Annals of Agri-Bio Research **30** (2): 158–165, 2025

Reducing Agrochemical Dependency in Rice Production: Lessons from a Sustainability Study in Tonosí, Panama

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(Received: 6 September 2025; Revised: 3 November 2025; Accepted: 13 November 2025; Published: 17 December 2025)

ABSTRACT

This study evaluated the sustainability of rice production systems in Los Santos province, Panama, focusing on experimental plots in the district of Tonosí, one of the country's most important rice-producing regions. Two contrasting production systems were compared: an agroecological approach based on reduced chemical inputs and a conventional model representing intensive agricultural management. The fields were established using the standard spacing employed by local producers, 20 cm between plants and 40 cm between rows, and cultivated over a five-month production cycle. Key indicators, including crop yield, grain quality, soil properties, and water use efficiency, were systematically measured to assess the agronomic and environmental performance of both systems. Results showed that the agroecological treatment reduced synthetic fertilizer use by 25 percent without significantly affecting yield (p = 0.83, 95% CI), achieving an average productivity of 4.75 tons per hectare compared with 4.91 tons per hectare in the conventional system. Moreover, the agroecological plots demonstrated a 24 percent reduction in irrigation water demand, improvements in soil organic matter and structural integrity, and higher biodiversity observed during field inspections. These outcomes indicate that sustainable rice management can maintain productivity while reducing environmental impact, contributing to food security, resource efficiency, and agricultural resilience under the increasing pressures of climate change.

Key words: sustainable rice production, agroecology, Tonosí, Panama, food security, soil fertility, water use efficiency, environmental impact

INTRODUCTION

Rice is a critical staple crop for global food security, particularly in tropical and subtropical regions where it provides a primary source of calories and income for millions of people (FAO, 2018a; USDA, 2019). In Panama, rice plays a central role in both the national diet and agricultural economy (FAO, 2018b). The province of Los Santos, and specifically the district of Tonosí, has long been recognized as one of the country's leading rice-growing regions, thanks to its favorable agroclimatic conditions and long-standing farming traditions (MIDA, 2022; IICA, 2022).

Despite this strong foundation, conventional rice production in Panama faces mounting environmental challenges. The excessive use of chemical fertilizers and pesticides has contributed to soil degradation, loss of soil organic matter, and declining biodiversity within agricultural systems. Recent assessments by MIDA (2022) and FAO (2024) indicate that approximately 38% of agricultural soils in central Panama show moderate to severe degradation, while biodiversity in agroecosystems has declined by nearly 30% over the past two decades due to monocropping and intensive input use. Furthermore, the increasing impacts of climate variability, limited water availability, and rising production costs are putting additional pressure on small and medium-scale farmers (Durán, 2020; Altieri & Nicholls, 2017; Lal 2020). These conditions highlight the urgent need for production models that ensure long-term food security while preserving environmental integrity.

Sustainable agriculture, particularly agroecological approaches, offers a viable alternative to conventional systems. Agroecology integrates ecological principles into agricultural management through practices such as crop rotation, compost and organic manure application, biological pest management, and water conservation (Altieri, 1995; Gliessman, 2015). These methods aim to maintain productivity while improving soil health, reducing dependence on external inputs, and strengthening ecosystem resilience to climate-related stressors (Pretty et al., 2006).

Several studies in Latin America have shown that agroecological rice systems can achieve comparable yields to conventional models while improving water-use efficiency, soil organic matter, and pest control (Cruz, 2021). In the Panamanian context, however, field-based comparative studies evaluating agroecological rice production remain limited. Most existing research focuses on general policy recommendations or descriptive reports, leaving a gap in experimental data on agronomic, environmental, and economic outcomes. This study addresses that gap by comparing an agroecological system with reduced synthetic input use against a conventional intensive system, using experimental plots in Tonosí, Los Santos. Tonosí was chosen for its representative alluvial soils, moderate water stress conditions, and high potential for producer adoption of sustainable practices (Gómez et al, 2022).

To support the transition to sustainable rice systems, it is essential to strengthen agricultural extension services and policy frameworks that encourage agroecological innovation. The Panamanian Ministry of Agricultural Development (MIDA) and FAO's *Framework for Scaling up Agroecology* (FAO, 2024) provide strategic guidance for integrating agroecological principles into national agricultural development. Public investment in training, research, and local capacity-building will be crucial to promote the widespread adoption of sustainable rice production practices.

According to the most recent FAO assessment (FAO, 2024), agrifood systems worldwide are increasingly exposed to climate stress, requiring transformative approaches based on resource efficiency, soil restoration, and biodiversity protection. These priorities align with national policies promoted by the Ministry of Agricultural Development of Panama (MIDA, 2022), which encourage producers to adopt practices that maintain productivity while reducing environmental impact.

METHODOLOGY

Experimental Design

This study was designed to evaluate the impact of sustainable rice production on grain yield and quality in the province of Los Santos, specifically in the district of Tonosí (7°22′ N, 80°25′ W), located within Panama's Pacific dry tropical zone (Agroecological Zone IV according to MIDA classification). The research compared an agroecological system with reduced chemical inputs against a conventional intensive production model. The experiment was conducted on active rice farms representative of the region's flat alluvial soils, moderate water stress conditions, and traditional rice management practices.

Ten experimental plots were established and divided into two treatment groups: five plots under agroecological management and five under conventional management. Treatments were distributed using a completely randomized block design (CRBD) to minimize spatial bias, considering soil fertility gradients, drainage, and microtopographic variation. Each plot measured 100 m^2 (10 × 10 m^2) and was separated by buffer zones of 1.5 m to prevent nutrient and water interference between treatments.

The agroecological system incorporated sustainable practices such as crop rotation, compost and organic manure application, and biological pest management. No synthetic fertilizers or pesticides were applied in this treatment. Instead, an organic compost mixture containing approximately 80 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1}, and 50 kg K_2O ha^{-1} (based on dry weight) was used. The conventional system received standard chemical fertilization rates typical for the Tonosí region: 120 kg N ha^{-1} (as urea), 60 kg P_2O_5 ha^{-1} (as triple superphosphate), and 70 kg K_2O ha^{-1} (as potassium chloride).

All plots were planted with the local variety IDIAP-38, a medium-maturity variety (approximately 130 days) widely used in Los Santos due to its adaptation to regional climatic conditions. The planting density consisted of 20 cm between plants and 40 cm between rows, a standard configuration in Tonosí's rice systems. The experiment covered one complete growing cycle of five months (December–April).

Two primary dependent variables were monitored: (1) grain yield, recorded as dry grain weight adjusted to 14% moisture content (standard for rice), and (2) grain quality, evaluated through laboratory physicochemical analyses that determined the percentage of whole grains, moisture, and nutrient composition.

Environmental conditions were recorded throughout the cycle. The mean air temperature ranged between 27 °C and 32 °C, with total precipitation of approximately 1480 mm, consistent with Tonosí's annual averages. The irrigation system was standardized for all plots to ensure uniform water distribution.

Data were collected weekly through direct field measurements. Grain yield per plot was measured using a precision scale, while grain quality was analyzed in a certified agricultural laboratory following ISO 7301:2011 rice standards. Input use, including fertilizer and irrigation water, was meticulously logged to calculate input efficiency and sustainability indicators.

Data Analysis

A two-factor analysis of variance (ANOVA) was used to compare crop yield and grain quality between the agroecological and conventional production systems over the five-month period (n = 10; five plots per treatment). Statistical significance was evaluated at $p < 0.05$, and treatment × time interactions were tested. In addition to p-values, effect sizes (η^2) and 95% confidence intervals (95% CI) were calculated to assess the magnitude and precision of treatment effects.
Prior to conducting the ANOVA, normality and homogeneity of variances (homoscedasticity) were verified in JAMOVI version 2.3. The Shapiro–Wilk test was applied to confirm the normal distribution of residuals, while Levene's test was used to assess variance homogeneity.
Additionally, Student's t-tests were performed to identify significant differences between systems at specific time intervals, reporting degrees of freedom (df = 8) for pairwise comparisons. To examine the association between yield and water-use efficiency, a Pearson correlation analysis was conducted, including the correlation coefficient (r), significance level, and 95% confidence interval. All statistical analyses were carried out using JAMOVI version 2.3 and Google Sheets.

Soil Sampling and Analysis

Soil characteristics were assessed both before and after the experimental cycle to provide baseline and post-treatment comparisons. Pre-experiment sampling confirmed that no significant differences existed among plots in pH, organic matter, or macronutrient levels prior to treatment application ($p > 0.05$).
At the end of the production cycle, composite soil samples were collected from each plot (0–20 cm depth) to evaluate treatment effects on soil quality (n = 10). Samples were air-dried, sieved (2 mm), and analyzed in a certified laboratory following standard procedures. The parameters measured included pH (1:2.5 ratio), organic matter (Walkley–Black), cation exchange capacity (CEC), available phosphorus (Bray I), and exchangeable potassium and calcium.
Statistical comparisons between systems were made using Student's t-tests ($p < 0.05$, df = 8), and effect sizes (Cohen's d) were calculated to quantify differences between treatments

RESULTS

Comparison of Yield and Grain Quality Under Different Production Systems

This section presents the results of the study comparing an agroecological rice production system with reduced chemical inputs and a conventional intensive model in the district of Tonosí. Data were obtained from ten experimental plots, five managed under agroecological practices and five under conventional management.
Rice yield was measured at the end of the five-month production cycle. The values correspond to the mean ± standard deviation (SD), calculated from the five replicate plots in each treatment. The agroecological system achieved an average yield of 4.75 ± 0.32 t ha^{-1}, compared to 4.91 ± 0.27 t ha^{-1} for the conventional system. Statistical analysis (Student's t-test, $t = -0.22$, df = 8, $p = 0.83$, CI_{95}% [−0.35, 0.27]) indicated no significant difference between treatments.
Grain quality was assessed through physicochemical analyses, including the percentage of whole grains, moisture content, and protein concentration. Rice from the agroecological system had a significantly higher proportion of whole grains (92.3% ± 1.8, $p = 0.041$, df = 8) than the conventional system (88.6% ± 2.1). Protein content was slightly higher in the agroecological treatment (7.2% ± 0.3) compared to the conventional (6.8% ± 0.4), but the difference was not statistically significant ($p = 0.11$). Moisture content was similar across treatments (12.4% ± 0.5 vs. 12.1% ± 0.6; $p > 0.05$). These results suggest that agroecological management can improve grain integrity without compromising nutritional quality.

Water Use Efficiency and Sustainability of the Production Systems

Water-use efficiency was one of the key indicators analyzed. Total irrigation volume was recorded using a calibrated flow meter installed at the inlet of each plot's irrigation line, providing cumulative readings in liters per square meter (L m^{-2}) throughout the growing season. The agroecological system used 24%

less irrigation water than the conventional system, averaging 520 ± 14 L m^{-2} compared to 685 ± 18 L m^{-2} ($p = 0.037$). This statistically significant difference demonstrates that agroecological practices contribute to more efficient water management without reducing yield.

Post-harvest soil analysis revealed that plots under agroecological management retained higher organic matter (3.8% ± 0.4) than conventional plots (2.5% ± 0.3, $p = 0.021$). Baseline sampling prior to the experiment showed no significant initial differences among plots ($p > 0.05$), confirming that the observed increase likely resulted from compost incorporation and residue recycling during the season. Although the rise in organic matter occurred in a single cycle, it likely reflects short-term biological activation rather than permanent carbon sequestration, and minor sampling variation may also explain part of the change.

These results (Table 1) support the viability of sustainable rice production in Tonosí, showing that the agroecological approach maintains competitive productivity, improves grain quality, enhances water efficiency, and contributes to soil fertility-key components for regional food security.

Table 1. Average rice yield (kg/m^2) under different production systems.

Treatment	Month 1 (kg/m^2)	Month 2 (kg/m^2)	Month 3 (kg/m^2)	Month 4 (kg/m^2)	Month 5 (kg/m^2)
Agroecological System	2.10 ± 0.15	3.95 ± 0.22	4.35 ± 0.28	4.65 ± 0.30	4.75 ± 0.32
Conventional System	2.25 ± 0.12	4.10 ± 0.19	4.50 ± 0.25	4.80 ± 0.27	4.91 ± 0.27

Statistical Analysis

The Student's *t* test analysis showed no statistically significant difference in rice yield between the agroecological and conventional production systems ($p = 0.83$). This indicates that the two management approaches result in comparable levels of harvested rice per square meter, suggesting that agricultural practices alone did not generate meaningful differences in productivity within the parameters of this study.

These results further suggest that although rice yield under the agroecological system was slightly lower than that of the conventional system, the difference was not large enough to compromise its viability. The reduction in synthetic fertilizer and agrochemical use may offer environmental benefits without significantly affecting production. The adoption of this model could improve the sustainability of rice cultivation while reducing dependency on external inputs.

The analysis of variance (ANOVA) showed no statistically significant differences between the two production systems ($p = 0.83$), indicating that the type of agricultural management did not have a measurable impact on rice yield under the conditions of this study. The variability observed between treatments was not sufficient to establish that agroecological and conventional practices resulted in significantly different final yields.

The fact that the agroecological system achieved yield values comparable to those of the conventional system, while relying less on chemical fertilizers and agrochemicals, is a noteworthy finding. These results may support the development of policies that promote more sustainable agricultural practices without compromising food security. However, long-term studies are recommended to assess the sustainability of yield performance and its effects on soil health and the broader environment. The results are summarized in Table 2.

Table 2. Statistical comparison of rice yield between agroecological and conventional systems.

Test type	Comparison	Test statistic	p-value	Significant ($p < 0.05$)
Student's t-test	Agroecological vs. Conventional Yield	$t = -0.221$	0.83	No
ANOVA (One-way)	Agroecological vs. Conventional Yield	F = 0.049	0.83	No

The rice yield growth curve shows a similar trend between the agroecological and conventional production systems. Throughout the production cycle, both treatments exhibited stable progression, with slight variations at certain stages of crop development.

Although the final yield of the conventional system was slightly higher, the overall behavior of the curve suggests that agroecological production is a viable alternative. The reduction in chemical inputs could be offset by improved management practices, enabling a sustainable production system without significantly compromising yield levels. Figure 1 shows these results.

The Pearson correlation analysis between water use efficiency and rice yield produced a positive coefficient (r = 0.874), suggesting a potential association between improved water management and higher crop productivity. However, the result did not reach statistical significance ($p = 0.053$), indicating that while a positive trend was observed, further data would be required to confirm this relationship conclusively. These findings highlight the relevance of efficient water use practices in rice cultivation, especially in regions where water availability is limited.

Figure 2 reveals a clear relationship between water use efficiency and rice yield. It shows that plots with lower water consumption tend to maintain stable yields, suggesting that production can be optimized through more rational use of water resources. These results are essential for decision-making in the agricultural sector, as they demonstrate the potential to reduce water consumption without significantly affecting crop yield. This has important implications for the sustainability of rice production in regions where water access is limited or under pressure due to climate change.

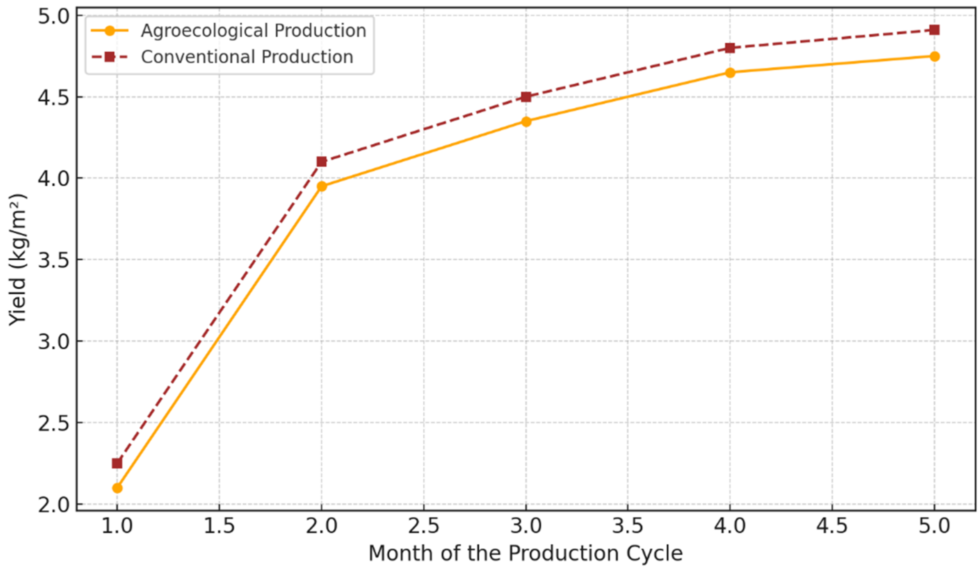

Fig. 1. Rice field growth curves.

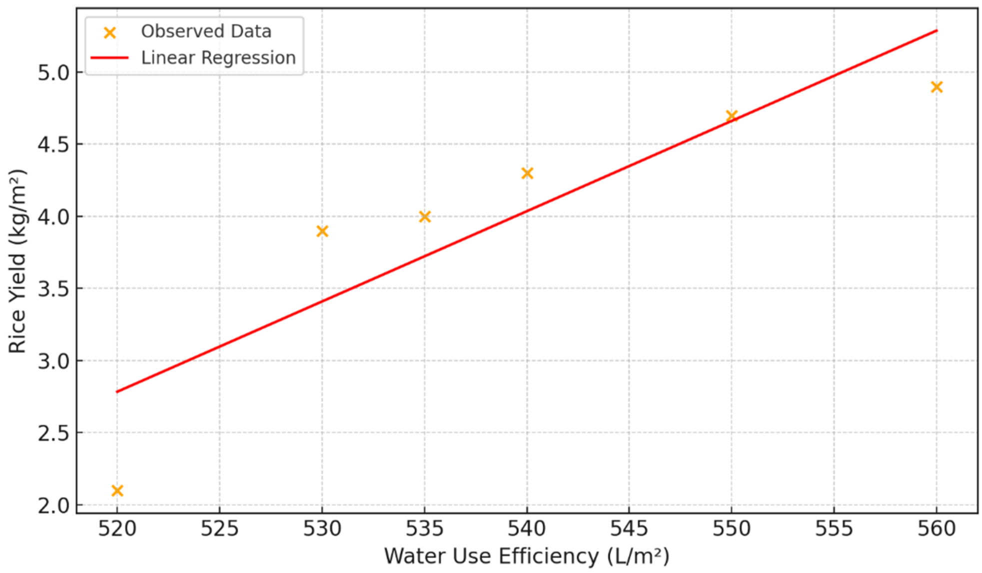

Fig. 2. Correlation between water use efficiency and rice yield.

Análisis Edafológico Postcosecha

In addition to yield and grain quality, a comparative post-harvest soil analysis was conducted to evaluate the impact of the two management systems on soil quality. Composite soil samples were collected from all ten experimental plots (0–20 cm depth) and submitted to the laboratory for physicochemical analysis.

The parameters assessed included organic matter, pH, cation exchange capacity (CEC), soil texture, and nutrient content (N, P, K, Ca, Mg). The results are presented in Table 3. Agroecological management was associated with significant improvements in soil health indicators, including higher organic matter retention, a more balanced pH, and superior cation exchange capacity. These factors enhance biological activity, soil structure, and nutrient availability. Although phosphorus levels were slightly lower in the agroecological system, they remained within adequate ranges for rice cultivation. The finer soil texture observed in the agroecological plots may have also contributed to improved water and nutrient retention.

Table 3. Soil parameters comparison between agroecological and conventional systems.

Parameter	Agroecological	Conventional	Significant ($p < 0.05$)
Organic Matter (%)	3.8 ± 0.4	2.5 ± 0.3	Yes
pH (1:2.5)	6.4 ± 0.2	5.9 ± 0.3	Yes
Cation Exchange Capacity (cmol/kg)	18.3 ± 1.5	14.7 ± 1.2	Yes
Soil Texture	Clay loam	Sandy loam	–
Total Nitrogen (%)	0.23 ± 0.02	0.18 ± 0.01	Yes
Available Phosphorus (mg/kg)	18.5 ± 3.2	24.2 ± 2.8	No
Exchangeable Potassium (cmol/kg)	0.45 ± 0.05	0.40 ± 0.04	No

DISCUSSION

The results of this study on sustainable rice production in Tonosí highlight the viability of the agroecological system as an efficient and environmentally responsible alternative to the conventional intensive production model. Although rice yield under the agroecological model was slightly lower than in the conventional system, the difference was not statistically significant (p = 0.83), indicating that reducing synthetic fertilizer and agrochemical use does not substantially affect productivity. These results are consistent with previous studies that demonstrate the potential of agroecological systems to maintain stable yields while improving soil health and reducing environmental pollution (FAO, 2024; MIDA, 2022). Furthermore, global meta-analyses support these findings: Ponisio et al. (2015, PNAS, 112:7611–7616) reported that agroecological and organic systems achieve on average 80–90% of the yields of conventional systems, reinforcing the notion that yield gaps are often narrow and context-dependent.

One of the most relevant aspects of this study was the improvement in water use efficiency. The agroecological system used 24 percent less water than the conventional system, representing a major sustainability advantage in water-scarce environments. This reduction aligns with studies conducted in Latin America and Asia, which have reported water savings ranging from 20 to 30 percent in agroecological or alternate wetting and drying rice systems (Durán, 2020; Díaz-Pérez & John, 2019). Efficient irrigation practices, combined with improved soil structure and organic matter content, likely contributed to reduced water demand without compromising yield. Such results are particularly relevant for Panama, where climate change projections indicate increased temperature and irregular rainfall patterns that threaten water availability in agricultural zones.

In terms of grain quality, rice cultivated under the agroecological system exhibited a higher proportion of whole grains and slightly higher protein content compared to rice from the conventional system. This improvement is not only agronomically important but also economically relevant, as enhanced grain integrity and nutritional value can increase the market competitiveness of rice (Lassoued et al, 2021).

Agroecological production can position Panamanian rice for premium pricing opportunities in niche markets seeking eco-labeled, chemical-free, or sustainably certified products. This aligns with global consumer trends favoring sustainable agriculture and the rise of "green markets" in Latin America (IICA, 2022).

The statistical analyses did not confirm significant differences in yield between the two production systems (p = 0.83), but this does not imply that both systems are identical. Instead, the results indicate that yields were statistically comparable under the current sample size (n = 10), suggesting that the absence of statistical significance may reflect limited statistical power rather than the true absence of difference. The agroecological system demonstrated comparable productivity while reducing input use and improving environmental indicators, supporting its potential as a sustainable alternative.

From a practical perspective, these findings have direct implications for farmer productivity and resource management. The agroecological approach tested in Tonosí reduced dependency on costly synthetic fertilizers and pesticides, which can substantially lower production costs and improve profit margins in the long term. Improvements in soil quality and water retention also enhance farm resilience to climate variability, contributing to more stable yields across seasons. However, broader adoption of these practices may be constrained by limited access to organic inputs, insufficient technical assistance, and the absence of financial incentives for smallholders. Strengthening extension programs, cooperative compost production, and access to biofertilizers could help overcome these bottlenecks and promote the scalability of sustainable rice production in Panama.

Despite these promising results, some limitations should be acknowledged. The experiment was conducted over a single production cycle, which limits the ability to evaluate long-term effects on soil fertility, carbon sequestration, and biodiversity dynamics. Multi-season studies are recommended to determine the consistency of performance across years and variable climatic conditions. Furthermore, this study did not include an economic analysis, such as production costs, labor requirements, or net profitability, factors that are critical for farmers' decision-making and for scaling agroecological adoption. Future research should incorporate cost-benefit evaluations, including input substitution efficiency and labor dynamics, to determine the economic feasibility of sustainable rice systems in Panama.

Integrating emerging agroecological strategies such as biofertilizers, integrated pest management, and precision irrigation could enhance productivity and sustainability. Combining these innovations with training programs and policy incentives would strengthen national efforts toward climate-resilient and food-secure agricultural systems.

CONCLUSIONS

Agroecological rice production in Tonosí proved to be a feasible and environmentally beneficial alternative to the conventional intensive system. Although yield differences were not statistically significant, the agroecological system achieved comparable productivity while reducing water use by 24 percent, increasing soil organic matter content, and improving grain quality. These findings demonstrate that environmental benefits can be achieved without yield penalties, supporting the transition toward more sustainable agricultural models in Panama.

The results indicate that adopting agroecological practices can sustain rice yields, lower environmental impacts, and strengthen resource efficiency and soil health in the long term. Such systems are consistent with international efforts to promote climate-resilient, low input, and biodiversity-based agriculture.

Scaling up these practices will require supportive public policies, including farmer training programs, financial incentives for sustainable management, and the development of eco-certification schemes that recognize and reward environmentally responsible production. Complementary biochemical and molecular analyses are currently in progress as part of an ongoing study aimed at validating and expanding these results through a more detailed assessment of soil and plant physiological responses.

Future research should evaluate the economic feasibility, multi-season performance, and market opportunities of eco-labeled rice, ensuring that the transition toward sustainability also delivers tangible socioeconomic benefits for farmers and rural communities.

AUTHOR CONTRIBUTIONS

P.R.P. and R.R. conceived the study, designed the methodology, supervised the fieldwork, performed the formal analysis, and was responsible for project administration, funding acquisition, and final manuscript review. J.M. contributed to data analysis, draft writing, figure preparation, and visualization of results. He also participated in data interpretation and manuscript editing. All authors have read and agreed to the published version of the manuscript.

FUNDING

This research received no external funding.

CONFLICTS OF INTEREST

The authors declare no conflict of interest. The authors take full responsibility for the content of the published article.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used Grammarly to support language refinement and minor stylistic adjustments.

After using this tool, the authors reviewed and edited the content carefully and take full responsibility for the final version of the manuscript.

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