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Plant-based elicitor improves nutrient efficiency and sustains rice yield under reduced fertilizer in a one-season field study

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Abstract. *Harwanto, Purwanti EW, Sunaryono JG, Wandansari NR. 2026. Plant-based elicitor improves nutrient efficiency and sustains rice yield under reduced fertilizer in a one-season field study. Asian J Agric 10 (1): g100179. https://doi.org/10.13057/asianjagric/g100179.* Excessive dependence on chemical fertilizers raises environmental concerns and reduces long-term soil fertility. A plant-based elicitor containing bioactive compounds (flavonoids, phenols, tannins) and phytohormones (IAA, cytokinins, gibberellins) such as Biosaka, has been promising elicitors to enhance nutrient efficiency and crop resilience. A field experiment was conducted in East Java, Indonesia, using a randomized block design with five treatments: 100% inorganic fertilizer (control), 100% inorganic fertilizer + Biosaka, 75% inorganic fertilizer + Biosaka, 50% inorganic fertilizer + Biosaka, and 25% inorganic fertilizer + Biosaka. Each treatment was replicated four times. Variables measured included plant growth, yield components, straw nutrient content (N, P, K), and soil chemical properties (pH, organic C, available N, P, K). The combination of 50% inorganic fertilizer + Biosaka maintained straw nitrogen comparable to full fertilizer and resulted in higher straw phosphorus content. The combination of 100% inorganic fertilizer + Biosaka produced the highest straw Kalium (0.53%) and milled rice weight (454.41 g 2 m^{-2}). Biosaka treatments were associated with higher soil pH (6.30), organic carbon (0.99%), and available N and K compared to non-Biosaka treatments. Biosaka supplements have not compensated for the nutrient deficiency in the treatments with excessive fertilizer reduction (≤25%). It resulted in lower nutrient content and reduced milled rice weight (265.09 g 2 m^{-2}). This study provides novel evidence that integrating Biosaka treatment with 50% inorganic fertilizer can sustain rice yield equivalently to the conventional 100% inorganic fertilizer application.

Keywords: Biosaka elicitor, integrated nutrient management, nutrient efficiency, rice yield, soil fertility

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the most strategic staple crops in the world, particularly in Asia, where it provides the main source of calories for more than half of the global population. The success of the Green Revolution during the latter half of the 20th century led to massive increases in rice yields, primarily through the intensive use of high-yielding varieties, irrigation, pesticides, and chemical fertilizers. However, despite these earlier gains, rice productivity in Indonesia has stagnated over the last two decades, raising concerns about the ability of conventional production systems to meet the increasing demands of a growing population (Yuan et al. 2022). Indonesia, as the fourth most populous nation globally, faces a particularly acute challenge in reconciling rising domestic food demand with the ecological and economic limits of its current agricultural model. National rice consumption continues to grow in parallel with population expansion, creating a structural gap between production capacity and food security requirements (Badan Pusat Statistik (BPS) 2023).

The progressive deterioration of soil physical and biological properties under intensive fertilization regimes has been well-documented across major rice-producing regions in Java and Sumatra (Sulaeman et al. 2024). Soil microbial communities, which play a pivotal role in organic matter decomposition, nitrogen fixation, and phosphorus solubilization, are particularly sensitive to chemical inputs, and their suppression further disrupts nutrient cycling and undermines the long-term fertility of paddy soils (Dai et al. 2020). Additionally, escalating fertilizer costs present a considerable economic constraint for smallholder farmers, many of whom allocate a disproportionate share of their production expenditure to purchased inputs, reducing net farm income and increasing vulnerability to market fluctuations (Touch et al. 2024). These consequences highlight the need for sustainable fertilization strategies that optimize nutrient use efficiency, restore soil health and reduce production costs without compromising yield.

In response to these challenges, biological and ecological innovations for rice cultivation have been explored. Within the broader framework of Integrated Nutrient Management (INM), which advocates for the combined use of organic, inorganic, and biological inputs to optimize nutrient use efficiency and soil health, elicitors have emerged as a particularly promising category of agricultural inputs (Rouphael and Colla 2020). Elicitors are defined as substances or microorganisms that, when applied to plants or soils, enhance nutrient use efficiency, stress tolerance, and crop quality independently of their direct nutrient content (du Jardin 2015). Their mechanisms of action include the modulation of phytohormone signaling, activation of antioxidant defense systems, upregulation of nutrient transporter genes, and stimulation of root architecture development (Rouphael and Colla 2020). Plant-derived elicitors potential to used in rice culture due to their ability to trigger systemic physiological responses with minimal environmental footprint (Thepbandit et al. 2023). One of plant-based elicitor is Biosaka, a solution that has derived from healthy green leaves. Biosaka represents an indigenous, farmer-led innovation that combines traditional ecological knowledge with scientific principles of plant physiology. Biosaka contains an array of secondary metabolites such as flavonoids, phenols, tannins, and bioactive phytohormones including indole-3-acetic acid (IAA), cytokinins, and gibberellins (Ramli et al. 2024). These compounds are known to stimulate plant growth, enhance stress tolerance, and activate systemic resistance against pests and diseases. Notably, Biosaka is low-cost, locally producible, and requires no specialized equipment, making it particularly accessible to resource-constrained smallholder farmers in tropical rice systems.

Biosaka, a plant-derived elicitor, has shown promise in reducing fertilizer dependency while maintaining or enhancing rice productivity, as evidenced by improved seed quality, growth potential, and yield in field and greenhouse studies when combined with NPK fertilizers (Ansar et al. 2023). Farmer reports and preliminary research indicate additional benefits such as lower input costs and reduced pest and disease incidence, aligning with the principles of Integrated Nutrient Management (INM) (Roopa et al. 2023). However, current evidence for Biosaka is largely derived from limited field trials conducted under uniform fertilizer application. The critical question of whether Biosaka application can maintain or improve rice yield across reduced NPK remains unsolved yet. In particular, the threshold of NPK reduction level at which Biosaka can effectively compensate for diminished inorganic inputs, without compromising rice productivity.

The novelty of this study lies in its systematic assessment of Biosaka's interaction with varying fertilizer doses using a controlled field experiment. Furthermore, it goes beyond yield measurement by analyzing straw nutrient content and soil chemical properties, thereby providing a comprehensive picture of nutrient dynamics. The findings are expected to elucidate the role of Biosaka in optimizing fertilizer efficiency within an INM framework, particularly through its influence on soil pH stabilization and nutrient cycle availability. This study contributes to understanding of elicitors mechanisms and provide an evidence-based foundation for sustainable intensification strategies in smallholder farming systems.

MATERIALS AND METHODS

Study area

The study was conducted from May to December 2023 in Sragi Village (8° 6′ 22.36″ S, 112° 17′ 39.29″ E), Blitar District, East Java, Indonesia. A Randomized Block Design (RBD) was employed, consisting of five treatments with four replications, resulting in 20 experimental plots. Each plot measured 150 m² with a uniform spacing of 25 × 25 cm to ensure consistency in plant density. The embankments between plots arranged high and sturdy, at least 40-50 cm high and 30-40 cm wide. The embankments were well compacted and lined with plastic mulch on the inside to prevent water seepage between plots. The treatments were as follows:

P0: 100% inorganic fertilizer (control, without Biosaka);
P1: 100% inorganic fertilizer + Biosaka;
P2: 75% inorganic fertilizer + Biosaka;
P3: 50% inorganic fertilizer + Biosaka;
P4: 25% inorganic fertilizer + Biosaka.

The 100% inorganic fertilizer dose represented conventional farmer practice, consist of: 400 kg ha^{-1} Urea and 300 kg ha^{-1} Phonska, without any organic fertilizer. In every 100 kg urea contain 46 kg Nitrogen. 100 kg phonska contain 15 kg Nitrogen, 12 kg Phosphor and 10 kg Kalium. The 75% inorganic fertilizer consist of 300 kg ha^{-1} Urea and 225 kg ha^{-1} Phonska. The 50% inorganic fertilizer consist of 200 kg ha^{-1} Urea and 150 kg ha^{-1} Phonska. The 25% inorganic fertilizer consist of 100 kg ha^{-1} Urea and 75 kg ha^{-1} Phonska The rice variety used was *O. sativa* L. cv. *Ciherang*. Biosaka applied seven times by foliar spraying from 14 days after transplanting to the reproductive stage at 400 mL ha^{-1} per application, using a nozzle diameter of 0.1 mm to ensure fine droplet distribution (Ansar et al. 2023).

Preparation and application of Biosaka

Biosaka solution was prepared following the procedure described by Saryanto et al. (2024). Biosaka is produced from healthy local plants that grow optimally in relatively infertile areas. Young leaves of multiple species such as *Gliricidia sepium, Leucaena leucocephala, Tithonia diversifolia, Manihot esculenta, Carica papaya, Cosmos caudatus, Moringa oleifera, Ageratum conyzoides, Phyllanthus urinaria, Hippobroma longiflora*, and *Euphorbia hirta* were used. The weight of each species of leaves used are 300 g approximately. Leaves were crushed and manually stirred counterclockwise for 15 minutes in 5 L of clean water to obtain an extract rich in secondary metabolites. The solution was filtered with a 50 mesh sieve.

Biosaka was prepared weekly and applied immediately, except at the thirth weeks application. Biosaka applied was derived from the same batch produced in the second week. Biosaka is made by the same individual farmer to maintain the consistency of the crushing and stirring procedure. The solution is stored at room temperature 25-28°C. Each preparation and application was labeled with the code B followed by the week number of production. Application commenced when the rice plants were 25 days after transplanting. Biosaka were applied 8 times in one planting season.

Biosaka was characterized using UV-Vis spectrophotometry to quantify bioactive compounds (flavonoids, tannins, phenols) at maximum absorbance wavelengths, as well as plant hormones (IAA, cytokinins, gibberellins). Standard curve for total flavonoids, 6.25 mg of quercetin powder was dissolved in 25 mL of 70% ethanol, with a stock solution concentration of 250 ppm and an absorbance wavelength of 0.5292. Standard curve for total tannin, 6.25 mg of tannin powder was dissolved in 25 mL of 70% ethanol, with a stock solution concentration of 250 ppm and an absorbance wavelength of 0.6551. Standard curve for total phenol, 12.5 mg of gallic acid powder was dissolved in 25 mL of 70% ethanol, with a stock solution concentration of 500 ppm and an absorbance wavelength of 2.0608. This characterization allowed the identification of Biosaka as a complex elicitor rather than a simple organic extract, thereby advancing the state of the art in elicitor-based nutrient management.

Data collection

Growth parameters were recorded at both vegetative and reproductive stages. Random samples of five rice clumps per plot were arranged for: plant height (cm), number of tillers, and number of productive tillers. The productivity parameters include number of grains per panicle, grain dry weight at harvest, grain dry weight after milling and milled rice weight per hill observed using the tiling method per experimental unit. The sample area for tiling is 2 square meters per experimental unit. The nutrient content of straw was analyzed using proximate analysis.

Soil samples were collected before planting and after harvest at 0-20 cm depth. A 500 g composite soil sample was collected per experimental unit, with sampling points determined randomly within the plot area (Kader 2021). Parameters analyzed included soil pH, organic C, total N (Kjeldahl method), available P (Olsen method), and exchangeable bases (K, Ca, Mg), expressed in cmol(+) kg^{-1}. Straw samples were collected at harvest and analyzed for N, P, and K content using standard Kjeldahl, spectrophotometric, and flame photometric methods, respectively (Balittanah 2009). The quantitative approach using the soil quality index also places parameters such as available N, P, K, organic carbon, as key variables in assessing fertility status and nutrient management efficiency.

Statistical analysis

All data were subjected to Analysis of Variance (ANOVA) appropriate for RBD using IBM SPSS Statistic 25. When significant effects were observed, mean comparisons were performed with Duncan's Multiple Range Test (DMRT) at the 5% probability level. Data tested for homogeneity of variance for running ANOVA.

Novelty of methodological approach

Unlike conventional trials focusing solely on yield outcomes, this study combined field experimentation with biochemical profiling of Biosaka. By characterizing bioactive compounds and phytohormones alongside plant and soil responses, the research provides mechanistic insights into how elicitors interact with fertilizer regimes. This integrated approach advances beyond descriptive farmer-led observations, offering reproducible, scientifically rigorous methods to evaluate elicitor-based strategies in rice farming systems.

RESULTS AND DISCUSSION

Phytochemical analysis of Biosaka solution

Bioactive compounds are essential substances naturally present in living organisms that play important physiological roles (Wang et al. 2025). Phytochemical analysis of Biosaka solution revealed the presence of several bioactive compounds, including flavonoids, tannins, and phenols. Quantitative analysis showed that the average flavonoid concentration was 74.04 mg g^{-1}, tannins 64.74 mg g^{-1}, and phenols 73.43 mg g^{-1} (Table 1).

Among these, flavonoids were the highest average compounds. Flavonoids are widely known as plant secondary metabolites synthesized through the phenylpropanoid pathway in response to microbial infection. They play crucial roles in antioxidative activity, enzyme induction, and plant defense mechanisms (Dias et al. 2021). Tannins, as polyphenolic compounds, form strong complexes with minerals and macromolecules, thereby providing protection against microbial attacks (Govindarajan et al. 2016). Phenols, also detected quantitatively, function as adaptive metabolites that enhance resilience to environmental stresses, interspecies competition, and herbivore deterrence (Liu et al. 2024).

In addition to bioactive compounds, Biosaka contained significant amounts of phytohormones such as indole-3-acetic acid (IAA), cytokinins (zeatin and kinetin), and gibberellins (Table 2). Zeatin recorded the highest average concentration (12.33 mg.L^{-1}), followed by IAA (8.63 mg.L^{-1}) and gibberellins (7.64 mg.L^{-1}). Cytokinins, particularly zeatin, are key regulators of plant development, delaying leaf senescence, enhancing stress tolerance, and mediating plant-environment interactions (Meena et al. 2017). IAA plays a fundamental role in cell elongation, bud development, and root initiation (Roopa et al. 2023), while gibberellins regulate seed germination, stem elongation, root growth, and flowering induction (Gao et al. 2017). These findings indicate that Biosaka functions as a complex elicitor that supports both growth promotion and stress adaptation in rice.

Effects of Biosaka solution on rice growth and yield

Rice growth parameters demonstrated varying responses to Biosaka and inorganic fertilizer treatments (Table 3). The application of 100% inorganic fertilizer + Biosaka produced the tallest plants (76.9 cm), indicating that full fertilization combined with Biosaka enhanced one part of vegetative growth. Plant height alone does not determine overall plant productivity or growth success. The number of productive tillers per plant is one of the important agronomic traits associated with grain yield of rice. Productive tiller number is highly correlated to the number of effective panicles, which is viewed as essential information for genetic improvement of rice yields (Liao et al. 2019).

The number of tillers per hill was highest under 100% inorganic fertilizer (24.3 tillers), while Biosaka treatments generally resulted in lower tiller numbers. However, no significant differences were observed in the number of productive tillers, ranging from 11.0 to 14.0 across treatments. Notably, the probability of tillers becoming productive was highest under 50% inorganic fertilizer + Biosaka (83%), compared to 58% under 100% inorganic fertilizer. This suggests that elicitation induced by Biosaka may redirect resources toward reproductive development, consistent with reports that elicitors stimulate biosynthetic pathways enhancing flowering and reproductive success (Naik and Al-Khayri 2016; Zhou et al. 2022).

Yield component analysis showed that Biosaka treatments did not significantly affect the number of grains per panicle but affect grain weight (Table 4). Therefore, milled rice weight was significantly higher under 100% inorganic fertilizer + Biosaka (454.4 g) and 50% inorganic fertilizer + Biosaka (423.6 g), compared to 100% inorganic fertilizer alone (303.36 g). These results suggest that Biosaka may contribute to improved grain filling and yield when fertilizer availability is sufficient. The results of this study indicate that Biosaka has the potential to significantly increase grain weight under conditions of adequate nutrient availability (100% and 50% inorganic fertilizer). The same phenomenon was reported by Kumar et al. (2024), where microbial biostimulants increased grain yield by up to 39% at full fertilizer doses and 34% at 75% nitrogen conditions. The mechanism occurs through modulation of photosynthesis and panicle development. The decrease in yield in the 25% inorganic fertilizer + Biosaka treatment in this study is consistent with the findings of Zhou et al. (2023) who reported that nitrogen reduction beyond a certain threshold (>10-20%) reduced yield by 2.8-7.6%, indicating that neither biostimulant nor elicitor mechanisms can fully compensate for excessive nutrient deficiencies. The standard deviations in plant height, number of tillers per hill, and number of productive tillers per hill are due to quantitative traits whose expression is strongly influenced by the interaction of genotype and environment. In field experiments, even when treatments are controlled, unavoidable environmental microvariations-such as uneven fertilizer distribution, small differences in irrigation, or local biotic disturbances (pests, weeds)-can be introduced. The limitation of study is the lack data about pest and disease intensity especially birds. Bird pest attacks cause a relatively high standard deviations in productivity parameters.

Post-harvest soil analysis revealed significant differences in soil pH among treatments, with values ranging from 5.97 to 6.57. The treatment combining 75% inorganic fertilizer with Biosaka yielded the highest pH value (6.57±0.34c), while the 50% inorganic fertilizer + Biosaka treatment recorded the lowest (5.97±0.09a), statistically equivalent to the sole 100% inorganic fertilizer treatment (6.10±0.00a). This pattern does not permit a straightforward directional interpretation wherein Biosaka uniformly elevates soil pH across all doses. Rather, the response appears dose-dependent and non-linear, suggesting that the interaction between inorganic fertilizer rate and Biosaka application governs pH dynamics in a complex manner. Significant treatment effects were detected for soil organic carbon (C-organic), with values ranging from 0.78% to 0.99%. The 100% inorganic fertilizer treatment without Biosaka recorded the lowest C-organic content (0.78%), whereas the 100% inorganic fertilizer + Biosaka treatment yielded the highest value (0.99%). Treatments combining Biosaka with reduced fertilizer doses (75%, 50%, and 25%) produced intermediate values (0.89%, 0.93%, and 0.84%, respectively), all of which were statistically comparable to one another but generally higher than the sole inorganic fertilizer control. This pattern suggests that Biosaka application may contribute positively to organic carbon accumulation, though its effect is most pronounced when combined with a full inorganic fertilizer dose that supports greater overall plant biomass production (Table 5).

Table 1. Bioactive compounds in Biosaka

Batch of Biosaka	**Flavonoid (mg g^{-1})**	**Phenol (mg g^{-1})**	**Tannin (mg g^{-1})**
B1	82.43	100.52	60.44
B2	87.33	121.20	73.61
B3*	87.33	121.20	73.61
B4	125.89	92.18	63.52
B5	27.85	44.40	42.86
B6	61.93	62.52	61.64
B7	72.31	25.26	79.07
B8	47.30	20,12	63.17
Mean	74.04	73.43	64.74

Note: *: Biosaka applied was derived from the same batch produced in the second week

Table 2. Hormones in Biosaka

Batch of Biosaka*	**IAA (mg L^{-1})**	**Giberelin (mg L^{-1})**	**Cytokinin**	
			Zeatin (mg L^{-1})	**Kinetin (mg L$^{-1)}$**
B1	8.51	6.25	8.08	4.43
B2	10.75	8.35	10.33	4.39
B3*	10.75	8.35	10.33	4.39
B4	6.90	9.43	15.10	5.29
B5	6.95	7.50	16.85	3.59
B6	8.88	7.47	14.40	4.41
B7	9.44	5.79	11.21	3.66
B8	6.88	7.99	12.30	3.24
Mean	8.63	7.64	12.33	4.18

Note: *: Biosaka applied was derived from the same batch produced in the second week

Table 3. Effects of Biosaka solution on rice growth

Treatments	Plant height (cm)	The number of tillers per hill (a)	The number of productive tillers per hill (b)	Probability tillers become productive (a:b ratio)
100% inorganic fertilizer	75.9±2.3bc	24.3±0.6c	14.0±2.1a	58%
100% inorganic fertilizer + Biosaka	76.90±0.9c	18.9±3.4b	12.5±1.6a	66%
75% inorganic fertilizer + Biosaka	68.3±4.6a	16.6±3.9ab	11.0±3.0a	69%
50% inorganic fertilizer + Biosaka	72.4±1.4abc	15.8±3.1a	13.1±2.5a	83%
25% inorganic fertilizer + Biosaka	71.5±2.3ab	15.0±3.5a	12.1±1.7a	81%

Note: Numbers followed by the same letter in the same column do not show significant differences based on the DMRT test at $\alpha = 0.05$

Table 4. Effects on yield per 2 m^2 area

Treatments	The number of grains per panicle	Grain weight (g 2 m^{-2})	Milled rice weight (g 2 m^{-2})
100% inorganic fertilizer	73.49±25.44a	636.25±116.83ab	303.36±55.71ab
100% inorg fertilizer + Biosaka	83.25±16.52a	795.25±15.97b	454.41±9.12c
75% inorg fertilizer + Biosaka	81.29±15.23a	724.5±58.54ab	417.66±33.75bc
50% inorg fertilizer + Biosaka	73.89±21.75a	743.25±180.98ab	423.56±14c
25% inorg fertilizer + Biosaka	87.62±38.51a	543.00±248.95a	265.09±54a

Note: Numbers followed by the same letter in the same column do not show significant differences based on the DMRT test at $\alpha = 0.05$

Table 5. Effect application on soil chemical index

Treatments	pH	C Organic (%)	Total N (%)	Available P (ppm)	Available K (cmol kg^{-1})
100% inorganic fertilizer	6.10±0.00a	0.78±0.02a	0.12±0.01a	36.00±0.82c	0.08±0.02ab
100% inorg. fertilizer + Biosaka	6.43±0.17bc	0.99±0.10c	0.13±0.01a	22.67±3.30a	0.11±0.03b
75% inorg. fertilizer + Biosaka	6.57±0.34c	0.89±0.03bc	0.14±0.03a	25.33±0.47a	0.09±0.01ab
50% inorg. fertilizer + Biosaka	5.97±0.09a	0.93±0.07bc	0.21±0.06b	31.33±2.62b	0.08±0.02a
25% inorg. fertilizer + Biosaka	6.23±0.09ab	0.84±0.06ab	0.14±0.02a	32.33±1.70b	0.08±0.02ab

Note: Numbers followed by the same letter in the same column do not show significant differences based on the DMRT test at $\alpha = 0.05$

Nitrogen levels were highest under 50% inorganic fertilizer + Biosaka (0.21%), suggesting optimized nitrogen cycling under moderate fertilizer reduction (Table 5). Reviews on nitrogen use efficiency show that lowering excessive N rates while using improved agronomic/biological strategies can increase N uptake efficiency and reduce N losses, thus optimizing N cycling rather than simply maximizing N input (Anas et al. 2020).

Available phosphorus in post-harvest soil samples ranging from 22.67 to 36.00 ppm. The 100% inorganic fertilizer treatment without Biosaka retained the highest residual available P (36.00 ppm), while the 100% inorganic fertilizer + Biosaka treatment showed the lowest post-harvest residual (22.67 ppm). Treatments combining Biosaka with reduced inorganic fertilizer doses yielded intermediate residual P values of 25.33, 31.33, and 32.33 ppm for the 75%, 50%, and 25% combinations, respectively. In soils that are constantly exposed to inorganic fertilizers, phosphorus in the soil, experiences fixation due to bonds with Ca, Fe, and Al metals and adsorption by iron/aluminum oxides, so that the efficiency of the applied P fertilizer utilization only reaches 10-25% (Pang et al. 2024). The high remaining P available in the soil in the single inorganic fertilizer treatment reflects low P uptake by plants, not a higher soil P supply capacity. A higher residual P in the sole inorganic fertilizer treatment indicates that a substantial proportion of applied phosphorus remained unabsorbed in the soil solution, suggesting comparatively low phosphorus use efficiency under exclusive mineral fertilization.

This interpretation is directly supported by the straw nutrient data presented in Table 6, wherein the P proportion retained in crop straw provides a complementary biological indicator of plant phosphorus acquisition during the growing season. Exchangeable potassium increased significantly under 100% inorganic fertilizer + Biosaka (0.11%), demonstrating Biosaka's contribution to K availability, which is essential for osmotic regulation, enzyme activation, and stress resistance in rice. In rice systems, straw return + K fertilization substantially increases exchangeable and non-exchangeable K stocks, and these K pools correlate positively with K uptake and grain yield (Zhou et al. 2025). Reviews emphasize that potassium is essential for osmotic regulation, enzyme activation, photosynthesis, and abiotic stress tolerance, including maintaining ion homeostasis, stomatal regulation, and enhancing antioxidant defenses under drought or salinity (Hasanuzzaman et al. 2018). In wheat, added K increases osmolyte accumulation and antioxidant activity under osmotic and water stress. These results support the fact that higher exchangeable K under 100% fertilizer + Biosaka reflects enhanced K availability and that this is agronomically important for osmotic regulation, enzyme function, and stress resistance in rice.

Table 6. Effect application on straw nutrient content

Treatments	N Proportion (%)	P Proportion (%)	K Proportion (%)
100% inorganic fertilizer	0.30±0.04b	0.03±0.00a	0.50±0.06ab
100% inorg. fertilizer + Biosaka	0.21±0.01a	0.03±0.02a	0.53±0.06b
75% inorg. fertilizer + Biosaka	0.25±0.08ab	0.02±0.01a	0.49±0.03ab
50% inorg. fertilizer + Biosaka	0.30±0.07b	0.07±0.03b	0.47±0.04ab
25% inorg. fertilizer + Biosaka	0.21±0.01a	0.05±0.01ab	0.42±0.05a

Note: Numbers followed by the same letter in the same column do not show significant differences based on the DMRT test at α = 0.05

In rice, combining green manure and straw with a 40% N reduction, maintained grain and straw yields and nutrient uptakes (N, P, K) at levels comparable to 100% inorganic N fertilization, while markedly increasing N, P and K agronomic efficiencies (Wei et al. 2025). This directly supports the finding that 50% inorganic fertilizer + Biosaka can sustain N at same point as 100% inorganic fertilizer, and even enhance straw P content. Similarly, straw return combined with P fertilization increased plant P accumulation compared to P fertilizer alone, Particularly, under adequate but not excessive P supply, indicating that organic inputs can enhance plant P uptake at moderate fertilizer rates (Guo et al. 2024). These results support interpreting the significantly highest straw P content at 50% inorganic fertilizer + Biosaka as a consequence of more efficient P mobilization and uptake when Biosaka is combined with reduced inorganic inputs. Long-term rice experiments further show that NPK + straw (NPKS) yields the highest soil available K than mineral NPK alone (Wei et al. 2025). These patterns support the interpretation that 100% fertilizer + Biosaka can maximize straw K content through adequate K input combined with enhanced recycling, whereas 25% inorganic fertilizer + Biosaka is consistent with insufficient K supply under drastic fertilizer reduction.

Integrated nutrient management implication

The results collectively highlight the synergistic role of Biosaka when combined with inorganic fertilizers in improving nutrient efficiency and rice productivity. Although Biosaka cannot fully replace inorganic fertilizers, it optimizes nutrient distribution and enhances soil health when applied alongside moderate fertilizer doses. These findings reinforce the Integrated Nutrient Management (INM) concept, which advocates combining chemical and biological inputs to maximize productivity while minimizing environmental impacts (Liu et al. 2024). Notably, the combination of 50% inorganic fertilizer + Biosaka proved most effective for nitrogen and phosphorus balance (Table 6), whereas 100% inorganic fertilizer + Biosaka performed best for potassium sufficiency and grain yield.

These findings offer actionable guidance for smallholder rice farmers seeking to reduce input costs without compromising productivity. A tiered approach is recommended based on the farmer's agronomic priority and economic capacity. For farmers prioritizing grain yield and potassium sufficiency, the 100% inorganic fertilizer + Biosaka combination remains advisable, as it significantly maximized straw K content and supported the highest grain yield. Conversely, for farmers aiming to reduce fertilizer expenditure while sustaining nitrogen supply and phosphorus efficiency, the 50% inorganic fertilizer + Biosaka combination represents the most cost-effective option: it maintained straw N at same levels to full fertilization and produced significantly the highest straw P content. This 50% reduction in inorganic fertilizer use could yield meaningful cost savings, particularly in smallholder systems where fertilizer costs represent a major share of production expenses.

In practice, adoption of the 50% inorganic fertilizer + Biosaka strategy should ideally be complemented by additional soil health management practices -such as straw incorporation, composting, green manure application, or legume intercropping- to further offset the reduction in inorganic inputs and sustain long-term soil fertility. Evidence from long-term rice experiments demonstrates that combining organic inputs with reduced mineral fertilization can maintain yield and nutrient uptake at levels statistically comparable to full inorganic fertilization, while significantly improving nutrient use efficiency (Wei et al. 2025). Farmers who already practise straw return or legume intercropping may therefore be better positioned to adopt the reduced-fertilizer + Biosaka approach with minimal yield risk.

In conclusion, Biosaka improves nutrient efficiency and soil fertility while sustaining rice yield across the treatments evaluated. The combination of 50% inorganic fertilizer + Biosaka statistically maintained straw nitrogen at levels equivalent to full inorganic fertilization and enhanced phosphorus content, whereas 100% fertilizer + Biosaka optimized potassium accumulation and achieved the highest milled rice yield. Collectively, these results indicate that a moderate reduction in inorganic fertilizer input up to 50%, when supplemented with Biosaka is agronomically feasible without significant yield penalty. Excessive reduction beyond this threshold leads to measurable declines in potassium supply and overall productivity. The conclusions drawn are based on a single growing season conducted under specific soil, climate, and management conditions, which constrains the generalizability of these findings. Nutrient dynamics, elicitor's efficacy and yield responses are known to vary considerably across seasons, soil types, and agroecological zones; therefore, the performance of the 50% inorganic fertilizer + Biosaka combination observed here cannot be assumed to remain consistent under different environmental conditions or in successive cropping cycles.

Future application should focus on adopting Biosaka within integrated nutrient management to lower chemical input dependency and promote sustainable rice cultivation.

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