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Application of silicate-solubilizing bacteria to reduce biotic stress and optimize rice yield in intensive paddy fields

Aplicação de bactérias solubilizadoras de silicato para reduzir o estresse biótico e otimizar a produtividade do arroz em arrozais intensivos

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ABSTRACT

Silica fertilizers remain underutilized in Indonesian rice farming despite the natural abundance of silica from volcanic ash in paddy fields. This is primarily due to the limited bioavailability of silica in rice plants. Silicate-solubilizing bacteria (SSB) offer a promising solution by enhancing silica availability and improving plant resilience. This study, conducted in Sukaresmi Village, Megamendung District, West Java, aimed to evaluate the combined effects of silica fertilizers, NPK fertilizers, and SSB on rice growth, yield, and resistance to biotic stress in Inceptisols. A randomized complete block design with 12 treatments and three replications was used, incorporating various silicate sources—such as straw, empty oil palm bunches, biosilica, RabanaSil, and silica gel—and the bacterium *Enterobacter cloacae* CmA12 as the SSB. Results showed that integrating silica fertilizers and SSB with NPK significantly improved rice productivity and plant vigour. Although plant height was unaffected, tiller number and overall plant health increased. Notably, yields rose from 4.96 to 8.57 tons per hectare. Biotic stress was also reduced, with a 22% decrease in blast disease, a 23% reduction in pest attacks, and 44% fewer empty panicles. These outcomes suggest SSB can reduce pesticide dependency while enhancing plant resilience and nutrient efficiency. The study highlights the potential of combining silica fertilization and microbial biofertilizers to boost rice production sustainably.

Index terms: Environmental stresses; mitigate; silica; biofertilizer, rice yield.

RESUMO

Fertilizantes à base de sílica ainda são pouco utilizados na rizicultura Indonésia, apesar da abundância natural de sílica proveniente das cinzas vulcânicas nos arrozais. Isso ocorre devido à baixa biodisponibilidade da sílica para as plantas de arroz. Bactérias solubilizadoras de silicato (BSS) representam uma solução promissora, aumentando a disponibilidade de sílica e fortalecendo a resiliência das plantas. Este estudo, realizado na Vila Sukaresmi, Distrito de Megamendung, Java Ocidental, avaliou os efeitos combinados de fertilizantes de sílica, NPK e BSS sobre o crescimento, a produtividade e a resistência a estresses bióticos do arroz cultivado em Inceptisols. Utilizou-se um delineamento em blocos ao acaso com 12 tratamentos e três repetições, incluindo diferentes fontes de silicato — como palha de arroz, cachos vazios de dendê, biossílica, RabanaSil e gel de sílica — e a bactéria *Enterobacter cloacae* CmA12 como BSS. A combinação de sílica e BSS com NPK melhorou significativamente o vigor das plantas e a produtividade do arroz. Embora a altura das plantas não tenha mudado, o número de perfilhos e a saúde geral aumentaram. A produção cresceu de 4,96 para 8,57 toneladas por hectare. Também houve redução de estresses bióticos: 22% menos brusone, 23% menos pragas e 44% menos espiguetas vazias. Esses resultados indicam que as BSS podem reduzir a dependência de pesticidas, aumentar a resiliência das plantas e melhorar a eficiência nutricional. O estudo destaca o potencial do uso combinado de fertilizantes silicatados e biofertilizantes microbianos para uma produção de arroz mais sustentável.

Termos para indexação: Estresses ambientais; mitigar; sílica; biofertilizante, rendimento do arroz.

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Introduction

Several initiatives have been implemented in response to the growing demand for rice in Indonesia. These efforts include expanding planting areas by creating new rice fields, increasing the cropping index, improving superior rice varieties, optimizing fertilization practices, and enhancing cultivation techniques. Indonesia has 7,463,952 hectares of paddy fields, with an average rice productivity of 5.1 tons per hectare (t ha^{-1}) (Statistics Indonesia, 2022). Historically, the development of rice farming in Indonesia has relied on intensification and extensification programs (Sutardi et al., 2023). Extensification on newly opened paddy fields can significantly boost rice productivity, increasing yields from 2.0 to 5.7 t ha^{-1}. In addition, balanced fertilization is crucial for maintaining soil quality and ensuring the sustainability of rice farming (Hatta et al., 2023). The decline in soil quality is attributable to an imbalance of nutrients, including micronutrients. Although plants require these nutrients in minimal amounts, an absence of micronutrients can impede plant growth due to their pivotal role in constraining rice production (Ma et al., 2023).

Intensive rice cultivation, if not appropriately managed, can deplete soil nutrients. Rice straw, abundant in paddy fields, can be used as a source of silicate (Si), which plays a vital role in promoting plant health, improving yields, and enhancing resistance to both biotic and abiotic stresses, such as low temperatures, salinity (Waqas et al., 2015; Li et al., 2018), lodging, and nutrient deficiencies (Garg, Dhar, & Jinger, 2020). While Si is not considered an essential macronutrient, rice plants absorb it at an accelerated rate compared to other macronutrients (Han et al., 2018; Mustafa et al., 2024). Rice plants accumulate approximately 108% more Si than nitrogen (N), with 230 to 470 kilograms of Si per hectare being transported through harvest each growing season (Camargo, & Keeping, 2021).

Despite the known benefits of Si, research on its effects on rice growth in Indonesia is limited (Siregar et al., 2016; Anggria et al., 2016; Wenneck et al., 2023). Yield losses due to biotic stresses, such as pest infestations and blast disease, and empty grains may indicate Si deficiency in intensively cultivated paddy fields. Blast disease alone can reduce rice yields by 50 to 90%. Si has been shown to strengthen rice plants by thickening the cuticle layer of the leaf epidermis, which helps prevent fungal invasion responsible for blast disease (Chaiwong et al., 2022).

While paddy soils are often rich in Si, much of it is unavailable to plants. Therefore, silicate-solubilizing bacteria (SSB) is especially important in Si-rich soils like volcanic soils. Studies have shown that Si application can improve rice growth and reduce blast disease incidence in Sukabumi, West Java, and Jakenan, Central Java (Siregar et al., 2016). Si has also been found to enhance rice plant resistance to lodging (Siregar et al., 2021). The application of foliar Si improved the plant's resilience to pathogens (Shivaraj et al., 2022). Using Si to combat blast disease offers an environmentally friendly alternative to fungicides.

Despite these benefits, SSBs are not widely used as biofertilizers in Indonesia. SSBs enhance the effectiveness of inorganic fertilizers by solubilizing soil silicate, making it more accessible to plants. However, their limited use may be due to a lack of awareness or understanding of their benefits (Santi, & Goenadi, 2017). The objective of this study is to evaluate the impact of SSB and its combination with various Si sources on rice yield and resistance to biotic stresses in paddy fields.

Material and Methods

The study was conducted from April to December 2021 on irrigated rice fields in Sukaresmi Village, Megamendung District, Bogor Regency, West Java, Indonesia (6°41'32.8" S 106°54'05.8" E) in Andic Dystrudepts (Figure 1), where water management was maintained throughout.

The determination of total nitrogen (N) utilizes a wet ignition method with H_2SO_4 (Kjeldahl method). In this method, organic nitrogen compounds are oxidized in a concentrated sulfuric acid environment with a selenium mixture catalyst to form $(NH_4)_2SO_4$. The determination of total phosphorus (P), potassium (K), and silicon (Si) utilizes a wet ignition method with HNO_3 and $HClO_4$. The nutrients P, K, and total Si in the plants were extracted using wet ignition with a mixture of concentrated acids, namely hydrofluoric acid (HF) and hydrochloric acid ($HClO_4$). The elemental concentrations in the extracts were subsequently quantified employing an atomic absorption spectrophotometer (AAS) and a visible light spectrophotometer.

The uptake of nutrients (N, P, K, and Si) in rice yield was calculated by multiplying the nutrient analysis results by the dry grain weight using the following formula:

Nutrient uptake (N, P, K, and Si) (kg ha^{-1}) = nutrient content (N, P, K, and Si) (mg kg^{-1}) × dry grain weight (kg ha^{-1}).

The bacteria used in this study, *Enterobacter cloacae* CmA12, were isolated from bamboo roots (*Bambusa* sp.) in Bogor Regency, West Java, Indonesia. The isolation process utilized a modified Bunt and Rovira medium containing 0.25% insoluble magnesium trisilicate and soil extract (Figure 2). The bacteria were cultured in Bunt and Rovira's medium (Chandrakala, 2019), supplemented with 10 g L^{-1} glucose, 1 g L^{-1} ammonium sulfate, 0.2 g L^{-1} potassium chloride, 0.1 g L^{-1} dipotassium hydrogen phosphate, 0.2 g L^{-1} magnesium sulfate, 15 g L^{-1} agar, 2.5 g L^{-1} magnesium trisilicate (as an insoluble Si source), pH 7, for two days. The culture was incubated at room temperature, reaching a population of 10^9 CFU mL^{-1}.

The isolate was screened for biofertilizer traits and assessed for its ability to solubilize silica both qualitatively and quantitatively. *Enterobacter cloacae* CmA12 showed the highest Si solubilization efficiency, nitrogen fixation capability, phosphorus solubilization, and production of IAA and organic acids such as acetic, lactic, and malic acid (Pratiwi et al., 2023).

The study utilized a randomized complete block design with 12 treatments and three replications. Table 1 shows the details of the treatment combinations and fertilizer rates. The silicon (Si) sources used were straw, empty oil palm bunches (EOPB), biosilica, RabanaSil, and silica gel. RabanaSil, a commercial product, contains 30% MgO, 50% SiO_2, and 5% solubilized SiO_2.

Inpari 42, a rice variety susceptible to blast disease, was used Urea was applied 7 days after transplanting (DAT), and KCl was applied in two splits, at 7 and 40 DAT, each at half the recommended rate. SP-36 was applied on day seven by incorporating it into the soil, while silica fertilizer, derived from both organic and inorganic sources, was applied 1 DAT. The silica sources included straw compost, EOPB compost, RabanaSil, biosilica fertilizer, and silica gel.

Figure 1: Location of the study site.
Source: The map was processed, sourced from Rupa Bumi Indonesia (RBI) maps. Badan Informasi Geospasial (2022).

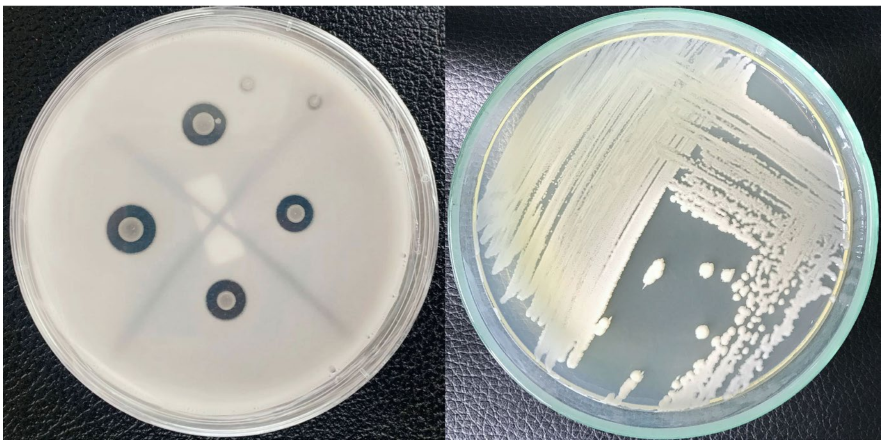

Figure 2: Cultivation of silicate-solubilizing bacteria was performed in Bunt and Rovira medium (left) and Luria Bertani agar (right).

Table 1: The combination of Si source treatments and fertilizer doses rates.

No	Treatments	Fertilizer dose (kg ha^{-1})				SSB inoculant (500 mL ha^{-1}, population 10^6 CFU mL^{-1})
		N	P_2O_5	K_2O	SiO_2*	
1	Control	0	0	0	0	–
2	NPK	90	40	60	0	–
3	NPK + straw	90	40	60	300	–
4	NPK + straw + SSB	90	40	60	300	+
5	NPK + EOPB	90	40	60	300	–
6	NPK + EOPB +SSB	90	40	60	300	+
7	NPK + biosilica	90	40	60	300	–
8	NPK + biosilica + SSB	90	40	60	300	+
9	NPK + RabanaSil	90	40	60	300	–
10	NPK + RabanaSil + SSB	90	40	60	300	+
11	NPK + Silica gel	90	40	60	300	–
12	NPK + Silica gel + SSB	90	40	60	300	+

Notes: SSB = Silicate-Solubilizing Bacteria, EOPB = Empty Oil Palm Bunches, N= Nitrogen, P_2O_5 = Phosphorus pentoxide, K_2O= Potassium Oxide, SiO_2= Silicon dioxide, NPK = (Urea (46% N), SP-36 (36% P_2O_5), KCl (60% K_2O), CFU = Colony Forming Unit (calculate the concentration of bacteria). *The amount of SiO_2 derived directly from the conversion of Si sources, including straw, EOPB, RabanaSil, Silica gel, and biosilica (Table 3), the dosage of which is made the same at 300 kg ha^{-1}.

Rice seeds were treated with a silicate-solubilizing bacterial inoculant before planting. After surface sterilization with 0.5% NaOCl solution and thorough rinsing, the seeds were soaked in the inoculant for 24 hours before being sown in the nursery.

The parameters measured in this study included: (i) silicate content of the silica sources; (ii) analysis of the soil's physical and chemical properties before the experiment and after harvest; (iii) vegetative measurements such as plant height and number of tillers per clump at 30, 45, and 60 DAT; and (iv) stem strength and lodging resistance.

Stem strength was measured by selecting a 15 cm long secondary rice stem, measuring 5 cm from the soil surface towards the panicle. The stem was inserted into the hook of a digital force gauge and slowly pulled until it broke, recording the force in Newtons. Resistance to lodging was assessed using a clamp and a wooden support at a 45° angle. Rice clumps were placed in the gripper, and the tool was slowly pushed until the clump bent to a 45° angle, with the required force recorded.

Observations on pest attacks were also carried out, and the following components of rice production, including dry harvested grain, dry milled grain, the weight of 1,000 grains, and the wet and dry weight of straw, were measured.

The research data were analysed using analysis of variance (ANOVA) with the SPSS version 22 program. In the event that a statistically significant difference between treatments was identified, subsequent analysis was conducted using Duncan's Multiple Range Test at a significance level of 5%.

Results and Discussion

The analysis indicates that the soil in Sukaresmi Village, in the Megamendung District of Bogor in West Java, has a silty clay texture, a slightly acidic pH level, low levels of organic carbon and total nitrogen, and a relatively low C/N ratio. Phosphorus (P) levels is high when extracted with 25% HCl, potassium (K) are moderate, and the Olsen method indicates that available P is also high. The exchangeable calcium (Ca) and magnesium (Mg) levels are moderate, the potassium level is low, and sodium level is moderate. The soil has a moderate cation exchange capacity (CEC), relatively high base saturation, and low silicon (Si) content (Table 2). These soil characteristics indicate that the soil at this site is classified as moderately fertile soil. As a result, the rice plants showed sufficient response to the NPK fertilizer treatments.

Analysis of Si sources shows that EOPB and biosilica have low available Si (40 and 122.5 mg kg^{-1}). In contrast, silica gel, RabanaSil, and straw compost has a high Si content (835, 809, and 237 mg kg^{-1}, respectively) (Table 3).

Various Si fertilizers and sources, including silica gel, biosilica, and RabanaSil, were tested and found to have higher solubility and Si availability than organic sources such as straw and EOPB, which have lower Si content. Inorganic Si fertilizers, such as silica gel and RabanaSil, were more soluble, allowing for faster plant uptake than organic materials like straw and EOPB, which take longer to decompose and release Si.

Table 2: Soil analysis results.

Type of analysis	Value	Level*
Texture:		
Clay (%)	42	
Silt (%)	49	Silty clay
Sand (%)	9	
pH : H_2O (1:5)	5.7	Slightly acidic
Organic matter:		
C organic (%)	2.18	Moderate
N total (%)	0.26	Moderate
C/N	8.38	Low
P_2O_5 (HCl 25%) mg 100 g^{-1}	142	Very high
K_2O (HCl 25%) mg 100 g^{-1}	14	Low
P-Bray 1 (mg kg^{-1})	34	Very high
Exchangeable cation:		
Ca ($cmol_{(+)}$ kg^{-1})	7.40	Moderate
Mg ($cmol_{(+)}$ kg^{-1})	2.36	Hight
K ($cmol_{(+)}kg^{-1}$)	0.77	Hight
Na ($cmol_{(+)}$ kg^{-1})	0.63	Moderate
Cation Exchange Capacity ($cmol_{(+)}$ kg^{-1})	17.14	Moderate
Base saturation (%)	65	Hight
Total silicon (%)	26.34	Moderate
Available silicon SiO_2 (mg kg^{-1})	120	Low

Notes: * Balai Pengujian Standar Instrumen Tanah dan Pupuk. (2023).

Table 3: Silicate content analysis of tested fertilizer sources.

Silicate source	Silicate total (%)	Silicate content available (mg kg^{-1})
Straw compost	4.5	237.0
EOPB	9.7	40.0
RabanaSil	50.0	808.6
Silica gel	90.0	835.0
Biosilica	90.0	122.5

The application of NPK fertilizer, silica from various sources, and SSB did not significantly affect the height of Inpari 42 rice plants during the vegetative growth phases at 30 and 60 DAT (Table 4). Research by Song et al. (2017); Pan, Chen and Chai (2021); Chen et al. (2024); Ebeed et al. (2024) found no direct relationship between Si and plant height, which supports the observation that silica fertilizers did not increase rice plant height. However, in this study at 45 DAT, adding SSB to the silica gel treatment significantly increased plant height compared to the control (Figure 3). The silica gel, RabanaSil, and EOPB treatments showed a notable increase in height compared to the control at harvest.

This indicates that inorganic Si fertilizers, such as silica gel and RabanaSil, have more excellent solubility and faster availability to plants than organic materials like straw and EOPB, which take longer to decompose and release Si. The lack of response in plant height could be attributed to the high fertility of the soil used, particularly its elevated P and K levels. Silica is not believed to significantly influence rice plant height since it is not directly involved in the metabolic processes that regulate plant growth.

NPK, silica, and SSB treatments significantly increased the number of tillers at all observation phases (30, 45, 60 DAT, and harvest) compared to the control. However, NPK fertilization with silica and SSB did not result in a substantial increase in tillers. The highest tiller count at harvest was observed in the RabanaSil treatment combined with NPK, averaging 18 tillers per clump, while the control had the lowest, averaging 11 tillers per clump (Figure 3).

Despite this, NPK, silica, and SSB treatments significantly increased the number of tillers across all observation phases. The treatment with RabanaSil, combined with urea, SP-36, and KCl fertilization, resulted in the highest number of tillers per hill, with an average of 18. At the same time, the control group had only 11 tillers per hill. The fulfilment of essential macronutrients N, P, and K during the growth period is crucial for the number of tillers, and the application of silica fertilizer contributes to more vigorous, more upright plants, optimizing photosynthesis and starch production for panicle formation. The tiller increase was consistent across treatments with inorganic and organic silica sources, although no significant ($P > 0.05$) differences were observed in plant height between these sources.

Table 4: Effect of Si fertilizer from various sources and silicate-solubilizing bacteria on plant height and number of tillers of Inpari 42 rice plants in intensive paddy fields.

Number	Treatments	Plant height (cm) DAT				Number of tillers per Clump DAT			
		30	45	60	Harvest	30	45	60	Harvest
1	Control	38.4 a	56.5 b	76.9 a	85.9 c	7.7 b	9.7 b	10.7 b	8.3 c
2	NPK	41.8 a	60.8 ab	70.8 a	91.2 ab	10.3 a	14.0 a	15.7 a	15.7 ab
3	NPK + straw	47.0 a	63.7 ab	84.9 a	92.9 ab	12.0 a	15.0 a	16.7 a	15.3 b
4	NPK + straw + SSB	44.4 a	63.6 ab	84.1 a	93.1 ab	11.0 a	14.3 a	16.7 a	16.7 ab
5	NPK + EOPB	45.0 a	65.2 ab	82.8 a	93.9 a	11.7 a	15.3 a	16.7 a	16.3 ab
6	NPK + EOPB + SSB	44.5 a	62.1 ab	83.7 a	92.3 ab	11.3 a	14.7 a	16.3 a	15.3 b
7	NPK + biosilica	42.8 a	60.8 ab	78.4 a	91.5 ab	10.3 a	14.0 a	16.7 a	16.3 ab
8	NPK + biosilica + SSB	44.8 a	62.9 ab	81.3 a	91.9 ab	11.7 a	15.7 a	17.3 a	17.3 ab
9	NPK + RabanaSil	47.2 a	64.4 ab	84.4 a	93.7 a	12.0 a	15.0 a	17.7 a	18.3 a
10	NPK + RabanaSil + SSB	44.6 a	65.6 ab	87.4 a	93.7 a	11.3 a	15.3 a	16.7 a	17.3 ab
11	NPK + silica gel	46.4 a	65.8 ab	83.6 a	94.0 a	12.3 a	16.0 a	17.3 a	17.0 ab
12	NPK + silica gel + SSB	44.0 a	67.6 a	84.4 a	90.4 ab	11.0 a	15.0 a	16.3 a	17.7 a
	CV (%)	11.9	18.4	17.9	14.1	15.2	12.4	12.9	18.1

Notes: Numbers with identical letters within the same column are not different according to the DMRT at $P < 0.05$. DAT= days after transplanting.

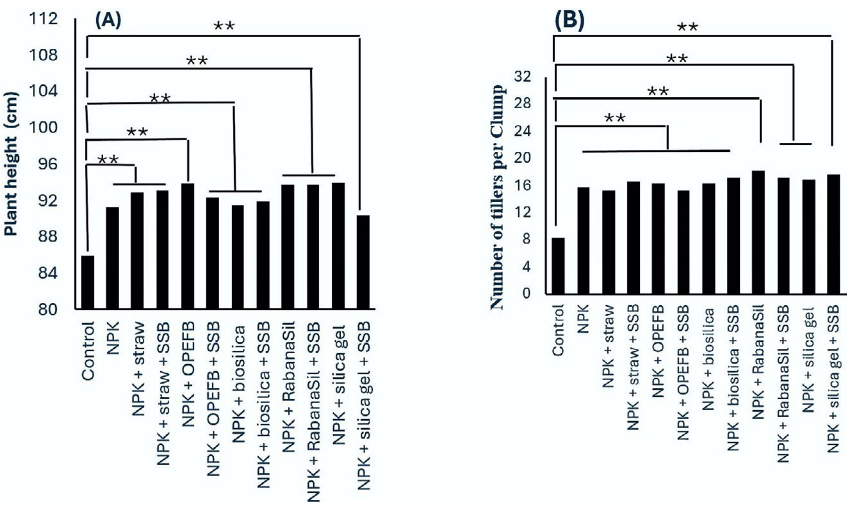

Figure 3: The effect of Si treatment from various sources and NPK fertilizer doses on rice plant height (A) and number of tillers per clump (B).

The application of SSB, along with NPK, RabanaSil, and silica gel, improved the stem strength of Inpari 42 rice plants at 75 DAT. The highest stem strength, 19.10 N, was recorded in the NPK + silica gel + SSB treatment, while the lowest, 12.30 N, was found in the control treatment (Figure 4). Meanwhile, at 105 DAT, rice plant stem strength and resistance to lodging decreased, and each treatment was not significant (P > 0.05) different (Table 5).

A similar trend was observed for lodging resistance. The most vigorous resistance, 17.56 N, was in rice plants treated with silica gel, NPK fertilizers, and SSB, while the weakest, 10.74 N, occurred in plants from the unfertilized control group. These results suggest that combining NPK, silica, and SSB inoculation strengthens rice plants and potentially boosts yield.

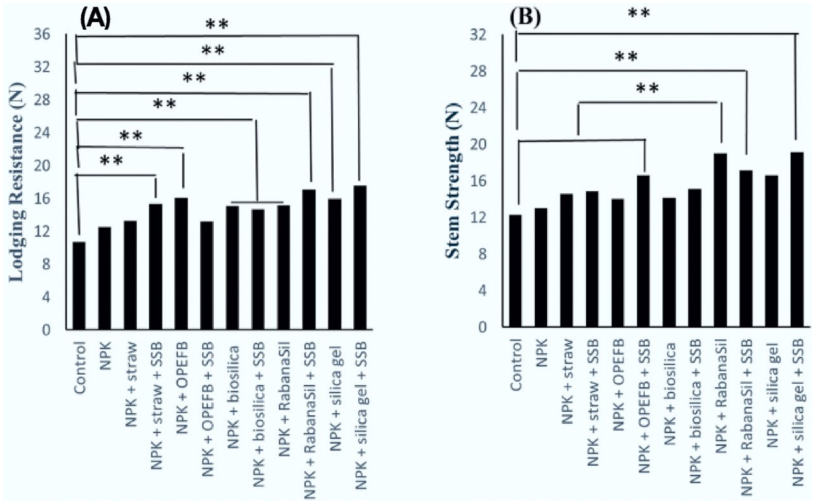

Figure 4: The effect of Si treatment from various sources and NPK fertilizer doses on lodging resistance (A) and stem strength of rice plant (B).

Table 5: Effect of Si fertilizer from various sources and silicate-solubilizing bacteria silica on stem strength and lodging resistance of rice plants Inpari 42.

Number	Treatments	Stem Strength (N) DAT		Lodging Resistance (N) DAT	
		75	105	75	105
1	Control	12.30 c	9.70 c	10.74 d	5.71 a
2	NPK	12.99 bc	13.49 ab	12.54 cd	7.03 a
3	NPK + straw	14.58 abc	12.60 ab	13.27 bcd	7.01 a
4	NPK + straw + SSB	14.86 abc	13.68 ab	15.36 abc	7.19 a
5	NPK + EOPB	14.02 bc	13.50 ab	16.05 ab	6.57 a
6	NPK + EOPB + SSB	16.58 abc	12.89 ab	13.21 cd	6.79 a
7	NPK + biosilica	14.13 bc	13.05 ab	15.06 abc	5.76 a
8	NPK + biosilica + SSB	15.08 abc	13.65 ab	14.68 abc	6.24 a
9	NPK + RabanaSil	19.03 a	15.94 a	15.12 abc	6.85 a
10	NPK + RabanaSil + SSB	17.17 ab	15.53 a	17.12 a	7.21 a
11	NPK + silica gel	16.58 abc	13.68 ab	15.97 ab	7.15 a
12	NPK + silica gel + SSB	19.10 a	15.61 a	17.56 a	7.42 a
	CV (%)	18.3	20.5	14.1	ns

Notes: Numbers with identical letters within the same column are not different according to the DMRT at P < 0.05. DAT = days after transplanting. ns = not significant.

Besides promoting more vigorous plants with upright leaves, silica is vital in increasing lodging resistance and stem strength. Excess nitrogen without a balance of potassium and silica can lead to softer stems, making plants more susceptible to lodging and pest attacks. Silica fertilizer helped enhance rice plants' resilience against lodging. Although SSB treatments did not significantly affect stem strength, rice plants inoculated with SSB showed higher lodging resistance and stem strength than non inoculated plants. Like those studied by (Raturi et al., 2021), silicon —a quasi-essential element for plants — is abundant in the soil typically as insoluble silicate forms. However, plants can uptake Si only in the soluble form of monosilicic acid. Production of monosilicic acid by rock-weathering mostly depends on temperature, pH, redox-potential, water-content, and microbial activities. In the present review, approaches involved in the efficient exploration of silicate-solubilizing bacteria (SSB) release organic acids and exopolysaccharides that increase Si availability in the soil, reducing susceptibility to abiotic stresses like drought, extreme temperatures, and lodging.

The highest incidence of blast disease was observed in the control treatment at 8.10%, while the lowest was in rice plants fertilized with silica gel at 0.5% (Figure 5). Silica fertilizers from various sources effectively reduced blast disease incidence in Inpari 42 rice plants in intensive cultivation systems. During the generative phase, the main pests were stink bugs, ladybugs, and grasshoppers, while spiders were the dominant natural enemies. Silica fertilizer reduced pest attacks by 7-48% compared to standard NPK fertilizer and up to 55% compared to untreated plants. However, statistical analysis showed no significant (P>0.05) difference in pest reduction across silica sources. Field observations revealed the highest percentage of empty panicles (15.79%) in the unfertilized control group. While the lowest (2.79%) was found in rice plants treated with silica gel and SSB.

Research by Mitani and Ma (2005) shows that increased silica intake enhances wall thickening and vascular tissue in rice stems, improving stem strength. Silica has also been shown to protect against various stresses, including drought, radiation, and metal toxicity. Kang et al. (2017) produce indole acetic acid (IAA) found that *Burkholderia eburnea* CS4-2 combined with insoluble silica increased Si accumulation and improved growth in rice plants. Blast disease, caused by the fungus *Pyricularia grisea*, can drastically reduce rice yields, with infections causing up to 100% yield loss. The accumulation of silica in plant tissues enhances pest and disease resistance by strengthening the epidermis, making it less appealing to pests. Rice plants fertilized with silica gel had the lowest percentage of empty panicles (2.78%) compared to the control group, which had the highest (15.79%). Inoculation with SSB helped reduce the intensity of blast disease by 22% and pest attacks by 23% while also reducing the percentage of empty panicles by 44%. The introduction of SSB promotes nutrient absorption by enhancing silica solubility in the soil, as demonstrated by (Shabbir et al., 2021), who found that *Enterobacter sp*. UPMSSB7 can solubilize P and K in addition to silicates. The bacterium also produces indole-3-acetic acid (IAA), a plant growth hormone, and inhibits the growth of rice pathogens like *Rhizopus microporus*.

The yields of Inpari 42 rice ranged from 4.96 to 8.57 t ha^{-1} of dry grain weight (Figure 6). The highest yield was achieved from plots treated with a combination of straw, NPK fertilizers, and SSB (8.27 t ha^{-1}), as well as silica gel, NPK, and SSB (8.57 t ha^{-1}).

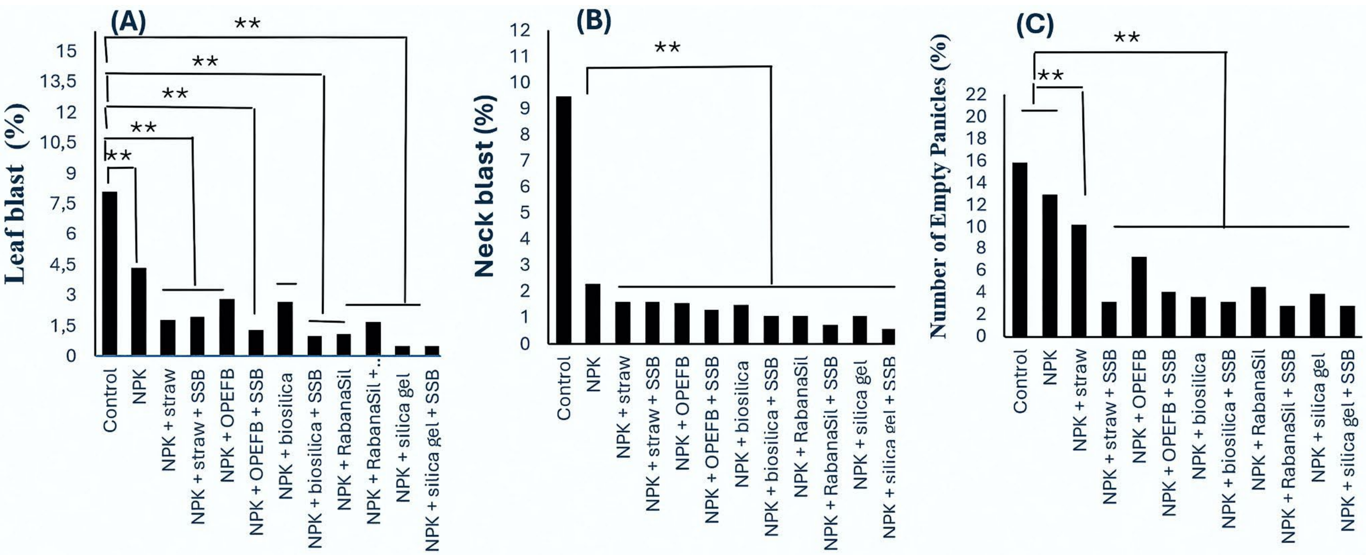

Figure 5: The effect of Si treatment from various sources and NPK fertilizer doses on leaf blast (A), neck blast (B), and number of empty panicles (C).

Combining silica and NPK fertilizers with SSB significantly increased dry straw biomass, reaching 16.40 t ha^{-1}. The treatment also had a notable impact on the dry weight of the straw. Additionally, the 1,000 grain weight was highest (28.2 g) in plots treated with silica fertilizer, NPK, and SSB. SSB has also been shown to enhance the solubility of soil silica, making it more available for plant uptake. *Enterobacter* sp. UPMSSB7, in particular, can solubilize silica, phosphorus, and potassium, thereby enhancing overall plant nutrition and productivity. The bacterium's ability to produce organic acids, siderophores, and exopolysaccharides further contributes to the dissolution of silicates and other nutrients in the soil, promoting plant growth and yield.

As rice plants grow, they absorb macronutrients and micronutrients, with nutrient uptake depending on their availability and balance in the soil. Nutrients such as N, P, K, and Si from inorganic fertilizers are immediately available, while organic nutrients require time to decompose with the help of soil microorganisms. The impact of silica fertilizers from various sources and SSB on nutrient absorption is shown in Table 6.

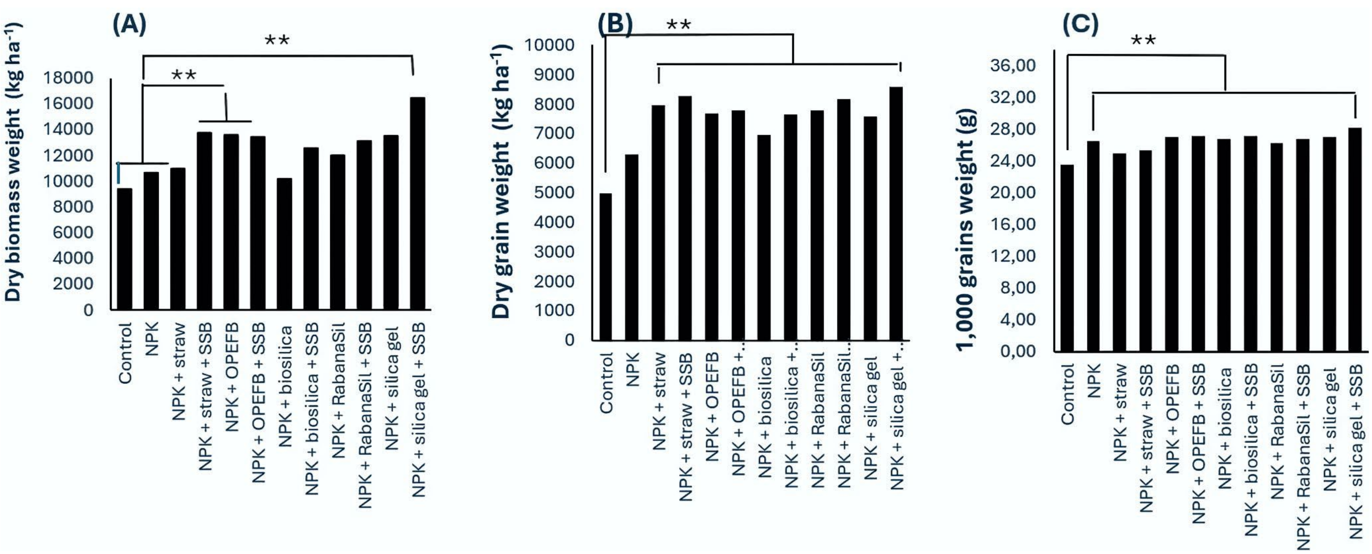

Figure 6: The effect of Si treatment from various sources and NPK fertilizer doses on dry biomass weight (A), dry grain weight (B), and 1,000 grains weight (C).

Table 6: N, P, K and Si nutrients uptake at several fertilizer doses and Si sources in rice plants.

Number	Treatments	Nutrients uptake (kg ha^{-1})			
		N	P_2O_5	K_2O	SiO_2
1	Control	93.1 f	18.6 b	75.4 c	736.3 c
2	NPK	131.7 de	25.5 ab	87.6 bc	1020.0 bc
3	NPK + straw	120.4 ef	28.1 a	109.7 ab	1021.3 bc
4	NPK + straw + SSB	173.1 abc	30.7 a	109.1 ab	1230.3 b
5	NPK + EOPB	120.9 ef	32.6 a	119.3 ab	1198.1 b
6	NPK + EOPB + SSB	179.7 ab	30.2 a	115.6 ab	1294.3 b
7	NPK + biosilica	141.6 cde	26.7 a	116.1 ab	998.6 bc
8	NPK + biosilica + SSB	139.7 cde	30.4 a	128.4 a	1278.9 b
9	NPK + RabanaSil	159.7 abcd	31.4 a	124.8 a	1080.0 b
10	NPK + RabanaSil + SSB	151.0 bcde	27.3 a	101.2 abc	1232.2 b
11	NPK + silica gel	144.5 cde	31.9 a	124.0 a	1262.8 b
12	NPK + silica gel + SSB	185.6 a	32.4 a	121.7 a	1645.7 a

Notes: Numbers with identical letters within the same column are not different according to the DMRT at P < 0.05.

Silica application enhances the absorption of N, K, and Si. However, no significant effect is seen on P absorption, likely due to the soil's high initial phosphorus content. The addition of SSB significantly boosts the absorption of N and Si (Figure 7), which also increases straw dry weight, the N and K content in straw, and the Si content in grains.

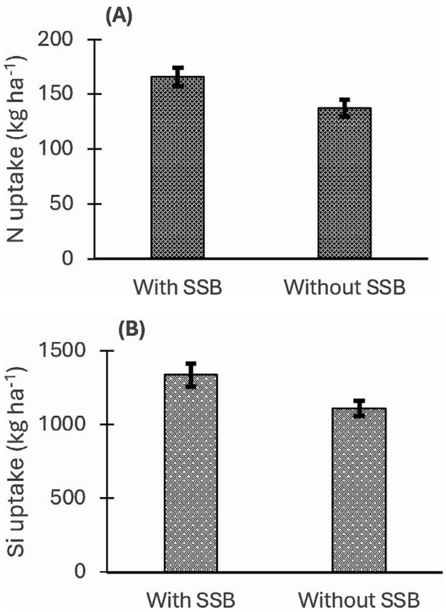

Figure 7: Effect of Si-solubilizing bacteria on N nutrient uptake (A) and Si nutrient uptake (B).

Conclusions

The combination of silica fertilization with NPK fertilizer and silicate-solubilizing bacteria significantly improved rice growth and yield and reduced biotic stress, resulting in a 22% reduction in blast disease intensity, a 23% reduction in pest infestation, a 44% reduction in empty panicles, and an increase in tillers and plant vigor, increasing yields from 4.96 to 8.57 tons per hectare (72.78%). Silicate-solubilizing bacteria increased tiller number, lodging resistance, and nutrient uptake, improved soil silica availability, and reduced disease and pest pressure.

Author contribution

Conceptual idea: Sipahutar, I.A.; Pratiwi, E.; Widowati, L.R.; Husnain; Methodology design: Sipahutar, I.A.; Pratiwi, E.; Siregar, A.F.; Data collection: Sipahutar, I.A.; Pratiwi, E.; Siregar, A.F.; Anggria, L; Data analysis and interpretation: Sipahutar, I.A.; Pratiwi, E.; Kasno, A; Hatta, M.; and Writing and editing: Sipahutar, I.A.; Pratiwi, E.; Siregar, A.F.; Anggria, L; Widowati, L.R.; Husnain; Kasno, A; Hatta, M.

References

Anggria, L. et al. (2016). Relationships between soil properties and rice growth with steel slug application in Indonesia. *Journal of Agricultural Science*, *8*(5):1-14.

Badan Informasi Geospasial. (2022). *Peta Rupa Bumi Indonesia (RBI)*. Badan Informasi Geospasial (BIG). Available in:https://tanahair.indonesia.go.id/portal-web/.

Balai Pengujian Standar Instrumen Tanah dan Pupuk. (2023). *Petunjuk teknis analisis kimia tanah, tanaman, air, dan pupuk.* (3rd ed.). Kementerian Pertanian Republik Indonesia. Available in: https://tanahpupuk.bsip.pertanian.go.id/storage/assets/uploads/publikasi/Ho07w2htwf9OzGNVgMnfb1rsJrfxzYAjN687bbNC.pdf.

Camargo, M. S., & Keeping, M. G. (2021). Silicon in sugarcane: Availability in soil, fertilization, and uptake. *Silicon*, *13*(10):3691-3701.

Chaiwong, N. et al. (2022). Silicon application promotes productivity, silicon accumulation and upregulates silicon transporter gene expression in rice. *Plants*, *11*(7):989.

Chandrakala, C. et al. (2019). Silicate solubilization and plant growth promoting potential of *Rhizobium* sp. isolated from rice rhizosphere. *Silicon*, *11*:2895-2906.

Chen, Y. et al. (2024). Regulation of 2-acetyl-1-pyrroline and grain quality in early-season indica fragrant rice by nitrogen and silicon fertilization under different plantation methods. *Journal of Integrative Agriculture*, *23*(2):511-535.

Ebeed, H. T., Ahmed, H. S., & Hassan, N. M. (2024). Silicon transporters in plants: Unravelling the molecular nexus with sodium and potassium transporters under salinity stress. *Plant Gene*, *38*:100453.

Garg, K., Dhar, S., & Jinger, D. (2020). Silicon nutrition in rice (*Oryza sativa* L.): A review. *Annals of Agricultural Research*, *41*(3):221-229.

Han, Y. Q. et al. (2018). Effects of silicon amendment on the occurrence of rice insect pests and diseases in a field test. *Journal of Integrative Agriculture*, *17*(10):2172-2181.

Hatta, M. et al. (2023). Food self-sufficiency: Managing the newly-opened tidal paddy fields for rice farming in Indonesia (A case study in West Kalimantan, Indonesia). *Heliyon*, *9*(3):e13839.

Kang, S. M. et al. (2017). Isolation and characterization of a novel silicate-solubilizing bacterial strain *Burkholderia eburnea* CS4-2 that promotes growth of japonica rice (*Oryza sativa* L. cv. Dongjin). *Soil Science and Plant Nutrition*, *63*(3):233-241.

Li, Z. et al. (2018). Silicon enhancement of estimated plant biomass carbon accumulation under abiotic and biotic stresses. A meta-analysis. *Agronomy for Sustainable Development*, *38*:26.

Ma, G. et al. (2023). Effects of organic and inorganic fertilizers on soil nutrient conditions in rice fields with varying soil fertility. *Land*, *12*(5):1026.

Mitani, N., & Ma, J. F. (2005). Uptake system of silicon in different plant species. *Journal of Experimental Botany*, *56*(414):1255-1261.

Mustafa, S. et al. (2024). Optimizing nutrient strategies for rice blast disease control and paddy yield enhancement. *International Journal of Phytopathology*, *13*(2):139-148.

Pan, T. W., Chen, Y., & Chai, K. Z. (2021). Effect of nitrogen and silicon fertilizer on plant nutrient content yield and quality rice. *Journal of Ecology and Rural Environment*, *37*(1):120-126.

Pratiwi, E. et al. (2023). Enhancing zinc uptake and grain yield of ciherang and inpari IR Nutri Zinc rice varieties using Zn-solubilizing bacteria. *E3S Web of Conferences*, *467*(01025):8.

Raturi, G. et al. (2021). Exploration of silicate solubilizing bacteria for sustainable agriculture and silicon biogeochemical cycle. *Plant Physiology and Biochemistry*, *166*:827-838.

Santi, L. P., & Goenadi, D. H. (2017). Solubilization of silicate from quartz mineral by potential silicate solubilizing bacteria (*Pelarutan silika asal mineral kuarsa oleh bakteri pelarut silika potensial*). *E-Journal Menara Perkebunan*, *85*(2):95-104.

Shabbir, I. et al. (2021). Evaluation of bioformulation of *Enterobacter* sp. UPMSSB7 and mycorrhizae with silicon for white root rot disease suppression and growth promotion of rubber seedlings inoculated with *Rigidoporus microporus*. *Biological Control*, *152*:104467.

Shivaraj, S. M. et al. (2022). Outstanding questions on the beneficial role of silicon in crop plants. Plant and Cell Physiology, *63*(1):4-18.

Siregar, A. F. et al. (2021). Improving rice growth and yield with silicon addition in oxisols. *IOP Conference Series: Earth and Environmental Science*, *648*:012202.

Siregar, A. F. et al. (2016). Empirical study on effect of silicon application on rice blast disease and plant morphology in Indonesia. *Journal of Agricultural Science*, *8*(6):137-148.

Song, A. et al. (2017). The effects of silicon fertilizer on denitrification potential and associated genes abundance in paddy soil. *Biology and Fertility of Soils*, *53*(6):627-638.

Statistics Indonesia (BPS). (2022). *Paddy harvested area, production and productivity by province, 2020–2022*. Available in: https://www.bps.go.id/indicator/53/1498/1/luas-panen-produksi-dan-produktivitas-padi-menurut-provinsi.html

Sutardi. et al. (2023). The transformation of rice crop technology in Indonesia: Innovation and sustainable food security. *Agronomy*, *13*(1):1.

Waqas, M. et al. (2015). Endophytic fungi promote plant growth and mitigate the adverse effects of stem rot: An example of *Penicillium citrinum* and *Aspergillus terreus*. *Journal of Plant Interactions*, *10*(1):280-287.

Wenneck, G. S. et al. (2023). Extraction and accumulation of silicon in tomato grown under different water regimes and application forms. Ciência e Agrotecnologia, *47*:005323.