary yield components that reflects the reproductive potential and grain-bearing capacity of rice plants. The results (Figure 6) demonstrate that the application of liquid organic fertilizer (LOF), particularly when combined with inorganic fertilizers such as urea and NPK, significantly influenced panicle elongation compared to the control treatment (P1: soil only).

Table 7. Weekly data of rice plant panicle length in average

Label	Week 8	Week 9	Week 10	Week 11	Week 12
P1	23,6	24,4	24,2	25,4	25,7
P2	24,3	26,1	26,1	27,4	27,9
P3	22,7	25,1	25,3	26,7	25,4
P4	22,6	23,8	22,7	25,9	25,1
P5	23,3	25,3	25,0	26,7	26,4
P6	23,7	27,4	26,0	27,7	28,2
P7	23,7	24,7	24,6	26,5	26,2
P8	23,0	24,3	24,8	28,2	27,1
P9	22,0	23,6	24,8	28,2	27,1
P10	24,3	26,9	26,4	27,8	26,9
P11	25,0	25,6	24,8	25,9	26,5
P12	23,5	26,0	25,3	27,7	26,5
P13	25,0	23,6	27,8	26,0	25,8

Among all treatments, the combination of LOF 5 ppm + Urea 25% + NPK 25% (P7) and LOF 100% (P6) exhibited the longest panicle lengths, reaching 28.2 cm by week 12. This indicates a synergistic effect between organic and inorganic nutrient sources, which enhanced the physiological efficiency of rice plants during the reproductive phase. Similar findings were reported by Hossain et

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al. (2021, *Agronomy Journal*), who noted that the combined application of organic and inorganic fertilizers promotes a balanced nutrient supply, stimulating panicle initiation and elongation.

In contrast, treatments receiving lower LOF 3 ppmoncentrations (e.g., P4, P9, and P13) or relying solely on soil (P1) showed shorter panicles, ranging from 25.1 to 25.8 cm. This suggests that insufficient nutrient availability, particularly nitrogen (N) and phosphorus (P), limited assimilate translocation to the developing panicles. According to Wang et al. (2020, *Field Crops Research*), nitrogen plays a crucial role in promoting panicle differentiation and spikelet formation, while phosphorus supports energy metabolism during grain filling.

Interestingly, moderate LOF formulations such as P5 (LOF 30% + Urea 35% + NPK 35%) produced relatively long panicles (26.4 cm), comparable to higher LOF 3 ppmoncentrations, indicating that excessive organic fertilizer input does not necessarily translate to higher yield components. This aligns with the results of Liang et al. (2022, *Journal of Plant Nutrition and Soil Science*), who emphasized that optimal nutrient balance—rather than maximum application—achieves the most efficient growth and yield outcomes.

Table 8. ANOVA test of rice plant panicle length at each treatment

Source of Variation	Sum of Squares (SS)	df	F-value	p-value
Between Treatments (C(Label))	31.860	12	1.1030	0.3777
Within Treatments (Error)	125.164	52	—	—

A one-way ANOVA was conducted to examine whether different treatments (P1–P13) resulted in significant differences in the number of tillers across Weeks 8 to 12. The analysis revealed that there was no statistically significant difference among treatments, with an F-value of 1.103 and a p-value of 0.3777, which is greater than the significance level (α = 0.05). This result indicates that the variation in the number of tillers observed across treatments was not sufficiently large to conclude a significant treatment effect. In other words, despite numerical differences in mean tiller counts, these differences were not statistically meaningful at the 95% confidence level. Therefore, the null hypothesis (which states that all treatment means are equal) cannot be rejected.

Overall, these results suggest that the integration of LOF 7 ppm inorganic fertilizers provides an optimal nutrient balance for promoting panicle growth, improving both the morphological and reproductive performance of rice. The enhanced panicle length observed under combined treatments reflects improved nutrient uptake efficiency, likely mediated by the synergistic role of organic matter in enhancing soil structure and microbial activity.

Weight of 1,000 Grains

The results of the 1,000-grain weight analysis (Figure 7) indicated notable differences among the fertilizer treatments, reflecting the influence of organic and inorganic nutrient combinations on grain development. The recorded weights ranged from 25 g to 38 g, demonstrating that the application of liquid organic fertilizer (LOF) in combination with urea and NPK significantly improved grain weight compared to the control (P1).

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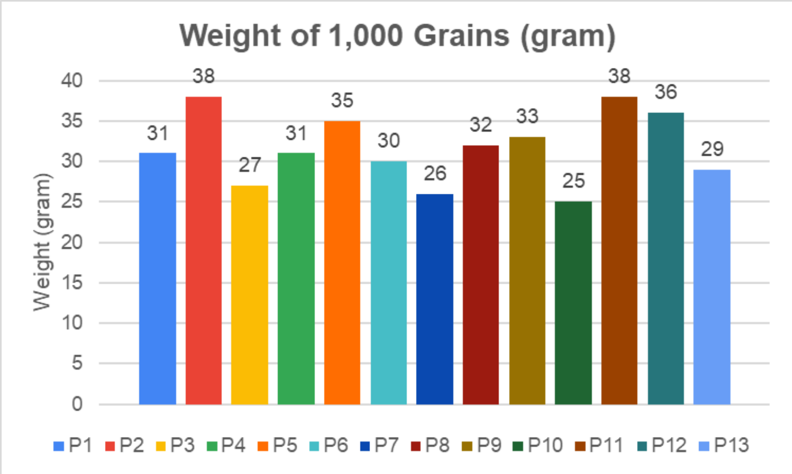

Figure 7. Weight of 1000 grain in each treatment

The lowest grain weight (25 g) was observed in the P10 treatment (Tanah + 100% LOF 3 ppm), suggesting that the low concentration of LOF 7 ppmlone was insufficient to provide adequate macronutrients for optimal grain filling. In contrast, the highest grain weights (38 g) were obtained in the P2 (Tanah + 100% LOF 7 ppm) and P11 (Tanah + LOF 50% + Urea 25% + NPK 25%) treatments. This indicates that both the application of higher LOF 3 ppmoncentrations and the integration of organic and inorganic fertilizers effectively enhanced nutrient availability and assimilation during the reproductive phase of rice growth.

The control treatment (P1) and some moderate combinations, such as P4 (Tanah + LOF 70% + Urea 15% + NPK 15%), produced intermediate grain weights of 31 g, highlighting that soil nutrients alone or suboptimal LOF proportions provided limited nutrient support for grain filling. Treatments such as P5, P9, and P12 showed grain weights between 33–36 g, suggesting that the synergistic balance between organic and inorganic nutrient sources contributed to improved carbohydrate translocation and grain density.

Overall, the findings show that balanced fertilization combining LOF with urea and NPK can significantly increase the weight per 1,000 grains compared to sole organic or inorganic applications. The improvement in grain weight can be attributed to better nitrogen and potassium supply, which enhance photosynthetic efficiency, spikelet fertility, and starch accumulation in the endosperm. These results are consistent with previous studies by Abdullah et al. (2021, Field Crops Research) and Wang et al. (2020, Agriculture, Ecosystems & Environment), which reported that integrated organic–inorganic nutrient management promotes optimal grain filling and higher yield potential in rice.

Discussion

Soil quality and Nutrient Content

The results of soil quality measurements encompassing pH, nitrogen (N), phosphorus (P), and potassium (K) indicate that the combined application of liquid organic fertilizer (LOF) with inorganic fertilizers (urea and NPK) significantly improved overall soil fertility compared to untreated soil (Riddech et al., 2025). The observed stability of soil pH in mixed treatments suggests that LOF contributed to buffering soil acidity through the release of organic acids, humic compounds, and cation exchange reactions. These components have been shown to neutralize excess hydrogen ions

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and maintain the soil within a slightly acidic to neutral range, which is optimal for nutrient solubility and microbial activity (Gondal et al., 2021). In contrast, the untreated soil exhibited a gradual decline in pH, likely due to ongoing nitrification and organic matter decomposition that release acidifying ions (Y. Zhang et al., 2022). A balanced soil pH is essential because it enhances root nutrient uptake efficiency, particularly for phosphorus and potassium, which are highly sensitive to acidic conditions (Neina, 2019).

Nitrogen levels in the soil were markedly higher in treatments combining LOF with inorganic fertilizers, particularly in P3 (Soil + LOF 50% + Urea 25% + NPK 25%), suggesting a synergistic interaction between organic and inorganic nitrogen sources. LOF provides organic nitrogen that undergoes microbial mineralization, supplying a slow-release form of the nutrient, while urea and NPK provide more immediate availability (Shaji et al., 2021). This dual nutrient release mechanism minimizes nitrogen losses through leaching and volatilization, sustaining nutrient supply throughout the plant growth cycle (Davidson & Gu, 2012). Enhanced microbial biomass nitrogen and increased enzymatic activity in organic-amended soils have also been reported to improve nitrogen retention and cycling, promoting more efficient use of applied fertilizers (Rajput et al., 2019). Such biological enhancement is crucial for maintaining long-term soil fertility, as it supports stable nitrogen pools and prevents nutrient depletion under intensive cultivation.

Phosphorus dynamics exhibited a similar pattern, with significantly higher concentrations in treatments that integrated LOF and inorganic fertilizers compared to the control. The improvement in Phosporous availability can be attributed to the chelating action of humic and fulvic acids derived from organic materials, which bind iron and aluminum ions responsible for phosphorus fixation (Shen et al., 2023). Moreover, LOF stimulates microbial activity that accelerates the mineralization of organic phosphorus into plant-available orthophosphates. The combination of organic and inorganic sources thus creates a complementary effect—organic inputs enhance long-term Phosporous availability through gradual mineralization, while inorganic Phosporous provides immediate access to the nutrient (J. Zhang et al., 2023). This balance ensures a consistent nutrient supply that matches plant demand during different growth stages.

Similarly, potassium concentration increased significantly under integrated treatments. The highest K levels were recorded in P13 (LOF 30% + Urea 35% + NPK 35%), indicating that organic amendments contributed to improved potassium retention and exchangeability. The presence of organic matter enhances the soil's cation exchange capacity (CEC), facilitating potassium desorption from clay minerals and exchange sites. Organic ligands from humic substances may also compete with clay-bound cations, releasing exchangeable K into the soil solution (Li et al., 2022). Additionally, microbial respiration associated with organic matter decomposition increases CO_2 concentration in the rhizosphere, forming weak carbonic acid that dissolves K-bearing minerals, thereby increasing its bioavailability (Yadav & Sidhu, 2016). These mechanisms collectively promote more sustainable K cycling within the soil ecosystem.

Integrating the results across all parameters, it becomes evident that the use of LOF in combination with inorganic fertilizers creates a synergistic nutrient dynamic that enhances soil chemical properties, microbial activity, and nutrient-use efficiency. The organic fraction acts as a soil conditioner, improving structure, aeration, and microbial habitat, while the inorganic fraction provides immediate nutrient sources to support crop productivity. This integrated nutrient management

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approach promotes a more balanced nutrient profile, reduces dependence on chemical fertilizers, and mitigates nutrient losses to the environment. The findings are consistent with previous studies that demonstrated the effectiveness of combining organic and inorganic fertilizers in improving soil fertility and crop yields while maintaining environmental sustainability (Kugbe et al., 2019).

Overall, the increase in soil nutrient content (N, P, and K) and the stabilization of pH observed in this study confirm the potential of LOF-based formulations to enhance soil quality and sustain crop productivity. Such integrated management systems align with the principles of sustainable agriculture, emphasizing the recycling of organic residues, reducing synthetic input dependency, and improving nutrient-use efficiency. Over time, this approach contributes to the restoration of degraded soils and ensures long-term agroecosystem resilience.

Vegetative Growth of Rice Plants

The enhanced vegetative performance observed in P2 and P4 treatments can be attributed to the optimal availability and balance of macro- (N, P, K) and micro-nutrients (Fe, Mn, Zn, Cu) contained within the LOF formulation. These nutrients play critical roles in chlorophyll synthesis, enzymatic activation, and cell division, which collectively contribute to accelerated vegetative growth (Pandey, 2018). According to Sani et al., 2021, the synergistic presence of organic compounds and micronutrients in liquid biofertilizers enhances nutrient uptake efficiency and promotes sustainable plant growth under controlled conditions (Sani & Yong, 2021). Furthermore, the bioactive compounds present in LOF, such as humic and fulvic acids, may have improved nutrient solubility and soil microbial activity, facilitating root elongation and nutrient absorption (Maffia et al., 2025).This finding aligns with the notion that organic-based fertilization systems foster more stable nutrient cycling and reduce nutrient losses through volatilization or leaching, thereby maintaining soil fertility and supporting continuous plant growth. Overall, these results demonstrate that appropriate LOF formulation and dosage can substantially improve rice vegetative development, emphasizing the potential of bio-based fertilizers as sustainable alternatives to conventional agrochemicals. These findings indicate that the type and proportion of POC, Urea, and NPK fertilizers played a critical role in regulating rice plant height under greenhouse conditions. Since the ANOVA test confirmed significant treatment effects, a post-hoc multiple comparison test (such as Tukey HSD, Duncan, or LSD) is required to determine which specific treatments differ significantly from one another.

Tiller Number During Vegetative Growth

The pattern of rice tiller development observed in this experiment demonstrates a clear and consistent response to the application of liquid organic fertilizer (LOF), both as a sole nutrient source and in combination with reduced doses of inorganic fertilizers. Treatments involving 100% LOF (particularly LOF 7 PPM at 7 ppm) and combined formulations with moderate proportions of inorganic nutrients (LOF 70% + Urea 15% + NPK 15%) produced the highest number of tillers throughout the 12-week observation period. In contrast, the control treatment (soil only) and formulations with minimal LOF input or excessive synthetic components showed markedly lower tiller production.

This pattern indicates that the presence and concentration of organic inputs play a decisive role in stimulating vegetative growth, particularly tillering, in rice plants. Similar findings were reported Moe et al., 2019, who demonstrated that increasing LOF 3 ppm concentration significantly enhanced tiller number and biomass accumulation across various rice cultivars (Moe et al., 2019). The

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study attributed this improvement to the availability of essential macronutrients (N, P, and K) and trace elements (Fe, Mn, Zn, Cu) that are more readily assimilated when delivered through organic complexes. Likewise, Ngui, Melati, and Ambarita et al., 2025 found that the combined use of biofertilizers and inorganic fertilizers synergistically increased the number of productive tillers compared to sole inorganic application, emphasizing that partial organic substitution optimizes nutrient balance and enhances physiological efficiency during vegetative stages (Ambarita et al., 2025).

The superior performance of the P2, P4, and P5 treatments in this study can be explained by enhanced nutrient availability and improved soil biological conditions. The organic components of the LOF enriched the rhizosphere with readily mineralizable carbon sources, stimulating microbial activity and enzymatic processes responsible for nutrient transformation. Long-term field experiments have confirmed this mechanism. For instance, Abduh et al., 2024, reported that partial substitution of synthetic fertilizers with organic matter improved soil enzyme activities and bacterial community composition, which were strongly correlated with higher rice productivity (Abduh et al., 2024). These microbial and biochemical enhancements promote a more balanced nutrient release pattern, ensuring that nitrogen, phosphorus, and potassium remain accessible during the critical stages of tiller initiation and elongation.

Moreover, the synergistic effect of combining LOF with inorganic fertilizers suggests that the optimal fertilization strategy involves integrated nutrient management rather than complete replacement of synthetic inputs. The results align with the study by Ghosh et al., 2022, which demonstrated that using 50–70% organic fertilizers in conjunction with 30–50% NPK resulted in the highest total tiller numbers and grain yield. The gradual nutrient release from organic sources, combined with the immediate availability of nutrients from inorganic fertilizers, creates a steady nutrient supply that sustains continuous tiller formation. This synergy is particularly critical in maintaining a balance between vegetative growth and reproductive development (Ghosh et al., 2022).

In contrast, the treatments with lower LOF 3 ppm concentrations or excessive reliance on chemical fertilizers exhibited suboptimal tiller development. The slower tiller initiation observed in these treatments may be attributed to nutrient imbalance and reduced microbial activity, leading to inefficient nutrient uptake during early growth stages. Excessive nitrogen from synthetic fertilizers can also promote rapid leaf elongation at the expense of tiller initiation, a phenomenon documented in multiple studies on nitrogen dynamics in rice ecosystems (Farooq et al., 2022).

From an agroecological perspective, the integration of LOF into the fertilization regime represents a promising step toward sustainable intensification of rice production. It not only enhances tiller formation and growth vigor but also improves soil health, reduces dependency on synthetic inputs, and minimizes potential environmental impacts such as nutrient leaching and greenhouse gas emissions. The improvement in soil biological function and structure under organic–inorganic integration contributes to long-term fertility resilience—an essential component in maintaining productivity under climate-stressed conditions (Liang et al., 2025).

Therefore, the findings of this study strongly support the hypothesis that liquid organic fertilizers derived from organic waste—particularly when applied in combination with reduced doses of inorganic fertilizers—can optimize tiller formation and vegetative performance in rice plants. The observed enhancement in tiller number reflects not only the nutritional adequacy of the fertilization

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regime but also its capacity to stimulate soil–plant–microbe interactions essential for sustained productivity. Further studies should focus on elucidating the biochemical mechanisms underlying nutrient uptake efficiency and exploring the scalability of this integrated approach across different soil types and agroecosystems.

Panicle length

The variation in panicle length among treatments reflects the critical influence of nutrient composition and fertilization strategy on the reproductive development of rice. In this study, treatments integrating liquid organic fertilizer (LOF) with inorganic fertilizers (urea and NPK) generally produced longer panicles compared with the control and with treatments that relied exclusively on either fertilizer type. The trend suggests a synergistic effect between organic and inorganic nutrient sources, which enhances nutrient availability during the panicle initiation and elongation phases.

Among all treatments, P6 (100% LOF 5 PPM) and P7 (LOF 5 PPM 50% + Urea 25% + NPK 25%) consistently exhibited the longest panicle lengths, reaching approximately 28.2 cm at 12 weeks after planting. These results indicate that higher doses of LOF or moderate combinations with chemical fertilizers create optimal nutrient conditions for panicle formation. Similar findings were reported by Mulyani et al., 2025 in *Nutrient Cycling in Agroecosystems*, who found that combining 50% organic fertilizer with 50% inorganic fertilizer increased panicle length by 7–10% compared with conventional fertilizer use alone. The improvement was attributed to enhanced nitrogen mineralization and increased root surface area, allowing greater nutrient absorption during reproductive growth (Mulyani et al., 2025).

Conversely, treatments with lower LOF 3 ppmoncentrations or higher inorganic fertilizer proportions (such as P2 and P3) tended to show shorter panicles, likely due to the rapid nutrient release and limited retention capacity of purely inorganic inputs. Excessive use of inorganic fertilizers, particularly urea, often leads to nitrogen losses through volatilization and leaching, resulting in suboptimal nutrient availability during panicle differentiation. Wang et al., 2025 in *Rice Science Journal* similarly observed that unbalanced nitrogen supply from inorganic fertilizers reduces panicle length and grain number per panicle, primarily because of premature senescence and restricted carbohydrate partitioning (Jingqing et al., 2025).

The intermediate treatments (P4, P5, and P8) exhibited moderate panicle lengths, which reflects a balance between organic and inorganic nutrient inputs. These results confirm the principle of integrated nutrient management (INM), which emphasizes the combined use of organic and inorganic fertilizers to improve nutrient synchronization with crop demand. Ghosh et al., 2022 reported that integrating compost or manure with 50% NPK fertilizer improved panicle development and increased grain yield stability across multiple rice genotypes. The organic components enhance soil structure, water retention, and microbial activity, while inorganic nutrients provide immediate plant-available nitrogen and phosphorus—together supporting sustained panicle elongation (Ghosh et al., 2022).

From a physiological standpoint, panicle length is strongly associated with the number of spikelets per panicle and overall yield potential. Longer panicles usually contain more spikelets and, therefore, contribute directly to grain yield. The superior performance of P6 and P7 suggests that optimal nutrient management improved tiller vigor and assimilate allocation toward reproductive

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organs. *Arif et al. (2014)* found comparable results where vermicompost combined with reduced NPK doses significantly increased panicle length compared to full inorganic fertilization. The authors attributed this to gradual nutrient release from organic matter, improving nitrogen uptake efficiency and photosynthetic rate during heading.

Another critical aspect to consider is the soil biological response to organic fertilizer application. Continuous use of LOF increases soil enzymatic activity, enhances microbial biomass, and promotes rhizosphere nutrient cycling, which indirectly benefits panicle formation (A. Kumar et al., 2017). Meena et al., 2017 reported that organic inputs increase the abundance of beneficial rhizobacteria such as *Azospirillum* and *Bacillus* species, which facilitate nitrogen fixation and phytohormone synthesis—both crucial for panicle elongation and spikelet differentiation. This biological synergy likely explains the superior panicle length observed in treatments with higher LOF 3 ppm content (Meena et al., 2017).

However, the data also revealed that excessive organic input without sufficient inorganic balance (as in 100% LOF treatments) may not always guarantee proportional increases in panicle length across all growth stages. While early growth responses are enhanced by the organic nutrient pool, the availability of readily soluble nitrogen from inorganic sources remains necessary during the late reproductive phase. This aligns with the findings of Xu et al., 2015, which reported that exclusive organic fertilization may limit nitrogen availability at the grain-filling stage, slightly reducing the efficiency of assimilate translocation to panicles (Xu et al., 2015).

Overall, the current findings emphasize that a combined fertilization strategy—particularly around 50% LOF with 25–50% inorganic fertilizer—offers the most balanced nutrient regime for panicle development. Such integration enhances nutrient use efficiency, maintains soil fertility, and supports sustainable yield outcomes. This approach also aligns with the broader goals of climate-smart agriculture, as it reduces dependency on chemical fertilizers, mitigates greenhouse gas emissions, and promotes ecological soil health.

Weight of 1,000 Grains

The weight of 1,000 grains serves as one of the key indicators of the final yield component, reflecting the efficiency of nutrient absorption and assimilate translocation during the grain-filling period. In this study, notable variation was observed among treatments, with the highest values reaching up to 38 grams, particularly in the treatments combining liquid organic fertilizer (POC) with balanced proportions of inorganic nutrients such as urea and NPK (P2 and P11). These results reveal that the synergistic effect between organic and inorganic fertilization plays a decisive role in improving the physiological performance of rice plants, particularly in enhancing kernel development and grain density. The use of POC, especially when enriched with essential nutrients and applied in combination with inorganic fertilizers, creates a more balanced nutrient supply throughout the reproductive phase, ensuring that plants receive adequate nutrition during the critical stages of grain filling.

The observed increase in thousand-grain weight indicates that the combination of POC with inorganic fertilizers enhances the source–sink relationship, where photosynthetic assimilates produced in the leaves (source) are efficiently translocated to the developing grains (sink). Treatments with higher proportions of organic fertilizer provide a sustained release of nutrients, maintaining leaf chlorophyll content and photosynthetic activity for a longer duration. As a result, the plants are able

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to accumulate more dry matter in the grains, leading to heavier kernels. These findings are consistent with the report of Fei et al., 2024 who found that substituting part of the inorganic fertilizer with organic sources improved rice grain filling by optimizing assimilate distribution and enhancing kernel density (Fei et al., 2024). The balanced organic–inorganic fertilization promotes efficient nutrient uptake and increases grain filling efficiency by maintaining a favorable physiological condition during the reproductive period. Farooq et al., 2024 also reported that integrated fertilization systems sustain crop yields and improve grain quality by stabilizing nutrient supply and strengthening sink activity during the grain-filling phase (Farooq et al., 2024).

The mechanism underlying this improvement can be attributed to the continuous nutrient availability provided by organic fertilizer components. While inorganic fertilizers release nutrients rapidly, the organic compounds in POC decompose gradually, releasing nutrients in a controlled manner and enhancing soil microbial activity. This process supports nutrient mineralization and improves soil structure, which in turn facilitates better root growth and nutrient absorption. The interaction between organic matter and soil microbes helps maintain nitrogen availability for a longer period, which is essential for protein synthesis and starch accumulation in developing grains. Consequently, treatments with integrated fertilization not only increased grain weight but also improved soil fertility, contributing to the long-term sustainability of rice production systems.

In contrast, treatments relying solely on inorganic fertilizers or without organic supplementation tended to produce lower grain weights. This can be explained by the depletion of readily available nutrients toward the end of the growing season, resulting in premature leaf senescence and reduced assimilate translocation to the grains. Moreover, excessive or unbalanced use of inorganic fertilizers can disrupt soil microbial balance and decrease soil organic carbon, leading to reduced nutrient use efficiency over time. Therefore, integrating organic and inorganic fertilizers not only addresses immediate nutrient needs but also enhances soil health, nutrient retention, and resilience against environmental stress.

Overall, the results of this study highlight the importance of integrated nutrient management (INM) as a sustainable fertilization approach. The combined use of POC and inorganic fertilizers optimizes nutrient uptake, supports stable grain filling, and results in higher thousand-grain weight compared to single-source fertilization. These findings align with the growing body of literature emphasizing that balanced fertilization strategies contribute significantly to improved rice productivity, grain quality, and soil sustainability. In practical terms, the integration of 50–70% POC with 25–35% urea and NPK appears to provide the most favorable results, producing grains with superior weight and indicating a more efficient nutrient utilization system that could be recommended for sustainable rice cultivation in nutrient-limited soils.

CONCLUSION

This study demonstrated that the application of LOF at a concentration of 7 ppm (P2) with a 100% application frequency produced the most optimal effect on the vegetative growth of the PMJ-01 rice variety, particularly in plant height, panicle length, 1000-grain weight, and yield per clump. Although yield differences among treatments were not statistically significant (P11), the application of LOF contributed notably to improving soil quality, especially by maintaining the pH within the

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standard range established by SNI. However, the concentrations of macronutrients (N, P, and K) in the soil remained below the recommended standards, indicating the need for further refinement of the LOF formulation to enrich its nutrient content and enhance long-term soil productivity. Overall, the results indicate that LOF has the potential to serve as a sustainable alternative in rice cultivation while reducing dependence on chemical fertilizers, It means that LOF can replace chemical fertilizers. Further development of LOF formulations enriched with macronutrients (N, P, and K) is necessary to optimize its benefits for rice productivity. In addition, long-term field trials should be conducted to evaluate the sustained effects of LOF on soil fertility and crop yield. Future studies are also recommended to explore variations in concentration and application frequency across different rice varieties, as well as to include economic analyses to assess the feasibility of LOF use at the farm scale.

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