



RESEARCH ARTICLE

Synergistic effects of foliar nano-silica and planting systems on the growth and yield of rice (*Oryza sativa* L.) cv. Inpari-32

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Abstract

Optimising nutrient management and planting systems is essential for enhancing rice productivity and reducing the gap between rice (*Oryza sativa* L.) production and consumption in Indonesia. A factorial field experiment based on a randomised complete block design (RCBD) evaluated four nano-silica concentrations (N) (0; 2.5; 5.0 and 10 mL L⁻¹) under three planting systems: conventional planting systems (P), system of rice intensification (SRI) and Jajar Legowo 3:1. All collected data were subjected to analysis of variance (ANOVA) to assess the effects of treatments and their interactions. Where significant differences were detected ($p < 0.05$). Treatment means were separated using Duncan's multiple range test (DMRT) at the 5 % significance level. Application of 5 mL L⁻¹ nano-silica significantly enhanced plant height, tiller production, productive tillers, grain weight and grain yield. The SRI system proved superior for tiller count (19.41), grain weight (232.75 g) and grain yield per hectare (2327.50 kg ha⁻¹). Notably, a significant interaction was observed for average leaf count (51.88) and grain weight (258 g m⁻²) where the combination of 2.5 mL L⁻¹ nano-silica and SRI system, the highest 1000-grain weight (26.21 g) occurred with 5 mL L⁻¹ nano-silica + Jajar Legowo 3:1. The findings suggest that SRI is more effective for maximising grain yield, whereas the combination of Jajar Legowo 3:1 and nano-silica enhanced grain quality traits such as 1000-grain weight, providing alternative management strategies for different production objectives.

Keywords: Inpari-32; nano-silica; planting systems; rice; system of rice intensification

Introduction

Rice (*Oryza sativa* L.) constitutes the bedrock of Indonesian food security; however, a widening disparity persists between domestic production and escalating national demand. Despite a gross output of 53.98 million t of unhusked rice in 2023, supply stability is increasingly compromised by rising consumption, which is projected to reach 99.08 kg per capita by 2025 (1, 2). This challenge is further exacerbated by production volatility exemplified by the notable decline between 2020 and 2021 which highlighting the imperative for agronomic intensification to address yield gaps (3).

Central to achieving intensification is the optimisation of nutrient management, specifically regarding elements often deficient in marginal soils (4). Among these, silicon (Si) has emerged as a critical agronomic input. Although technically classified as a beneficial rather than essential nutrient, Si deficiency induces stress and severely reduces grain productivity (5). To address soil bioavailability constraints, nanotechnology presents a pivotal advancement. Nano-silica fertilisers, characterised by high specific surface area and reactivity, augment the efficiency of Si uptake, thereby enhancing physiological resilience. Prior investigations demonstrate that nano-silica application directly correlates with

improvements in critical yield components, including productive tiller count and grain weight per hill (6).

Concurrently, optimising canopy architecture and plant density represents a parallel strategy for yield maximisation. Advanced planting configurations have been developed to enhance resource use efficiency relative to conventional methods. The Jajar Legowo system, for instance, manipulates row spacing to maximise border effects, thereby improving light interception and nutrient accessibility; specifically, the 3:1 configuration has demonstrated superior grain weight outcomes (7, 8). Similarly, the system of rice intensification (SRI) prioritises the minimisation of inter-plant competition and the optimisation of soil health, strategies proven to significantly increase filled grain percentage and milled yield (9, 10).

Although the benefits of SRI and Si fertilisation have been reported individually, their combined effects on rice growth and yield remain insufficiently explored. It was hypothesised that wider plant spacing could enhance the benefits of nano-silica application by improving canopy light distribution and resource utilisation. Therefore, this study aims to evaluate the interactive effects of varying nano-silica concentrations and distinct planting systems on the vegetative growth and yield determinants of rice.

Materials and Methods

The field experiment was conducted during the wet season, spanning December 2024 to April 2025, in Teluk Awur, Jepara Regency, Central Java, Indonesia (Fig. 1). The experimental site had a tropical climate, with average monthly temperatures ranged from 26.6–28.0 °C while monthly precipitation varied from 145 mm in April to 859.8 mm in December (Table 1). The study employed a factorial randomised complete block design (RCBD) with three replications to evaluate the interaction between four nano-silica concentrations (N) (0; 2.5; 5.0 and 10 mL L⁻¹) and three planting systems (P): (Conventional planting system at 20 x 20 cm, SRI at 30 x 30 cm and Jajar Legowo 3:1 at 20 x 15 cm). This factorial arrangement resulted in 12 treatment combinations distributed across 36 experimental plots, each measuring 5 m² (2 x 2.5 m).

Prior to tillage, composite soil samples were collected from a depth of 0–35 cm, homogenised via the quartering method and analysed at the Laboratory of Ecology and Plant Production, Universitas Diponegoro, to establish baseline physicochemical properties, including total nitrogen (N) (Kjedahl), phosphorus (P) (Olsen), potassium (K) (Ammonium Acetate Saturation), organic carbon (Walkley & Black, pH (Aquadest 1:5) and electrical conductivity (EC Meter) (Table 2).

Crop establishment began with the cultivation of rice seeds (*Oryza sativa* L., cv. Inpari-32) in a nursery for 27 days. Following land preparation, which involved mechanical ploughing and weed clearance, seedlings were transplanted into experimental plots according to their specific planting system treatments. These

configurations resulted in distinct plant populations per plot: 125 hills for the conventional system, 55 hills for SRI and 36 hills for the Jajar Legowo system. Standard agronomic practices were applied uniformly across all experimental units to ensure that nutrient and pest pressures did not interfere with treatment effects. Basal and supplementary fertilisation were administered using 250 kg ha⁻¹ urea (46 % N), 100 kg ha⁻¹ SP-36 (36 % phosphorus pentoxide (P₂O₅)), 100 kg ha⁻¹ potassium chloride (KCl) (60 % potassium oxide (K₂O)) applied on vegetative and generative phase, while pest management was conducted curatively using the insecticide prevathon 50 SC (active ingredient: chlorantraniliprole), applied twice during the growing season to mitigate biotic stress.

Foliar application of a commercial liquid nano-silica formulation (Mestaku™, Semesta Agro Teknologi, Indonesia), containing 20.0 % w/v active silicon (SiO₂) with Si particles size at < 50 nm, was applied at 0; 2.5; 5.0; and 10 mL L⁻¹ at 10; 20; 30; and 40 days after planting (DAP). Applications were executed using a calibrated manual knapsack sprayer at 400 L ha⁻¹ (0.2 L per 5 m²) plot during early morning hours (07:00–09:00 a.m.) to optimise stomatal uptake and minimise evaporation. Data collection encompassed both vegetative and reproductive parameters, including plant height, leaf number, tiller number, productive tiller count, grain weight per clump, 1000-grain weight and final yield per hectare. All collected data were subjected to analysis of variance (ANOVA) to assess the effects of treatments and their interactions using Rstudio version 4.3.2, where significant differences were detected ($P < 0.05$), treatment means were separated using Duncan's multiple range test (DMRT) at the 5 % significance level.



Fig. 1. Location map of Teluk Awur in Jepara, Jawa Tengah, Indonesia.

Table 1. Average air temperature and precipitation during growth period of rice

Factor	December	January	February	March	April
Average air temperature (°C)	28	26.6	26.8	27.5	28
Precipitation (mm/year)	859.8	510	478	298	145

Table 2. Soil chemical properties in experiment plot on Teluk Awur, Jepara at 0–5 cm depth

Soil property	Unit	Mean value
Total nitrogen	%	0.28
Total phosphorus	ppm	0.06
Total potassium	ppm	0.15
Organic carbon	%	1.99
pH	-	8.00
Electric conductivity	dS/m	0.51

Results and Discussion

Plant height

Analysis of variance revealed that nano-silica concentration significantly affected plant height. Conversely, neither the planting system nor the interaction between nano-silica and planting system exerted a significant effect on this parameter. Specifically, the application of 5 mL L⁻¹ nano-silica elicited the maximum plant height, representing a statistically significant increase relative to the untreated control (Fig. 2). The observed enhancement in vertical growth can be attributed to the physiological role of silica in metabolic optimisation. The observed increase may be associated with improved physiological performance and structural reinforcement resulting from Si accumulation (11). Furthermore, upon absorption, Si is deposited within the culm and leaf epidermal cells to form a polymerised 'cuticle-silica double layer.' This structural reinforcement serves as a mechanical barrier that prevents lodging and maintains the upright architecture necessary to support increased height (12).

Leaves count

A significant interaction was observed between nano-silica concentration and planting system regarding leaf number. The highest leaf count was achieved with the specific combination of 2.5 mL L⁻¹ nano-silica and the SRI planting system (Table 3). This result suggests a synergistic relationship between canopy architecture and nutrient modulation. The SRI method inherently reduces self-shading through wider spacing. The interaction may reflect improved resource availability under wider spacing combined with the beneficial effects of nano-silica on plant growth. This optimisation allows lower leaves to maintain photosynthetic activity for longer periods, thereby delaying senescence and preserving a higher number of functional leaves (12). The SRI system created a

conducive growing environment by minimising inter-plant competition for light, water and nutrients (13). Under these favourable conditions, a moderate application of nano-silica was sufficient to stimulate maximum leaf production. Physiologically, Si is absorbed as monosilicic acid and loaded into xylem vessels via an as-yet unidentified transporter. Its subsequent translocation to leaf tissues is facilitated by the LSi6 transporter, where it precipitates as silica beneath the cell wall layer (14). This resulting increase in leaf retention is critical for crop productivity, as it directly expands the photosynthetic surface area required for assimilate production, which fuels vegetative growth and grain development (15).

Tiller count

Analysis of variance showed that both nano-silica concentration and planting system had significant main effects on the number of tillers per plant; however, their interaction was not significant (Fig. 3). The application of 5 mL L⁻¹ nano-silica produced the highest tiller count. This result is consistent with previous studies demonstrating that silica fertilisation supports an increase in tillering (8). Since the number of productive tillers is a primary component of rice productivity, the enhanced tillering from nano-silica application is a key factor in increasing potential grain yield per clump (6). Among the planting systems, the SRI method yielded a significantly greater number of tillers. The wider spacing inherent to the SRI system reduces competition between plants for essential resources like light, water and nutrients. This optimal growing space allows each plant to develop more robustly, leading to the formation of more tillers (13).

Productive tiller count

The analysis of variance elucidated significant, independent effects of both nano-silica concentration and planting system on the number of productive tillers, though no significant interaction was detected (Fig. 4). A nano-silica application of 5 mL L⁻¹ proved optimal, a result that is likely attributable to the physiological potentiation of the plant's reproductive development. This enhancement is potentially linked to silica's role in improving the uptake and translocation efficiency of other essential nutrients, particularly P. Since P is indispensable for the energy transfer processes that govern flowering and the formation of yield components (16), its improved availability is critical for increasing the number of tillers that successfully become productive and bear grain.

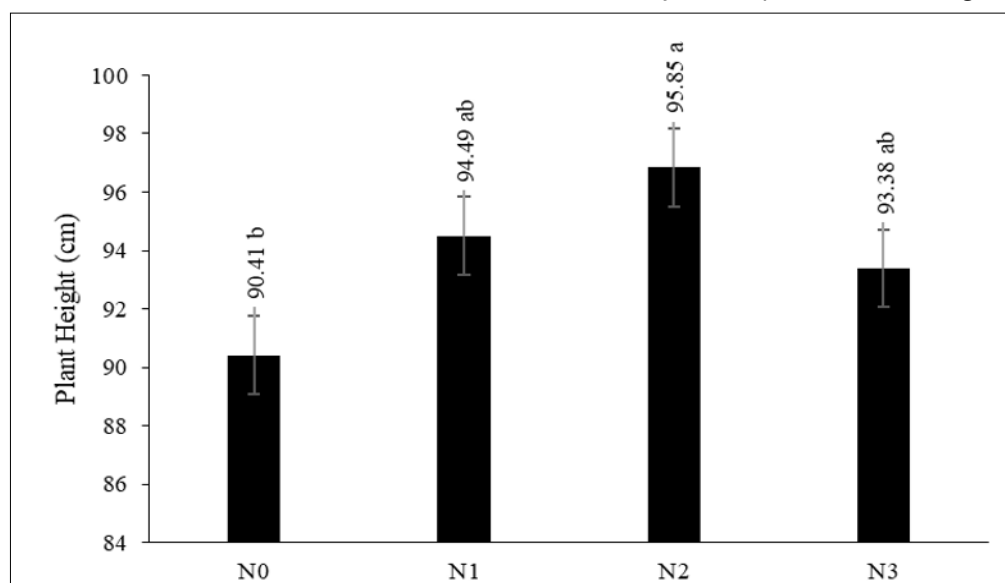
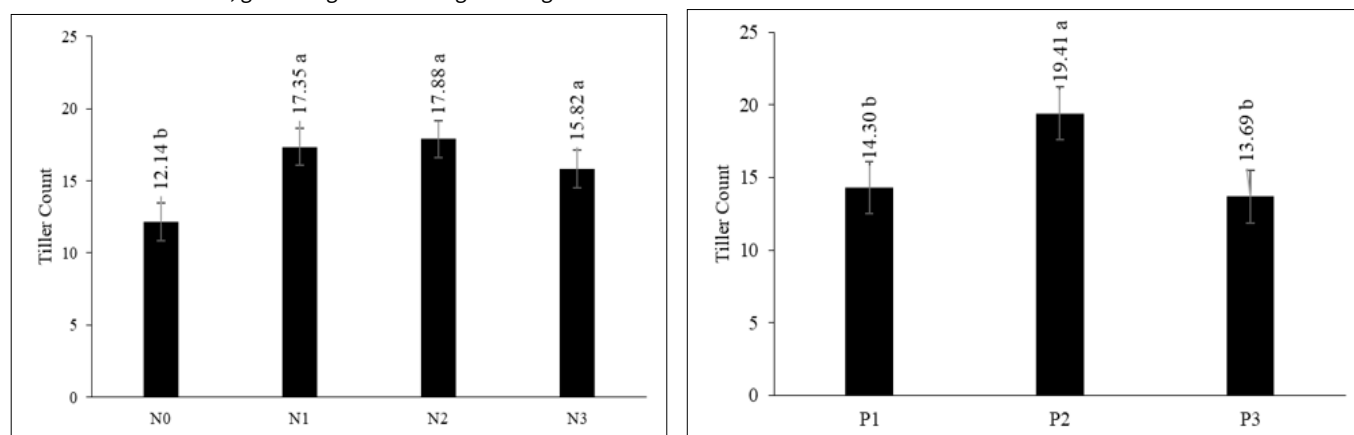
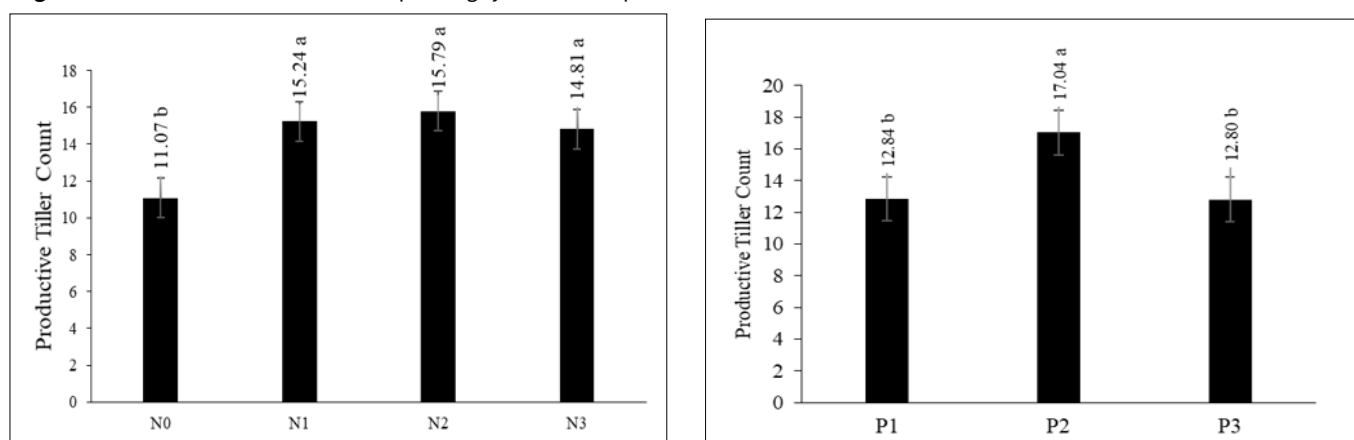


Fig. 2. Effects of nano-silica and different planting system on rice plant height.

Table 3. Leaves count, grain weight and 1000-grain weight affected by nano-silica and different planting system

Nanosilica (mL.L ⁻¹)	Planting system	Leaves count	Grain weight (g.m ⁻²)	1000-grain weight (g.m ⁻²)
0	Konvensional	19.55 ± 1.70 ^d	115.66 ± 20.30	22.50 ± 0.85 ^{cde}
	SRI	24.83 ± 7.21 ^{cd}	183.00 ± 23.81	21.19 ± 1.87 ^{def}
	Jajar Legowo 3 :1	21.44 ± 5.64 ^d	147.00 ± 39.83	23.28 ± 1.25 ^{bcd}
2,5	Konvensional	26.83 ± 5.69 ^c	186.00 ± 61.53	24.29 ± 1.41 ^{abc}
	SRI	51.88 ± 20.33 ^a	258.00 ± 36.51	18.98 ± 1.34 ^{ef}
	Jajar Legowo 3 :1	23.55 ± 1.98 ^{cd}	188.00 ± 30.80	20.32 ± 2.53 ^{ef}
5	Konvensional	38.88 ± 1.25 ^b	225.00 ± 30.64	25.28 ± 1.05 ^{ab}
	SRI	35.56 ± 4.93 ^{bc}	245.33 ± 23.96	25.09 ± 1.47 ^{abc}
	Jajar Legowo 3 :1	28.39 ± 1.94 ^c	205.33 ± 40.20	26.21 ± 1.39 ^a
10	Konvensional	30.22 ± 0.92 ^{bc}	203.00 ± 55.67	19.46 ± 0.72 ^{ef}
	SRI	38.83 ± 0.93 ^{bc}	244.66 ± 48.83	20.45 ± 1.04 ^{ef}
	Jajar Legowo 3 :1	30.00 ± 1.36 ^c	186.33 ± 87.46	23.09 ± 1.68 ^{bcd}

Note: The leaves count, grain weight and 1000-grain weight data showed as mean ± SD.

**Fig. 3.** Effect of nano-silica and different planting system on rice plant tiller count.**Fig. 4.** Effect of nano-silica and different planting system on rice plant productive tiller count.

Concurrently, the SRI planting system was demonstrably superior to both Jajar Legowo and conventional planting systems methods in fostering a higher count of productive tillers. The efficacy of the SRI system stems from its fundamental alteration of the agroecological microenvironment through wider plant spacing. This increased per-plant resource pool minimises both below-ground competition for soil nutrients and above-ground competition for photosynthetically active radiation (17). By preventing the mutual shading that can inhibit photosynthesis in denser plantings, the SRI system enables a higher rate of carbon assimilation per plant, thereby providing the necessary energy to support the development and sustenance of a greater number of productive tillers.

Grain weight

Analysis of variance indicated that both nano-silica concentration and the planting system had significant main effects on grain weight, while their interaction was not significant (Table 3). The application of 5 mL L⁻¹ nano-silica produced the highest grain weight, a result attributed to its ability to create a more stable physiological environment for the plant. Nano-silica likely enhanced the 'source' activity (photosynthesis in flag leaves) and 'sink' strength (grain filling). The SRI system provided the necessary root volume to support nutrient uptake for this increased metabolic demand by improving leaf structure, reducing excessive transpiration and increasing resistance to stress, nano-silica enhances photosynthetic efficiency, which leads to optimal accumulation of photosynthates and the formation of fuller, heavier grains (6, 8, 11, 13).

Similarly, the SRI planting system yielded a significantly greater grain weight compared to the Jajar Legowo and conventional planting systems methods. This superiority was attributed to the wider spacing of the SRI system, which minimises inter-plant competition for sunlight (13, 17). This ensures that each plant can effectively carry out the photosynthesis required for the grain-filling process, directly contributing to an increase in the final grain weight.

1000-grain weight

A significant interaction effect between the nano-silica treatment and planting system was detected for the 1000-grain weight (Table 3). The maximum 1000-grain weight was recorded in the treatment combining 5 mL L⁻¹ nano-silica with the Jajar Legowo 3:1 planting system. This result points to a strong synergistic effect between the two factors. The Jajar Legowo 3:1 planting pattern modifies the crop canopy by creating empty rows, which allows for optimal sunlight penetration to each plant. At the same time, the availability of silica within the plant tissues creates a more stable physiological environment by regulating transpiration and increasing resistance to pests and diseases (18). The convergence of these two factors enhanced energy capture from sunlight and an optimised physiological state for grain filling creates the ideal conditions for producing denser, heavier grains (19).

Final yield per hectare

Analysis of variance demonstrated that both nano-silica concentration and planting system independently exerted a significant influence on final grain yield per hectare (Fig. 5). However, the interaction between these two factors was not significant. As detailed in Table 3, the application of nano-silica resulted in a statistically significant enhancement of yield per hectare compared to the control. This productivity gain is attributed to the physiological role of Si in fortifying the cell wall matrix, specifically through the deposition of a silica-cuticle double layer in leaf epidermal cells. This structural reinforcement improves leaf erectness, which optimises the interception of photosynthetically active radiation (PAR) and minimises mutual shading within the canopy (20). Furthermore, nano-silica improves water use efficiency by regulating stomatal conductance and transpiration rates, thereby maintaining turgor pressure and sustaining physiological activity during the critical grain-filling stage.

Regarding the planting configuration, the SRI produced a significantly higher yield per hectare compared to both the Jajar Legowo 3:1 and conventional planting systems. This superiority is driven by the reduction of intra-specific competition inherent to

wider spacing. By optimising the spatial distribution of plants, the SRI system maximises solar radiation capture and nutrient absorption efficiency for each individual hill (21). This creates a favourable source-sink relationship where elevated photosynthetic rates support the development of a higher quantity of filled grains, ultimately translating to greater bulk yield per unit area.

Conclusion

This study demonstrates that the integration of nanotechnology and optimised canopy architecture is a viable strategy for sustainable rice intensification. The results confirm that while nano-silica application (2.5 mL L⁻¹) and the system of rice intensification (SRI) individually enhance the morpho-physiological traits of rice cv. Inpari-32, their interaction dictates specific production outcomes. The study identified different management combinations were found to be optimal depending on the production objective. For maximising bulk grain productivity (kg ha⁻¹), the SRI system proved superior, likely due to reduced intraspecific competition which amplifies the vegetative benefits of nano-silica. However, for prioritising grain physical quality (grain density), the interaction between the Jajar Legowo 3:1 system and 5 mL L⁻¹ nano-silica yielded the highest 1000-grain weight. This response may be associated with improved growing conditions created by the planting arrangement and nano-silica application. Based on the present findings, SRI combined with 5 mL L⁻¹ nano-silica may be recommended for maximising grain yield, whereas Jajar Legowo 3:1 with the same nano-silica concentration may be suitable when greater 1000-grain weight is desired. Future research should further elucidate the molecular mechanisms governing silica uptake under these varying canopy densities.

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Authors' contributions

FK and A were responsible for the conceptualisation of the study. FK and BH developed the methodology. NKS and CNA handled software and validation tasks. Formal analysis was conducted by A and BH. MTA and NKS performed the investigation. FK provided the

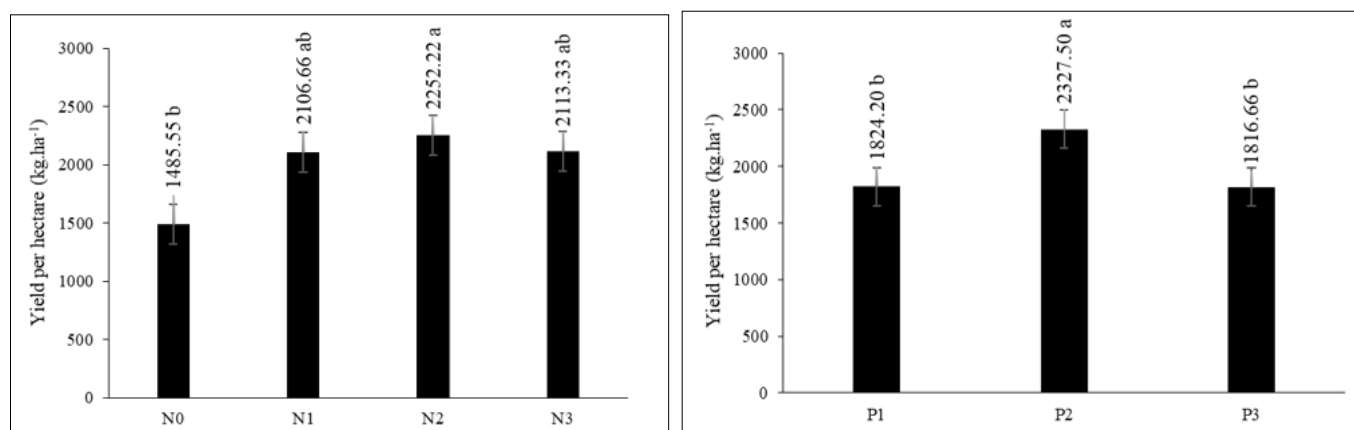


Fig. 5. Effect of nano-silica and planting system on rice plant final yield per hectare.

necessary resources. MTA was responsible for data curation. The original draft was written by FK, A and MTA, while A, NKS, CNA and BH reviewed and edited the manuscript. MTA and NKS prepared the visualisations. FK was responsible for supervision and project administration. All authors have read and approved the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Google Gemini AI in order to improve the grammar and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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