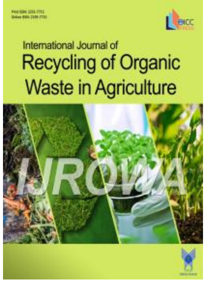

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Research Article

Yield and Profit Improvement of Maize Utilizing Optimal Planting Density and Rice-Husk Waste as Effective Silicon Fertilizer

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Abstract

Purpose: Using silicon fertilizer from rice husk waste and double-narrow row (DNR) plant spacing can increase maize yield. Therefore, the study aimed to improve farmers' productivity and profitability by applying biosilica fertilizer with DNR plant spacing and closing the maize yield gap.
Method: The field experiment was set up in a completely randomized design with three replications in a 2 × 6 × 2 factorial arrangement consisting of two plant spatial arrangements: DNR and conventional row (CR) plant spacing; six maize cultivars: Pioneer-27, Bisi-18, NK-22, JH-37, RK-457, and RK-57; and two levels of biosilica fertilizer application in the form of Si-nanoparticles: with and without biosilica fertilizer. We observed the correlation among yield and yield components, yield increase, profitability, and yield gap analysis.
Results: The number of seeds per row and the number of leaves per plant both showed the highest estimates of positive correlation and positive direct effect as the dominant characteristic that directly affected the variation of maize grain yield. Application of biosilica fertilizer with DNR plant spacing indicated a significant increase in maize productivity of 0.96 t ha^{-1} or 9.90% and additional net return gains of USD 183.49 ha^{-1} compared to CR plant spacing without application of silicon fertilizer. This represents an exploitable yield gap of 21.35%
Conclusion: The DNR planting system and the application of biosilica fertilizer from rice husks were consistently more effective than CR spacing without biosilica fertilizer, demonstrating their reliability and potential for increasing maize yields, improving net income, and narrowing the yield gap.

Keywords: Biosilica fertilizer, Double-narrow row, Grain yield, Net income, Sustainable agriculture, Yield gap

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1. Introduction

The increasing generation of agricultural waste has become a significant global issue. Indonesia is the world's third-largest rice-producing country. In 2023, total rice production was recorded at 54.0 million tons (Statistics Indonesia, 2023), and rice husks make up around 20% of the bulk grain weight of rice (Geethakarthi, 2021). There were 169,789 rice milling units in 2020, and around 95.1 % were small-scale rice mills (Statistics Indonesia, 2021). They usually burn rice husks in situ because the quantity is enormous, requiring ample space. The improper handling and disposal of rice husks have resulted in environmental and population health risks. Prolonged burning of rice waste contributes to air pollution and increases greenhouse gas emissions (Parihar et al., 2023). Rice husks collected from rice milling are considered one of the abundant and invaluable agro-based residues. Rice husks, once considered a by-product with limited utility, have emerged as a promising solution in tropical agriculture. Recent developments in the reuse of agricultural waste have led to environmental sustainability and cleaner technology, focusing on utilizing natural resources. The conversion of rice husks into new products such as rice husk mulch (Osadebe et al., 2024), biochar (Isimikalu et al., 2023; Barus et al., 2023), and silicon fertilizer (Sarong et al., 2020 ; Dorairaj et al., 2022) has the potential to contribute significantly to sustainable agriculture and the circular economy. Numerous silicon fertilizer products have recently been widely used in agriculture. In addition to soil application, different Si-containing compounds have been applied as foliar sprays, such as Si-nanoparticles (Si-NP) (Ahmed et al., 2023). Foliar application of Si-nanoparticles improved the adaptability of maize in cadmium-contaminated soils (Ahmed et al., 2023) and protected the maize plants against heavy metal stress (Rahman et al., 2023) and drought stress conditions (Alowaiesh et al., 2024). Combining Si-NP with organic or inorganic compounds limits the utilization of hazardous chemical fertilizers, aside from their capability to improve maize production (Frank-Stefano et al., 2021; El-Mahrouk et al., 2024). Maize is the second strategic commodity after rice. Around 70% of maize farmers in Indonesia cultivate their crops in degraded acid upland soils. The acid upland area with a pH < 5.5 covers about 107.4 million ha or 74.3% of 144.47 million ha of the total dry land in Indonesia (Sutriadi et al., 2022). Most tropical upland soils are acidic, with high aluminum (Al) saturation, low phosphorus, and low base saturation (Silva et al., 2021). Acidity and Al toxicity are the most critical agronomic problems, resulting in low crop productivity. Maize productivity under this condition is approximately 6.2 t ha^{-1} (Statistics Indonesia, 2023), which is still much lower than the yield potential of maize in Indonesia (12.0 t ha^{-1}) (Agus et al. 2019). The maize yield is about 48.3% of the yield potential, suggesting that there is still a large yield gap in maize productivity. This gap could be filled, among others, by implementing improved cultivation practices (Kuyah et al., 2021). Most farmers in Indonesia use conventional row (CR) spacing of 75 cm between rows and 20 cm in a row, with an expected plant density often lower than 66,667 plants ha^{-1}. One of the strategies for increasing maize yield is appropriately adjusting plant density. The double-narrow row (DNR) or twin-row maize planting system represents an opportunity to gain the benefits of narrow rows without requiring significant changes in water use efficiency and nutrient management (Anapalli et al., 2023). However, maize hybrids can vary significantly in their response to planting density (Bernhard & Below 2020). Small family farms characterize farming under degrading acid upland soils. They are usually less than 1 ha in size, and farm income is an essential element of their livelihoods. Thus, farmers must consider several factors in adopting improved cultivation practices, such as adapting high-yielding cultivars, increasing production costs, and yields and profits (Yokamo, 2020). Many studies have focused on the effect of DNR spacing and silicon fertilizer separately on crop productivity. *"Few studies have reported the combined effect of DNR planting and silicon fertilizer application on yield and profitability."*

This information is essential for a better understanding of the spatial arrangement of maize plant spacing and silicon fertilizer as innovative technology practices for optimizing productivity. We hypothesize that using a DNR planting system and applying biosilica fertilizer from rice husks can increase maize hybrids' yield and profit margin. Narrowing the yield gap in the existing agricultural land has become the main effort worldwide. Therefore, the study aimed to improve farmers' productivity and profit by combining biosilica fertilizer from rice husk with DNR plant spacing to narrow the maize yield gap in degraded upland acid soil.

2. Materials and methods

2.1. Description of study area

The study was carried out at the Assessment Institute for Agricultural Technology (AIAT), Natar Agricultural Experimental Station (-5°19′ S, 105°10′ E, altitude 127 m), South Lampung District, Lampung Province. Some weather variables, including maximum and minimum temperature, precipitation, and sunshine hours, were retrieved from meteorological stations near the study site operated by the Indonesian Agency for Meteorology, Climatology, and Geophysics (Table 1). The Lampung province, with its high rainfall and temperatures throughout the year, experiences high soil leaching and weathering potential. The soil texture was clay loam with 24.3% sand, 30.6% clay, and 45.1% silt. Before sowing, topsoil characteristics were low organic carbon content (1.13%), total N 0.19%, and relatively low available P (18.7 me 100g−1). Soil pH was classified as acid (4.6), low base saturation (31.8%), and low CEC (14.9 cmol kg−1), with Al saturation classified as moderate (11.7%).

Table 1. Some meteorological variables at Natar Experimental Station during growing seasons (2021) and the average of the last ten years

Climate parameter	Year	Month			
		Mar.	Apr.	May	Jun.
Minimum temperature, °C	2021	23.40 (0.05)	22.80 (0.06)	23.80 (0.08)	22.30 (0.11)
	10-year average	23.46	23.62	23.65	22.86
Maximum temperature, °C	2021	34.00 (0.19)	34.40 (0.08)	34.10 (0.07)	34.00 (0.07)
	10-year average	33.80	33.95	33.96	33.56
Rainfall, mm month^{-1}	2021	260.1 10.10)	265.7 (6.33)	164.5 (6.51)	53.4 (4.97)
	10-year average	276.46	224.81	128.21	79.48
Sunshine, hours day^{-1}	2021	4.68 (0.07)	4.58 (0.09)	5.49 (0.08)	5.16 (0.14)
	10-year average	5.03	5.29	6.30	6.10

Values presented are the average monthly air temperature, accumulated rainfall, and monthly sunshine, with deviations from the 10-year average in parentheses

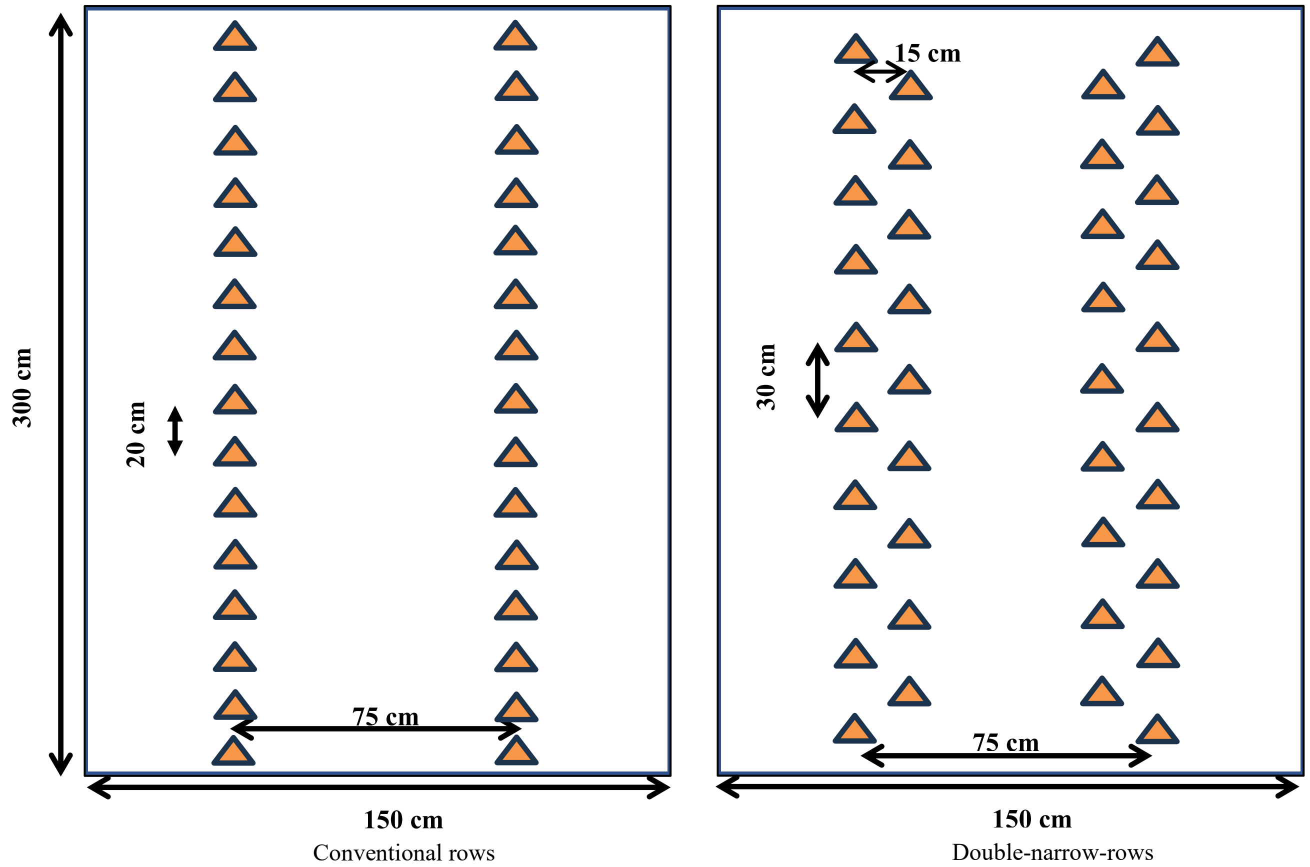

Figure 1. Sampling unit (1.5 × 3 m) and schematic representation of CR and DNR maize planting

2.2. Field experiments

The field experiment was set up in a completely randomized design with three replications in a 2 × 6 × 2 factorial arrangements. Two spatial arrangements of the plants, DNR, and CR spacing were assigned as the main plot. The maize was planted in DNR [(75+15) ×30 cm] and in the CR 75 cm distance between rows and 20 cm distance in a row. With DNR, wide rows (75 cm width) and narrow rows (15 cm width) alternated or zigzag within a 30 cm distance in a row (Figure 1). The expected plant density for DNR spacing was 84,444 compared to 66,667 plant ha^{-1} with CR spacing. Six commercial hybrid maize cultivars, Pioneer-27, Bisi-18, NK-22, JH-37, RK-457, and RK-57, with relative maturity of 96 – 105 days, were randomized as a subplot treatment in each main plot. Two levels of biosilica fertilizer application, with and without biosilica fertilizer, were randomly allocated as a sub-sub-plot. The maize was planted on 02 March 2021 with two seed hill^{-1} in each hole and later thinned to a single plant per hill. The net plot size for individual sub-sub plots was 9 × 6 m^2. After digging, 1 t ha^{-1} of manure was used to cover the seed holes. Fertilizers consisted of 300 kg NPK and 300 kg urea ha^{-1} are used as blanket fertilizers. All NPK was given 5 days after planting (DAP), 50% urea was given at 27 DAP, and another 50% at 42 DAP.

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2.3. Biosilica fertilizer

Biosilica fertilizer in the form of Si-nanoparticles used in this research was a product of the Indonesian Agricultural Postharvest Research and Development, Ministry of Agriculture, in Bogor, West Java, Indonesia. The extraction methods of silica from rice husk to obtain dry silica powder cover the carbonization of agricultural wastes, the silica extraction process, and the nucleation process, as Nandiyanto et al. (2020) explain. Using a fast hydrothermal technique, silica powder from rice husk produces liquid silica with a 10-25 nm particle size. Nanoparticles are materials with sizes ranging between 1 and 100 nm in surface area (El-Mahrouk et al., 2024). The SiO_2 content in liquid biosilica was 10%. Depending on the treatment, biosilica fertilizer was sprayed twice as a foliar application at a dose of 4 L/ha at 28 and 45 DAP. The foliar application method involves spraying liquid biosilica fertilizer on the leaf surfaces, and the uptake occurs by stomata or leaf epidermal cells (Ahmed et al., 2023).

2.4. Parameters observed

The crop was harvested based on the plant's physiological maturity on 14 June 2021. Plant height was measured from the ground level to the base of the tassel for five randomly selected plants from each sampling area during harvest. The same plants were used to calculate the number of leaves per plant, and yield components were determined. The number of cobs harvested for grain yield and plant biomass was obtained by collecting all plants in the 3 × 1.5 m^2 sampling area.

The plant biomass was cut at the stem base, chopped, dried to a constant weight at 60 °C, and weighed to determine plant biomass. The harvest index was estimated as the grain weight and plant biomass ratio at harvest. Yield and cob weight were reported for 15.5% moisture content. The 1000-seed weight was the mean of four random samples of 500 seeds. The yield increase was calculated as the difference in maize yield under DNR with biosilica fertilizer applied in dosages of 4 L/ha compared to maize yield under CR without biosilica fertilizer. It is calculated in tons ha^{-1} and percentage.

2.5. Partial budget analysis

An agro-economic analysis based on partial budgets was constructed using CR with a plant density of 66,667 ha^{-1}, compared to DNR with 84,444 plants ha^{-1} plus 4 L ha^{-1} of biosilica fertilizer as a foliar application. In the partial budget analysis, we considered only the varied costs among the management practice systems. The additional costs included the Si-NP as a liquid biosilica fertilizer, labor for foliar application, and the addition of seed for the DNR planting system. The profit analysis compared expected costs and profits using combined DNR plant spacing plus biosilica fertilizer and CR without biosilica. Revenue is calculated by multiplying the grain yield of maize crops by the farm gate price in Lampung province. The change in benefit is the difference between the extra profit and the total cost of using combined DNR plus biosilica fertilizer and CR without biosilica. All the economic data were converted into USD using the average exchange rate 2021 of USD 1 = IDR14,300.

2.6. Yield gap analysis

The exploitable yield gap of a crop grown in a particular location is defined as the difference between the yield under optimum management and the average yield achieved by farmers (Stuart et al., 2016). The exploitable yield gap is described as a percentage by dividing this value by the yield under optimum management. Agro-economic analysis based on the average yield revealed yield gaps between CR, as the farmers' current practices, and the DNR, as innovative technology practices.

2.7. Data analysis

All collected data were processed in MS Excel. Data for each variable underwent a comprehensive ANOVA and were statistically analyzed using the statistical package of IRRISTAT for Windows 4.0.

The main effects and all interactions were considered significant when $P < 0.05$. For the segregation of means, Duncan's Multiple Range Test (DMRT) was used at a 5% significance level. Correlation analysis was done to study the nature and degree of the relationship between yield and contributing factors. A correlation coefficient value (r) was calculated, and the significance test was analyzed using the Pearson correlation procedure.

3. Results and discussion

3.1. Maize grain yield

The results of the ANOVA showed that spatial arrangement, maize cultivar, and biosilica fertilizer application were the main factors significantly affecting grain yield. However, the interactions among the main factors did not significantly affect grain yield (Table 2). The average maize yield using DNR was 10.240 t ha^{-1}, significantly higher than CR spacing 9.703 t ha^{-1} or an increase in maize productivity of 0.537 t ha^{-1} (5.53%) (Table 3).

Table 2. Mean square values for effects of spatial arrangement, cultivar, and biosilica fertilizer application, and their interaction for each maize parameter observed

Parameter observed	Source of variance						
	Spatial arrangement (A)	Cultivar (B)	Interaction A × B	Biosilica fertilizer (C)	Interaction A × C	Interaction B × C	Interaction A × B × C
	Mean square						
PH	14087.0***	807.1**	725.3^{ns}	497.1**	136.9^{ns}	52.7^{ns}	15.7^{ns}
L/P	5.9502*	4.6799**	0.6772^{ns}	0.8119**	0.0677^{ns}	0.0749^{ns}	0.0687^{ns}
CL	0.2904^{ns}	1.2244*	2.3919**	0.7240^{ns}	0.0568^{ns}	0.3280^{ns}	0.1417^{ns}
CD	0.0771^{ns}	0.1637**	0.2565^{ns}	0.2565**	0.0011^{ns}	0.0038^{ns}	0.0055^{ns}
R/C	3.6778^{ns}	1.8507**	0.7069^{ns}	6.3127**	0.0240^{ns}	0.1901^{ns}	0.1303^{ns}
S/R	57.84^{ns}	120.169**	2.066 ^{ns}	38.578**	5.865^{ns}	0.246^{ns}	0.821^{ns}
CB	60.301***	0.037^{ns}	0.013^{ns}	0.024^{ns}	0.014^{ns}	0.017^{ns}	0.063^{ns}
CW/P	5826.1^{ns}	9860.3**	3120.1**	9285.8**	109.7^{ns}	751.4^{ns}	1038.5^{ns}
KW/P	10016.7*	5333.9***	358.3^{ns}	116.7^{ns}	258.0^{ns}	456.5**	251.2^{ns}
SDW	2897.7**	12090.8**	5.5$^{NS\ ns}$	709.7**	2.4$^{NS\ ns}$	146.9**	32.4^{ns}
BY	10.4471^{ns}	6.0267^{ns}	5.1464^{ns}	2.2956*	1.0401^{ns}	2.4072^{ns}	1.0604^{ns}
AGB	0.0349^{ns}	1.2504**	0.5096^{ns}	2.2156**	0.5096^{ns}	0.7009^{ns}	0.4212^{ns}
HI	0.0041^{ns}	0.0084^{ns}	0.0013^{ns}	0.0065^{ns}	0.0010^{ns}	0.0002^{ns}	0.0001^{ns}
GY	9.2752**	19.8059***	3.3843^{ns}	4.0994***	0.5316^{ns}	0.6936^{ns}	0.2537^{ns}

*Significant effect on 5% level; **significant effect on 1% level; *** significant effect on 0.1% level; ^{ns}: nonsignificant; PH: plant height; L/P: number of leaves per plant; CL: cob length; CD: cob diameter; R/C: number of rows per cob; S/R: number of seed per row; CB: cob number per m^2; CW/P: cob weight per plant; KW/P: kernel weight per plant; SDW: weight of 1000 seeds; BY: biological yield; AGB: above ground biomass; HI: harvest index; GY: grain yield

Table 3. Main effect of spatial arrangement, cultivar, and biosilica fertilizer on means of maize grain yields, plant biomass, biological yield, and harvest index

Treatments	Grain yield (t ha^{-1})	Plant biomass (t ha^{-1})	Biological yield (t ha^{-1})	Harvest index (%)
Spatial arrangement				
DNR	10.240^{a}	12.030^{a}	22.221^{a}	45.76^{a}
CR	9.703^{b}	11.996^{a}	21.762^{b}	44.55^{a}
SEM±	0.209	0.076	0.044	0.029
Cultivar				
Pioneer-27	10.658^{a}	12.354^{a}	23.329^{a}	47.03^{a}
Bisi-18	11.373^{a}	12.204^{a}	22.900^{a}	46.84^{a}
NK-22	11.576^{a}	12.130^{a}	23.094^{a}	47.12^{a}
RK-57	9.836^{b}	11.842^{b}	21.315^{b}	44.38^{a}
RK-457	9.126^{b}	11.914^{b}	20.794^{b}	42.57^{a}
JH-37	8.881^{b}	11.634^{b}	20.425^{b}	42.97^{a}
SEM±	0.308	0.288	0.350	0.049
Biosilica fertilizer				
Without	9.700^{b}	11.737^{b}	21.934^{b}	46.60^{a}
With	10.359^{a}	12.191^{a}	22.096^{a}	44.11^{a}
SEM±	0.103	0.104	0.172	0.026
cv(a) (%)	8.7	14.5	11.5	4.1
cv(b) (%)	13.1	12.7	16.8	5.5
cv(c) (%)	6.2	10.2	14.6	10.6

Within the same column means followed by the same letter are not significantly different at the 0.05 probability level; SEM: standard error of the mean

The present study's results, in line with Liang et al. (2020) and Meira et al. (2022), indicated that DNR significantly increased grain yield. Yan et al. (2021) showed that increasing planting density to the medium level (105,000 plants ha^{-1}) in China significantly increased grain yield compared to the low level (75,000 plants ha^{-1}). However, further increasing planting density to 135,000 plants ha^{-1} did not result in an additional yield increase. High planting density may provide a high yield due to increased leaf area index, photosynthetically active radiation, and improved dry matter and nitrogen accumulation (Shah et al., 2021).

Cultivar treatment has significantly affected grain yield (Table 3). On average, the mean grain yield of cultivars Pioneer-27, Bisi-18, and NK-22 was considerably higher than that of cultivars RK-57, RK-457, and JH-37 under DNR and CR spacing. These findings indicate the importance of selecting cultivars that suit the spatial arrangement or planting density to increase maize production (Bernhard & Below 2020). Biosilica fertilizer significantly impacts grain yield, leading to a notable increase compared to those without biosilica applications (Table 3).

Across different spatial arrangements and cultivars, applying biosilica fertilizer increased maize productivity by 0.659 t ha^{-1} (6.79%). Biosilica fertilizer minimizes water evaporation from the soil surface, enhances antioxidant activity, and reduces soil pollutant absorption from degraded acid upland soil (Nongbet et al., 2022; Alowaiesh et al., 2024). Furthermore, silica fertilizers have been found to enhance plants' resistance to biotic and abiotic stress (Rajput et al., 2021) and various harmful metals (Yadav et al., 2023).

3.2. Plant biomass and harvest index

Spatial arrangement substantially affects biological yield but did not affect plant biomass and harvest index (Table 3).

The DNR showed a considerably higher biological yield than the CR plant spacing. The harvest index, a measure of its efficiency in converting photosynthesized products into economic value, is a crucial factor in crop productivity (Garcia et al., 2023). It did not differ significantly between DNR and CR spacing. According to Ruiz et al. (2023), the increase in harvest index has been attributed to breeding, not to crop management. They further concluded that the fertilizer treatments affected the magnitude of the harvest index, but plant density did not.

On average, maize cultivars Pioneer-27, Bisi-18, and NK-22 have significantly higher plant biomass and biological yield than cultivars RK-57, RK-457, and JH-37. Applying biosilica fertilizer significantly increased plant biomass and biological yield compared to those without biosilica fertilizer application.

The positive effects of biosilica fertilizer in our study align with El-Mahrouk et al. (2024) mentioned that SiO_2 enhanced plant growth via increasing photosynthetic level, stomal conductance, electron transport rate, and photochemical processes. However, applying biosilica fertilizer increased the harvest index by 5.6% but was not statistically different.

3.3. Plant height and yield component

Plant height, number of leaves per plant, cob number per unit area, number of rows per cob, and number of seeds per row were significantly higher under double-narrow rows than conventional spacing (Table 4).

Table 4. Main effect of spatial arrangement, cultivar, and biosilica fertilizer on the means of maize plant height, number of leaves per plant, and several yield components

Treatment	Plant height (cm)	Number of leaves per plant	Cob number m^{-2}	Number row cob^{-1}	Number seed row^{-1}
Spatial arrangement					
DNR	233.1a	13.6a	8.05a	15.88a	31.23a
CR	211.0b	13.2b	6.56b	15.46b	29.78b
SEM±	0.044	0.044	0.010	0.043	0.131
Cultivar					
Pioneer-27	225.0b	13.5a	7.36a	15.75b	32.97a
Bisi-18	234.5a	14.4a	7.23a	16.13a	32.55a
NK-22	215.4c	13.6a	7.34a	16.33a	32.99a
RK-57	216.3bc	13.0b	7.29a	15.55b	29.09b
RK-457	221.5b	13.2b	7.29a	15.79b	27.79b
JH-37	219.4b	13.0b	7.32a	15.48b	27.67b
SEM±	0.063	0.064	0.016	0.172	0.224
Biosilica fertilizer					
Without	219.2b	13.3b	7.29a	15.26b	29.38c
With	226.2a	13.6a	7.31a	16.10a	31.44a
SEM±	0.041	0.041	0.014	0.066	0.112
cv(a) (%)	14.6	6.4	11.0	7.7	6.6
cv(b) (%)	7.8	12.9	12.5	14.6	13.1
cv(c) (%)	9.2	8.2	12.6	12.5	12.2

Within the same column means followed by the same letter are not significantly different at the 0.05 probability level; SEM: standard error of the mean

Maize cultivars varied in their response to those parameters observed. On average, among the cultivars tested, Bisi-18 had the highest plant height, and NK-22 had the shortest plant height.

The number of leaves per plant was significantly higher for Bisi-18, Pioneer-27, and NK-22 than for other cultivars tested. Cob numbers per unit area did not significantly differ for all cultivars tested.

Cob numbers per unit area did not significantly differ for all cultivars tested. At the same time, their response varied with the number of rows per cob and the number of seeds per row (Table 4). Bisi-18 and NK-22 had more rows/cob, while Pioneer-27, Bisi-18, and NK-22 had more seeds/rows than other cultivars tested. The higher number of leaves per plant, number of rows per corn cob, and number of kernels per row may explain why the Pioneer-27, Bisi-18, and NK-22 maize cultivars produced significantly higher grain yields than the RK-57, RK-457, and JH-37 cultivars. Moreover, we found that cultivar NK-22 had the highest number of rows per cob and the number of seeds per row.

Except for cob number per unit area, application of biosilica fertilizer significantly increased plant height, number of leaves per plant, number of rows per cob, and number of seeds per row compared to without application of biosilica fertilizer (Table 4). These results, in line with Torabi et al. (2023), showed that foliar application of silicon fertilizer improved the yield through an increase in the number of seeds per ear, number of rows per ear, chlorophyll content, and relative water content of maize leaves.

Cob length (Figure 2) and cob weight plant^{-1} (Figure 3) were affected by the interaction between spatial arrangement and cultivar (Table 2). The results show that, except for cultivars JH-37 and RK-457, the cob length of maize cultivars RK-57, Pioneer 27, Bisi-18, and NK-22 decreased in a DNR compared to CR plant spacing. Similarly, except for maize cultivar JH-37, the cob weight of maize cultivars RK-457, RK-57, Pioneer 27, Bisi-18, and NK-22 also decreased in DNR compared to CR plant spacing. These findings showed that cob length and weight tend to decline under the DNR planting system, which has a higher plant density than CR. These results align with data from Bernhard & Below (2020), and Worku et al. (2020), that increased plant density decreases the cob length and weight of maize cultivars.

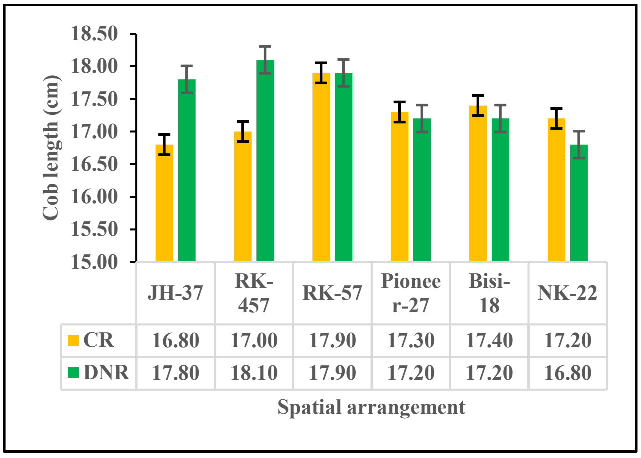
Kernel weight and the weight of 1000 seeds were affected by the interaction between cultivar and biosilica fertilizer (Table 2). The interaction between the cultivar and biosilica fertilizer application on kernel weight (Figure 4) and weight of 1000 seeds (Figure 5) showed that the application of biosilica fertilizer was superior compared to without. It notably increased the kernel weight and weight of 1000 seeds of cultivars Pioneer-27, Bisi-18, and NK-22 more than RK-457, RK-57, and JH-37, on average.

3.4. Correlation analysis of grain yield

The correlation coefficient measures the strength of the relationship between two variables and provides an overview of the simple relationship between variables, both in the same direction (positive correlation) and in the opposite direction (negative correlation) (Sadeghi, 2022). The magnitudes of the correlation coefficients were classified as Paez et al. (2022): if r < | 0.1 |, the correlation is negligible; if | 0.1 | < r < = | 0.3 |, the correlation is week; if | 0.3: < r < = | 0.5 |, the correlation is medium; and if r > | 0.5 |, the correlation is high or strong. Based on the correlation, as shown in Table 5 and Figure 6, the maize grain yield had a positive and strong correlation with the number of seeds per row (0.731) and number of leaves per plant (0.562), medium correlation with cob diameter (0.496), cob weight per plant 0.365), and kernel weight per plant (0.470). However, the number of rows per cob and cob number per unit area, weakly correlated with grain yield. A thousand-grain weight had a weak and negative correlation with grain yield, implying that grain yield is due to the number of seeds per row rather than to grain weight. This result agrees with those obtained by Fadhli et al. (2023), where the increase in the number of seeds per row causes an increase in the number of grains per cob and cob diameter, contributing to the rise in the biological yield and productivity of maize.

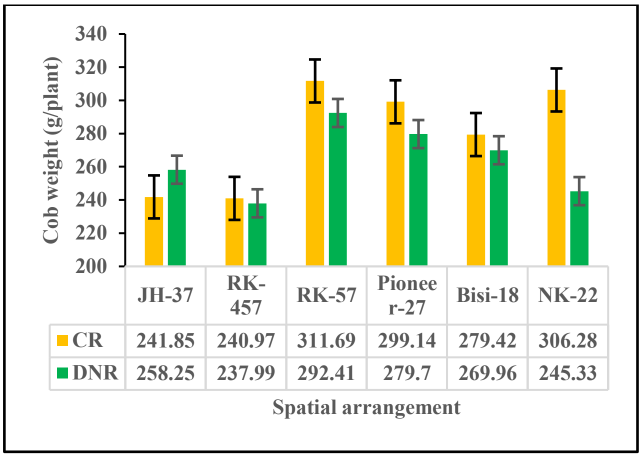
According to Magar et al. (2021), an increase in cob diameter will lead to a simultaneous increase in the number of rows per cob, as longer and broader kernels can accommodate more seed per row and consequently more kernel and cob weight per plant, which contributes to increased maize yield. Path analysis effectively divides the correlation coefficients into direct and indirect impacts, explaining their associations in more detail (Marak et al., 2023).

The path coefficient analysis revealed that the number of seeds per row showed the highest estimate of positive correlation ($r = 0.731$) and positive direct effect ($r = 0.523$). The number of leaves per plant also showed a positive correlation ($r = 0.562$) and a positive direct effect ($r = 0.377$) as the dominant characteristics that directly affected productivity (Table 6). Thus, correlation and path analysis of the matrix yield component correlation revealed that the number of seeds per row and the number of leaves per plant were responsible for the variation of grain yield analysis as affected by spatial arrangement, cultivar, and biosilica fertilizer.



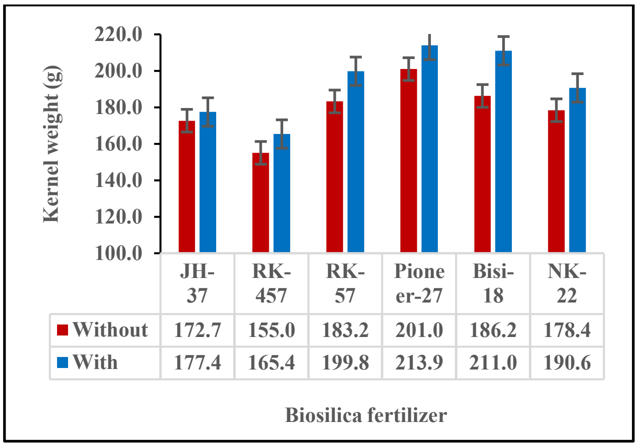
	JH-37	RK-457	RK-57	Pioneer-27	Bisi-18	NK-22
🟨 CR	16.80	17.00	17.90	17.30	17.40	17.20
🟩 DNR	17.80	18.10	17.90	17.20	17.20	16.80

Figure 2. Cob length was affected by the interaction between spatial arrangement and cultivar



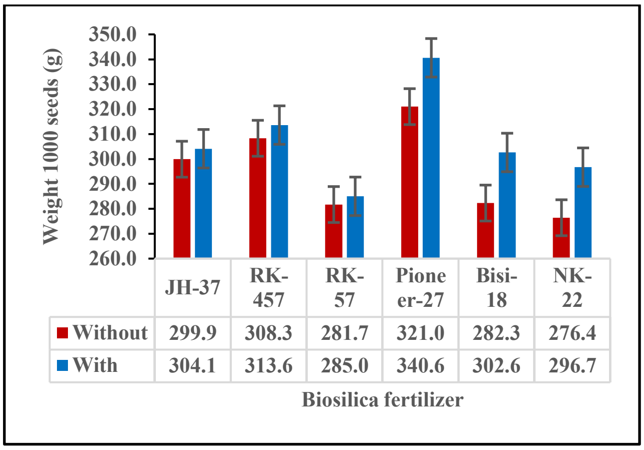
	JH-37	RK-457	RK-57	Pioneer-27	Bisi-18	NK-22
🟨 CR	241.85	240.97	311.69	299.14	279.42	306.28
🟩 DNR	258.25	237.99	292.41	279.7	269.96	245.33

Figure 3. Cob weight was affected by the interaction between spatial arrangement and cultivar



	JH-37	RK-457	RK-57	Pioneer-27	Bisi-18	NK-22
🟥 Without	172.7	155.0	183.2	201.0	186.2	178.4
🟦 With	177.4	165.4	199.8	213.9	211.0	190.6

Figure 4. Kernel weight per plant was affected by the interaction between biosilica fertilizer and cultivar



	JH-37	RK-457	RK-57	Pioneer-27	Bisi-18	NK-22
🟥 Without	299.9	308.3	281.7	321.0	282.3	276.4
🟦 With	304.1	313.6	285.0	340.6	302.6	296.7

Figure 5. Weight of 1000 seeds was affected by the interaction between biosilica fertilizer and cultivar

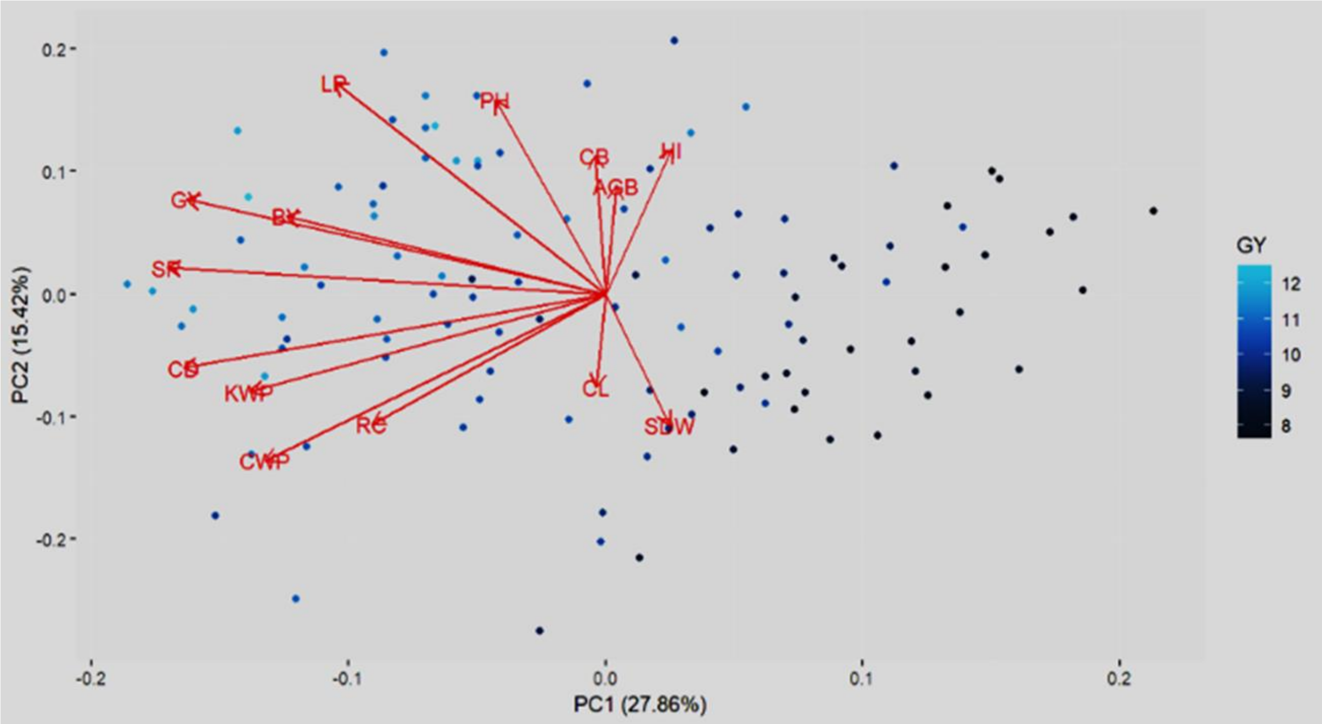


Figure 6. Principal component analysis biplot expressing the relationship of the first two principal components as affected by spatial arrangement, cultivar, and biosilica fertilize

Table 5. Correlation of yield and yield components of maize as affected by spatial arrangement, cultivar, and biosilica fertilizer

	PH	L/P	CL	CD	R/C	S/R	CB	CW/P	KW/P	SDW	BY	AGB	HI	GY
PH	1													
L/P	0.688**	1												
CL	0.056^{ns}	-0.075^{ns}	1											
CD	0.172^{ns}	0.281**	0.075^{ns}	1										
R/C	0.056^{ns}	0.177^{ns}	0.108^{ns}	0.450**	1									
S/R	-0.006^{ns}	0.369**	-0.192*	0.636**	0.267**	1								
CB	0.266**	0.171^{ns}	0.136^{ns}	0.020^{ns}	-0.167^{ns}	-0.001^{ns}	1							
CW/P	0.078^{ns}	-0.002^{ns}	0.166^{ns}	0.633**	0.342**	0.424**	-0.122^{ns}	1						
KW/P	-0.213*	0.120^{ns}	0.181^{ns}	0.590**	0.233*	0.572**	-0.071^{ns}	0.536**	1					
SDW	0.056^{ns}	-0.187^{ns}	0.161^{ns}	0.087^{ns}	0.136^{ns}	-0.239*	0.088^{ns}	0.186^{ns}	-0.066^{ns}	1				
BY	0.184^{ns}	0.323**	-0.065^{ns}	0.326**	0.068^{ns}	0.543**	-0.023^{ns}	0.356**	0.275**	-0.221*	1			
AGB	0.020^{ns}	0.126^{ns}	-0.183^{ns}	-0.054^{ns}	-0.134^{ns}	0.030^{ns}	0.014^{ns}	-0.104^{ns}	-0.074^{ns}	-0.120^{ns}	-0.017^{ns}	1		
HI	0.018^{ns}	0.067^{ns}	-0.031^{ns}	-0.172^{ns}	-0.373**	-0.004^{ns}	0.216*	-0.276**	0.061^{ns}	-0.135^{ns}	0.120^{ns}	0.067^{ns}	1	
GY	0.230*	0.562**	-0.062^{ns}	0.496**	0.193*	0.731**	0.190*	0.365**	0.470**	-0.202*	0.479**	0.087^{ns}	-0.059^{ns}	1

**Significant effect on 1% level; *significant effect on 5% level; ^{ns}: nonsignificant; PH: plant height; L/P: number of leaves per plant; CL: cob length; CD: cob diameter; R/C: number of rows per cob; S/R: number of seed per row; CB: cob number per m^2; CW/P: cob weight per plant; KW/P: kernel weight per plant; SDW: weight of 1000 seeds; BY: biological yield; AGB: above ground biomass; HI: harvest index; GY: grain yield

Table 6. Partitioning the correlation coefficient into direct and indirect effects of path analysis as affected by spatial arrangement, cultivar, and biosilica fertilizer

Characteristic	Direct effect	Indirect effect						Corr
		L/P	CD	S/R	CW/P	KW/P	BY	
L/P	0.377		-0.100	0.121	-0.219	-0.057	0.197	0.562
CD	-0.101	0.322		0.373	0.527	0.224	-0.202	0.496
S/R	0.523	0.084	0.108		-0.108	0.377	0.229	0.731
CW/P	0.144	-0.006	0.064	0.033		0.077	0.042	0.365
KW/P	0.100	-0.065	0.132	0.030	0.182		0.103	0.470
BY	0.027	-0.009	0.220	0.217	0.231	-0.080		0.479

L/P: number of leaves per plant; CD: cob diameter; S/R: number of seed per row; CW/P: cob weight per plant; KW/P: kernel weight per plant; BY: biological yield

3.5. Yield increased

Table 7 showed that, across cultivar tested, DNR plus biosilica fertilizer as foliar application and CR plant spacing without biosilica fertilizer indicated a significant increase in maize grain yield. On average, maize productivity increased by 0.957 t ha^{-1} (between 0.322 and 2.116 t ha^{-1}) or 9.90% (between 2.99 and 21.35%) compared to CR spacing without applying biosilica fertilizer. Compared with each main factor individually, DNR or biosilica fertilizer application only increased the average maize yield by 5.53% and 6.79%, respectively (Table 3). However, using a combined DNR plant spacing of maize and biosilica fertilizer increased the maize yield by 9.90%. Our results, in line with Frank-Stephano et al. (2021), indicated that combined silicon fertilizer with straw returns to the soil, increasing maize productivity by 6.3% compared to only 4.3% without straw returned to the soil.

3.6. Profit increased

Under combined DNR plant spacing and the application of biosilica fertilizer in the form of Si-nanoparticles 4 L ha^{-1} across cultivar tested, we observed practical benefits in the form of additional net return gains of USD 183.49 ha^{-1} (ranging between USD 25.58 and 471.94 ha^{-1}) per cycle after deducting the costs of biosica fertilizer in the form of Si-nanoparticles, a paid worker, and additional seed compared to CR spacing without biosilica fertilizer (Table 8). The result was corroborated by the study of Prabha et al. (2022), which found that applying silica fertilizer increased the net return and B/C ratio of maize.

3.7. Narrowing the yield gap

Our findings indicate that achieving higher yields (Table 7) and net returns (Table 8) under the DNR planting system by applying silica fertilizer is likely more significant than that under the conventional row spacing used in current farmers' practices. The highest increase in attainable yield, 21.35% (Table 7), showed that narrowing the gap between current and potential maize grain yields as big as 48.3% is possible (Agus et al. 2019). Agronomic practices should be modified with consideration for plant density optimization (Luo et al., 2020).

Biosilica fertilizer has become a common agronomic technique (Ghosh et al., 2023). The use of biosilica fertilizer, in combination with double-narrow row plant spacing, represents an innovative approach to sustainable agriculture. This practice increases productivity and promotes a circular economy, highlighting the potential of biosilica fertilizer for sustainable farming. Converting bio-waste into biofertilizers can enhance agricultural productivity, promote sustainable agricultural practices, and reduce pollution (Hiranmai et al., 2024; Haruni et al., 2024).

Table 7. Maize grain yield and yield increase compared between combined DNR plus biosilica fertilizer and CR spacing without biosilica fertilizer

Cultivar	Mean CR spacing without biosilica fertilizer	Mean DNR plant spacing with biosilica fertilizer	Yield increased	
			t/ha	%
Pioneer-27	10.757	11.079	0.322	2.99
Bisi-18	10.726	11.817	1.091	10.17
NK-22	9.911	12.027	2.116	21.35
RK-57	9.473	10.187	0.714	7.53
RK-457	8.795	9.503	0.708	8.05
JH-37	8.472	9.261	0.789	9.31
Average	9.689 b	10.646 a	0.957	9.90

Within the same row means followed by the same letter are not significantly different at the 0.05 probability level

Table 8. Profit analysis between combined DNR plus biosilica fertilizer and CR spacing without biosilica fertilizer

Cultivar	Yield increased (t ha^{-1})	Benefit	Additional cost (USD ha^{-1})				Change in benefit (USD ha^{-1})
			Silica fertilizer	Paid worker	Seed	Total	
Pioneer-27	0.322	80.12	27.97	20.98	5.59	54.54	25.58
Bisi-18	1.091	271.45	27.97	20.98	5.59	54.54	216.91
NK-22	2.116	526.48	27.97	20.98	5.59	54.54	471.94
RK-57	0.714	177.65	27.97	20.98	5.59	54.54	123.11
RK-457	0.708	176.16	27.97	20.98	5.59	54.54	121.62
JH-37	0.789	196.31	27.97	20.98	5.59	54.54	141.77
Average	0.957	238.03				54.54	183.49

4. Conclusion

The double-narrow row planting system and applying biosilica fertilizer from rice husks were consistently more effective than conventional row spacing without biosilica fertilizer. These results demonstrate the potential for increasing maize yields, generating higher net income, and narrowing the yield gap as an innovative pathway to sustainable agriculture.

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Authors Contribution

Conceptualization and design: Slameto, Erythrina; field investigation and data collection: Slameto, Erythrina, Endriani, Darwis; formal analysis: Darwis, Slameto; analysis and interpretation of results: Erythrina, Slameto, Darwis; writing-original draft preparation: Erythrina; review and editing: Slameto, Erythrina; supervision: Slameto; project administration: Endriani. All authors have read and agreed to the published version of the manuscript. All co-authors reviewed the final version and approved the manuscript before submission.

Availability of data and materials

Data will be made available on request

Conflict of interests

The authors declare that there are no conflicts of interest associated with this study.

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