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Inorganic and Natural Silicon Sources as Soil Amendment on Growth of Local Aromatic Rice Variety

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ABSTRACT

Lodging causes a yield loss of approximately 1 ton per hectare as 20% of the total rice production. Silicon (Si) fertilisers significantly improve paddy grain yield, and lodging resistance by improving leaf firmness besides promoting better plant canopy and boosting photosynthesis. The objective of this study was to determine the effects of Si derived from calcium silicate ($CaSiO_3$), rice husk ash, and rice straw on paddy plant growth. A pot study was conducted at MARDI Seberang Perai during the main season (2019/2020) and the off-season (2020) using the MRQ 76 rice variety to evaluate 10 Si carriers. The growth parameters of the paddy plants such as number of tillers, plant height, and chlorophyll content at different growth stages were evaluated. During season 1, treatment with 100% $CaSiO_3$ (T4) significantly improved the plant height. Nevertheless, the organic Si (T1, T2, and T3) and combination between organic Si with $CaSiO_3$ (T5, T6, T7, and T8) resulted in the tallest plants during season 2. Treatment T7 increased the tillering number per meter square during season 1 whereas in season 2 treatment T8 performed better compared to the standard fertiliser (T9) and control (T10). However, the treatments evaluated in this study did not significantly affect the chlorophyll content of the paddy plants. Applying a combination of rice straw (50%) and rice husk ash (50%) a day before transplanting, followed by $CaSiO_3$ (100%) as a silicate material during panicle initiation, along with additional NPK fertiliser (17:3:25:2MgO) during heading stage (T7), and without additional NPK fertiliser (17:3:25:2MgO) at the heading stage (T8) were most effective in enhancing crop growth and maintaining the paddy cultivation. Therefore, the findings in this study suggested the potential of using inorganic and organic Si to improve the growth and development of aromatic rice variety.

Keywords: Aromatic rice, lodging, silicon fertiliser, soil amendment.

INTRODUCTION

Rice (*Oryza sativa* L.) is the staple food of Malaysia and an essential source of income for small-scale agricultural Malaysian farmers. In the coming years, rice production is projected to continue increasing due to ongoing urbanisation and global population growth. Nonetheless, lodging, which is the bending or breaking of rice plants, significantly contributes to rice yield losses.

In the Philippines, lodging led to a one-ton per-hectare yield loss, accounting for approximately 20% of the total rice production, while Southern India recorded a 26 kg/ha (Duwayri et al., 2000). The impact of lodging is also evident in the Muda granary region in Malaysia. The area, which covers 98,860 hectares and represents 25% of the total rice production in the country, documented a substantial loss of 41% in rice yield (MOA, 2008).

Typically, lodging occurs just before the harvest, when the lower portion of the rice plant stems becomes incapable of supporting the weight of their panicles. According to Gowariker et al. (2009), lodging could occur in three forms which are stem bending at the base or breakage along its length or root lodging. Consequently, maintaining an appropriate paddy plant height with shorter basal stems is crucial to prevent lodging (Zhang et al., 2014).

The application of silicon (Si) is an effective approach in enhancing lodging resistance. This fertiliser improves leaf firmness, promotes better canopy development, and indirectly increases the overall photosynthesis rate of paddy, thus improving rice grain production (Tamai and Ma, 2008). Dorairaj et al. (2017) also found that carbon and Si fertilisers enhanced crop lodging resistance. Furthermore, organic carbon and Si fertilisers boost lignin biosynthesis enzyme activities and upregulate gene expression associated with the enzymes. The improvements would lead to increased lignin accumulation in the culm, ultimately enhancing the ability of the paddy plants to withstand lodging (Hu et al., 2022). Moreover, Gong et al. (2021) discovered that applying Si fertiliser improved the flexural strength of individual stems and increased Si, lignin, and cellulose levels in rice stalks. The accumulation of Si in plant cell walls translates into enhanced resilience to diseases, pests, and lodging.

Nitrogen (N) fertilisers often lead to droopy rice leaves, whereas Si aid in keeping them upright. Moreover, Yoshida (1981) reported that appropriate Si management in maintaining erect leaves resulted in a 10% increment in crop photosynthesis. The findings also highlight the significance of employing adequate Si fertilisation primarily in lowland rice cultivations with highly weathered tropical soils and generous N fertiliser employment.

Rice grain yield response to Si fertiliser considerably depends on available Si, Si sources, soil pH, and environmental factors, including climate (Wang et al., 2014). Although calcium silicate ($CaSiO_3$) is widely recognised as the ideal source of inorganic Si, its high cost renders it unaffordable for most Malaysian paddy farmers. Therefore, exploring alternatives and more affordable and abundant sources in Malaysia is essential.

Rice straw is a significant Si reservoir, storing approximately 86% of the total Si content in rice plants (Klotzbücher et al., 2015). Furthermore, rice straw contains essential nutrients, such as N, phosphorus (P), and a substantial quantity of potassium (K) (Ismail et al., 2013). Rice plants absorb silicic acid from soils and transport it through their xylems, which are deposited as phytoliths. Phytolith deposition varies among different plant parts and cultivars. Commonly, rice straws contain approximately 10% phytoliths, while rice husks could store up to 20% (Sun et al., 2019). Phytoliths are crucial in providing structural support to paddy plants, enhancing rice yields and resistance to pests and diseases, and preventing lodging (Patil et al., 2017).

Exploring cost-effective recycling alternatives is imperative as paddy plants, a C3 crop, are rich in Si, and rice cultivation generates abundant biomass residues. Utilising rice straw and rice husk ash as supplementary inorganic Si fertilisers are promising. Therefore, the objective of this study was to determine the effects of Si derived from $CaSiO_3$, rice husk ash, and rice straw on the growth of paddy plants.

MATERIALS AND METHODS

Experimental Sites and Plant Materials

The pot study was conducted at the Malaysian Agricultural Research and Development Institute (MARDI) in Seberang Perai, Pulau Pinang, during season 1 (main season 2019/2020) and season 2 (off-season 2020). The MRQ 76 variety of aromatic rice was selected as the test crop. The MRQ 76 seeds were soaked in water for 24 h and kept in a moist and shaded environment for 36 h to ensure good establishment (Othman et al., 2008). Subsequently, the rice seedlings were nursed for 18 days before being transplanted. Five seedlings were planted in each planting point at a 20 cm × 20 cm distance.

Experimental Design and Treatments

Table 1 summarises the physical and chemical properties of the soil (Paramanathan, 2000) and the amendments used in this study. The present study utilised three soil amendments. Rice straw and rice husk ash were incorporated as the basal application (a day before planting), which represented organic Si. During panicle initiations, $CaSiO_3$ was applied as inorganic Si.

Table 1. The physical and chemical properties of the soil and the amendments used

Properties	Soil	Rice straw	Rice husk ash	$CaSiO_3$
pH	5.54	5.83	8.23	-
EC (mS/cm)	63.93	8.42	0.23	-
Bulk density (g/cm^3)	1.31	-	-	-
Total N (%)	0.22	0.73	0.50	-
Total Si (%)	15.73	43.49	62.41	70.00
Total calcium (Ca) (mg/100 g)	6.07	0.36	0.10	17.00

This study used a completely randomised design (CRD), and a 1.2 m × 1.2 m trough was set with 10 treatments and four replications (Figure 1). The treatments evaluated were as follows:

i. T1: 100% rice straw,
ii. T2: 100% rice husk ash,
iii. T3: 50% rice straw + 50% rice husk ash,
iv. T4: 100% $CaSiO_3$,
v. T5: 100% rice straw + 100% $CaSiO_3$,
vi. T6: 100% rice husk ash + 100% $CaSiO_3$,
vii. T7: 50% rice straw + 50% rice husk ash + 100% $CaSiO_3$ with additional NPK fertiliser (17:3:25:2MgO) at 50 kg/ha during the heading stage,
viii. T8: 50% rice straw + 50% rice husk ash + 100% $CaSiO_3$ without additional NPK fertiliser (17:3:25:2MgO) at 50 kg/ha at the heading stage,
ix. T9: Lestari Fertiliser (LF), a standard fertiliser package containing a total NPK of 120:70:80 kg N, P_2O_5, and K_2O per ha, and
x. T10: No fertiliser (control plot)

Treatment plots T1 to T9 were applied with standard fertilisers at four different stages which were the three-leaf [7 days after transplanting (DAT)], active tillering (25 DAT), panicle initiation (45 DAT), and heading (65 DAT) stages. The standard fertiliser (T9) was applied at the recommended fertiliser application rate based on Lestary Fertilizer (LF) Package (Othman et al., 2008) with the details listed in Table 2.

Figure 1. The cultivation plots and treatment arrangements based on the CRD experimental design with four replications in a plant house at MARDI Seberang Perai Station, Pulau Pinang, Malaysia

Table 2. The standard LF fertiliser application rates

DAT	Padi 1 (kg/ha)	Triple super phosphate (TSP) (kg/ha)	Muriate of potash (MOP) (kg/ha)	Urea (kg/ha)	Additional NPK fertilizer (kg/ha)
7	140	57	42		
25				80	
45	107			12	100
65				20	50
Total	247	57	42	112	150

[Note: Total NPK = 120:70:80 kg N, P_2O_5, and K_2O/ha, Padi 1 = NPK 17.5:15.5:10, and additional NPK fertiliser = NPKMg 17:3:25:2MgO]

Plant Height

Using a measuring tape, the plant height was recorded from the soil surface until the tip of the highest leaf (or panicle, whichever is longer) at 35, 60, and 90 (DAT) (Figure 2(a)).

Number of Tillers

The number of productive tillers was obtained by manually counting the number of tillers that grew from the main stem of the paddy plants at 35, 60, and 90 (DAT) (Figure 2(b)). The recorded data were then converted to per square metre.

Relative Chlorophyll Content

The chlorophyll measurements were conducted using a chlorophyll meter (SPAD-502, Minolta Camera Co., Osaka, Japan) (Figure 2(c)). Four fully expanded uppermost leaves (Y leaf or flag leaf) were selected at four different growth stages (35, 60, and 90 DAT, and at maturation days). The chlorophyll readings obtained from the SPAD meter were averaged to represent the mean SPAD readings for each plot (IRRI, 2002).

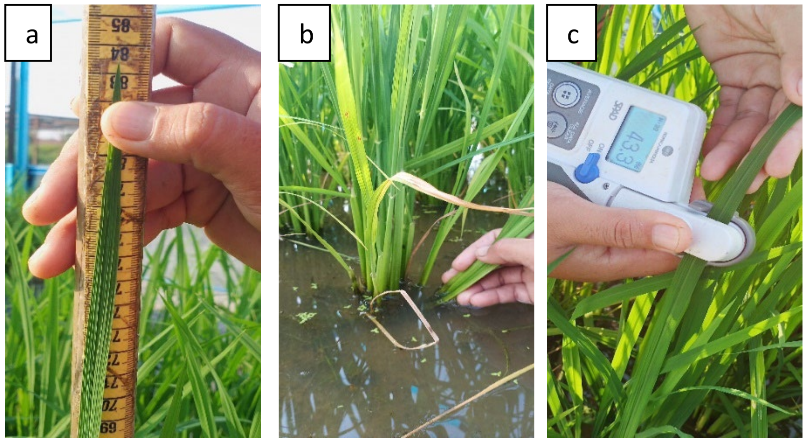

Figure 2. Measuring the (a) height, (b) number of tillers, and (c) relative chlorophyll content of the paddy plants with a SPAD meter

Statistical Analysis

The treatment effects were analysed using analysis of variance (ANOVA), and the means of the treatment were compared using Duncan's New Multiple Range Test (DNMRT) at a significant level of $p \leq 0.05$. The statistical analysis was performed with Statistical Analysis System (SAS) version 9.4 (SAS Institute 2011, Gary, NC).

RESULTS AND DISCUSSION

The Effects of $CaSiO_3$, Rice Straw, and Rice Husk Ash on Paddy Plant Height

The height of a plant is directly linked to the centre of gravity of the culm on the plant (Okuno et al., 2014). Shorter plants possess lower centres of gravity, therefore improved resistance against shoot self-weight movements, an advantage against lodging (Okuno et al., 2014). Consequently, achieving the appropriate paddy plant height is crucial in rice cultivation as it directly affects the overall yield.

Although taller paddy plant varieties often possess higher yield potential, their denser canopies could diminish their ability to withstand lateral forces, thereby increasing their lodging index. Plant height is a practical and simple measurable trait for assessing the lodging behaviours of cultivars (Navabi et al., 2006). A common hypothesis suggests that various physicochemical processes are restricted in shorter plants, hence reducing yield (Navabi et al., 2006). Zhang et al. (2017) stated that shorter rice varieties are less prone to lodging, but the decreased height resulted in weak growth that ultimately led to low rice yields.

In this study, the MRQ 76 aromatic rice variety reached the optimal and suitable plant height, which enabled benefits including effective weed suppression and efficient light absorption while maintaining structural integrity. Furthermore, the potential yield of the rice variety was maximised by avoiding lodging. Nonetheless, the season and treatment applied significantly influenced the height of the MRQ 76 rice variety.

Throughout season 1, the plants treated with T10 consistently recorded the shortest plant height at all growth stages assessed, measuring 62.34, 77.06, and 97.83 cm at 35, 60, and 90 DAT, respectively, while in season 2, the plants recorded 62.11, 70.94, and 96.73 cm, at 35, 60, and 90 DAT, respectively. Treatment (T10) consistently showed the shortest plant height in both seasons, followed by the standard fertiliser (T9) and the 100% CaSiO3 alone (T4).

The observations highlighted that using organic Si alone (T1, T2, and T3) and combining organic and inorganic Si (T5, T6, T7, and T8) along with NPK fertilisers were particularly effective in promoting plant height and sustaining overall plant growth.

Stewart and Roberts (2012) suggested that applying fertilisers could lead to a substantial increase in yield, ranging from 30 to 50%. Moreover, adding Si in conjunction with fertilisers could synergistically affect the rice N use efficiency (NUE) and total biomass production (Savant et al., 1997). Si deposition in paddy plant cell walls also plays a crucial role in enhancing cultivar heights by promoting more upright leaves and stems. The vertical growth pattern facilitated improved light absorption, hence increasing photosynthetic rates in the plant. The upright leaves and stems also reduced mutual shading caused by densely populated plants (Pati et al., 2016).

During season 1 (main season 2019/2020), the treatment involving 100% CaSiO3 (T4) exhibited the highest plant height, measuring 75.49, 88.70, and 120.50 cm at 35, 60, and 90 DAT, respectively (Figure 3). Nevertheless, the height documented at 90 DAT was comparable to the reading obtained from the plants treated with the standard fertiliser (T9) at 120.86 cm. This finding aligned with a previous study by Cuong et al. (2017), which reported that the application of silicon (Si) fertiliser resulted in increased plant height, although no significant differences were observed among different treatments. Pati et al. (2016) also found that adding Si fertilisers enhanced the height of paddy plants compared to those without Si supplements.

Mahmad-Toher et al. (2021) revealed that treating the MR219 rice variety with $CaSiO_3$ alone led to the best height performance, followed by a rice husk ash and manganese combination. The findings provided additional evidence supporting the effectiveness of incorporating $CaSiO_3$ to enhance rice plant heights. In another study, Kowalska et al. (2021) investigated the effects of different forms of silicon fertilisers on wheat. The liquid Si formulation (monosilicic acid solution) was more effective than the powder version (diatomaceous earth). The Si stimulations promoted growth, which increased ear numbers and plant height, thus leading to higher yields. Furthermore, soil and foliar applications of Si were more effective than only treating the soil or leaves.

The paddy plants cultivated in season 2, which was the off-season in 2020, documented height improvements when treated with organic (T1, T2, and T3) and combinations of organic and inorganic (T5, T6, T7, and T8) Si compared to the application of 100% $CaSiO_3$ (T4), standard fertiliser (T9), and the control treatment, which was without fertiliser (T10) (Figure 4). The T8 treatment resulted in the highest plant height of the MRQ 76 at 35 DAT, measuring 83.81 cm, comparable to the plants supplemented with T6, T2, and T3.

At 60 DAT, the highest plant height obtained from the plants cultivated in season 2 was from the T6 treatment plot, which reached 96.85 cm, followed by the T2, T5, T7, T8, T3, and T1-treated plot, resulting in 95.80, 95.66, 95.14, 94.93, 94.61, and 94.39 cm, respectively. The trend continued at 90 DAT, where the T6 treatment showed the most significant plant height of 123.31 cm, followed by the plants treated with T2, T3, T7, T5, T8, and T1, at 122.48, 122.43, 121.80, 121.63, 121.26, and 118.59 cm, respectively. Conclusively, the control treatment (T10), which did not include fertilisers, documented the shortest plant across all growth stages for both seasons, thus indicating that fertilisers are required for optimal plant growth (height) (Figures 3 and 4).

The Effects of $CaSiO_3$, Rice Straw, and Rice Husk Ash on Number of Tillers per Meter Square

Tillering capacity is vital in determining rice grain yield as it is closely associated with the number of panicles per unit area (Pati et al., 2016). Supplementing with Si fertilisers, inorganic and organic, reportedly positively affected the number of tillers per square metre of rice plants (Pati et al., 2016). The enhancement in tillering capacity could improve grain yield potential in rice cultivation (Pati et al., 2016).

In this study, the number of tillers per meter square demonstrated a significant difference among the treatments when assessed at 35, 60, and 90 DAT during the main season (2019/2020) and off-season (2020) (Figures 5 and 6). The T8 treatment, which involved combination of rice straw (50%) and rice husk ash (50%) a day before planting, followed by $CaSiO_3$ (100%) during the panicle initiation without additional NPK fertiliser (17:3:25:2MgO) at the heading stage, resulted in an increased number of tillers per meter square at 35 and 60 DAT in both seasons compared to the plants treated with standard fertiliser (T9) and the control (T10) plot.

At 90 DAT, the treatment T7 recorded the highest tiller number during season 1, while in season 2, the T8 treatment performed better. The findings revealed that incorporating inorganic and organic Si fertilisers enhanced rice growth by increasing the number of tillers per plant. The results supported the observations reported by Pati et al. (2016), where an improved number of tillers per hill occurred with the supplementation of Si fertiliser in paddy fields. Hosseini et al. (2011) also reported a significant increase in tillering with higher SiO_2 levels (10 g SiO_2). In another study, Yasari et al. (2012) also observed a notable enhancement in tillering after application of 250 kg Si per hectare.

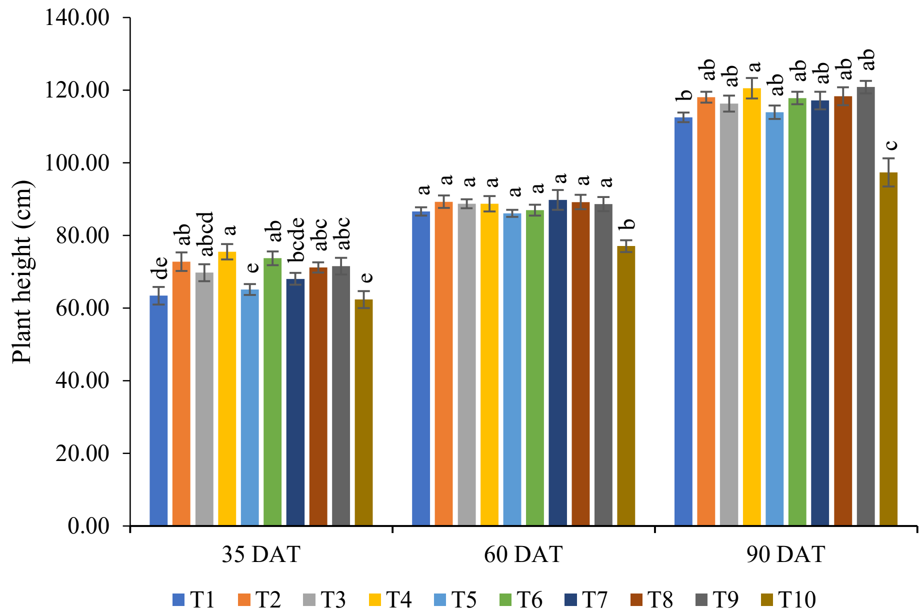

Figure 3. Effects of treatments on the paddy plants height during main season 2019/2020. Note: Same alphabet indicates insignificant difference between treatment means using DNMRT at $p \leq 0.05$

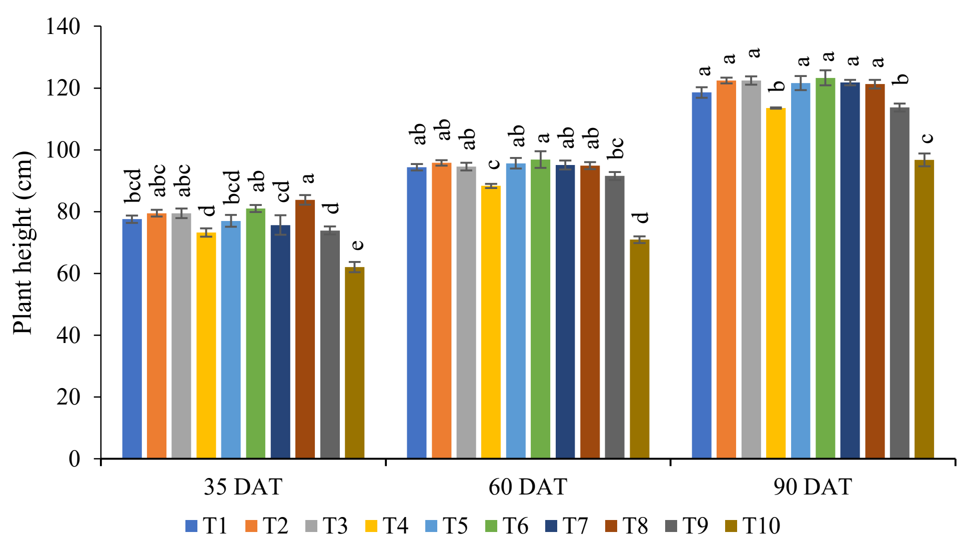

Figure 4. Effects of treatments on the paddy plants height during off season 2020. Note: Same alphabet indicates insignificant difference between treatment means using DNMRT at $p \leq 0.05$

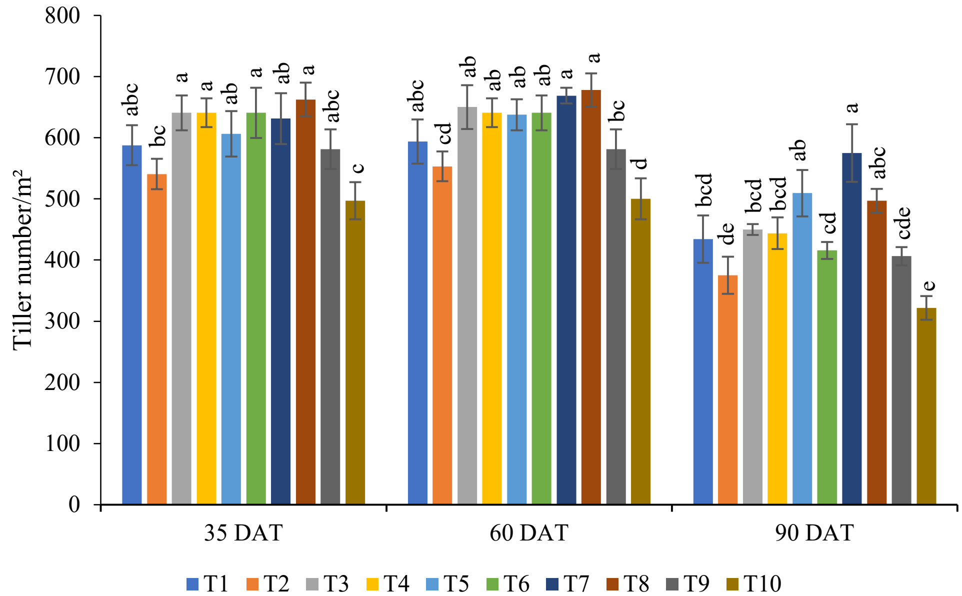

Figure 5. Effect of treatments on tillers number per metre square of paddy plants during main season 2019/2020. Note: Same alphabet indicates insignificant difference between treatment means using DNMRT at $p \leq 0.05$

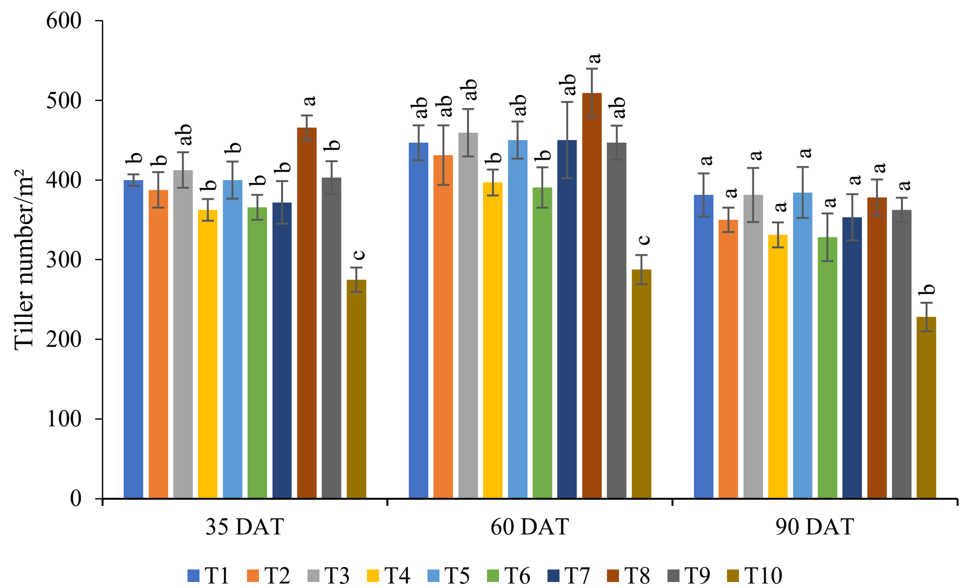

Figure 6. Effect of treatments on tillers number per metre square of paddy plants during off season 2020. Note: Same alphabet indicates insignificant difference between treatment means using DNMRT $p \leq 0.05$

The Effects of $CaSiO_3$, Rice Straw, and Rice Husk on Chlorophyll Content

The SPAD chlorophyll meters are commonly utilised in agricultural systems to assess the N levels in plant leaves, which is required for photosynthesis (Xiong et al., 2015). Dobermann and Fairhurst (2000) reported that the optimal SPAD threshold for direct-seeded rice in the Philippines with 800 productive tiller planting densities was within the 29 to 30 range. Nonetheless, it is essential to maintain a minimum 1.4 g N/m^2 N concentration in the uppermost fully expanded leaf to achieve the maximum yield target, regardless of the genotypes (Dobermann and Fairhurst, 2000). The treatments applied in this study did not significantly affect the chlorophyll contents of the paddy plants at 35, 60 and 90 DAT and during harvest for both seasons (Figures 7 and 8), suggesting that the N applied was sufficient.

Si fertilisers enhance the optimal N rate due to their synergistic effects, thus improving crop yields (Elawad and Green, 1979). Li et al. (2023) discovered that Si nanoparticles (SiNPs) enhanced chlorophyll levels and net photosynthetic rate of wheat. The study also observed that SiNPs positively influenced the expression of genes involved in chlorophyll synthesis, potentially leading to higher chlorophyll a and b concentrations in wheat leaves. Furthermore, a remarkable 17.8% enlargement in leaf areas where SiNPs were applied was recorded compared to the control group. Leaf area expansions could also enhance photosynthesis and contribute to increased biomass production.

Sandhya and Prakash (2017) reported that applying $CaSiO_3$ and rice hull significantly affected various growth parameters and enabled rice plant component yields in acidic and alkaline soils. Si treatments facilitate the mobility and translocation of iron (Fe) within the xylems of plants, thus promoting the remobilisation of Fe from older leaves to younger leaves (Pavlovic et al., 2013). The mechanism potentially contributes to improved chlorophyll content (SPAD values) observed in rice plants treated with Si sources. The applied treatments produced a noticeable influence on the chlorophyll content of the paddy plants cultivated during season 1 (main season 2019/2020), with lower chlorophyll content compared to season 2 (off-season 2020) (Figures 7 and 8). The difference in chlorophyll contents between the plants from both seasons could be attributed to the distinct environmental conditions during the periods of this study.

In a study conducted in the granary areas of Peninsular Malaysia, Tan et al. (2021) found that the main season is characterised by higher rainfall levels and lower average minimum and maximum temperatures compared to the off-season. The abundance of rainfall during the main season translates into highly moist soils and ample water availability for plant uptake. The optimal water supply facilitates active photosynthesis and stimulates chlorophyll synthesis, hence a higher chlorophyll content.

Restrepo and Garcés (2013) noted that paddy leaves exhibited higher chlorophyll contents when exposed to lower light levels, as measured by SPAD meters. The ability of paddy plants to adapt and thrive in diverse conditions is closely linked to the synthesis and breakdown of their photosynthetic pigments, which primarily occurs in the presence of light (Zervoudakis et al., 2012). Conversely, the off-season is characterised by higher temperatures and increased solar radiation, which could exacerbate water stress and accelerate chlorophyll molecule degradation. Moreover, elevated temperatures enhance processes involving photo-oxidation, which leads to diminished chlorophyll content.

Strong winds and heavy rains during extreme weather events and excessive N fertiliser supplementations could increase the risk of crop lodging. Consequently, applying Si could enhance light interception by modifying leaf architecture and promoting sclerenchyma development, vascular tissues, and vascular sheaths in wheat and rice to mitigate lodging (Hernandez-Apaolaza, 2014). Berahim et al. (2021) conducted a study using PadiU Putra rice variety, observed that the foliar application of Si resulted in the highest mean SPAD value of 32.52 units at 55 DAT. However, no significant differences were recorded between the plants evaluated at 75 DAT with Si top-dressed and control groups.

The mean SPAD values recorded during season 1 in this study varied between 33.98 and 36.14, 32.96 and 35.74, 28.20 and 38.72, and from 25.41 to 28.93 at 35, 60, 90 DAT, and harvest, respectively (Figure 7). While in season 2, the mean SPAD values ranged from 36.06 to 38.59, 34.06 to 36.31, 31.10 to 33.16, and 26.23 to 29.01 at the corresponding growth stages (Figure 8). Nevertheless, the relationship between the SPAD values and leaf N concentration might vary due to different growth stages, plant variety, solar radiation, and local conditions. The differences could be attributable to varied leaf thickness or specific leaf weight (Turner and Jund, 1994; Dobermann and Fairhurst, 2000; Peng et al., 1993).

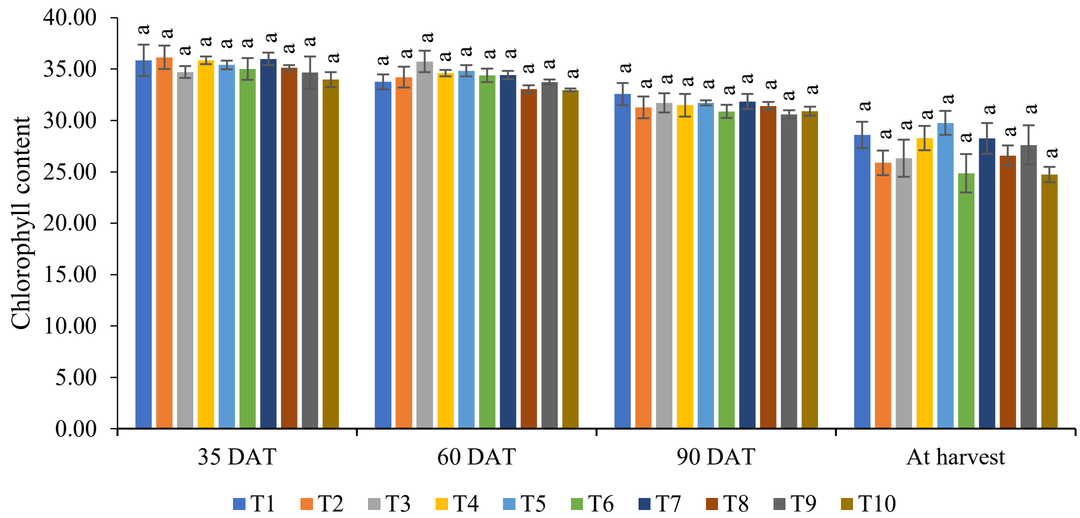

Figure 7. Effects of treatments on SPAD value of the paddy plants during main season 2019/2020. Note: Same alphabet indicates insignificant difference between treatment means using DNMRT at $p \leq 0.05$

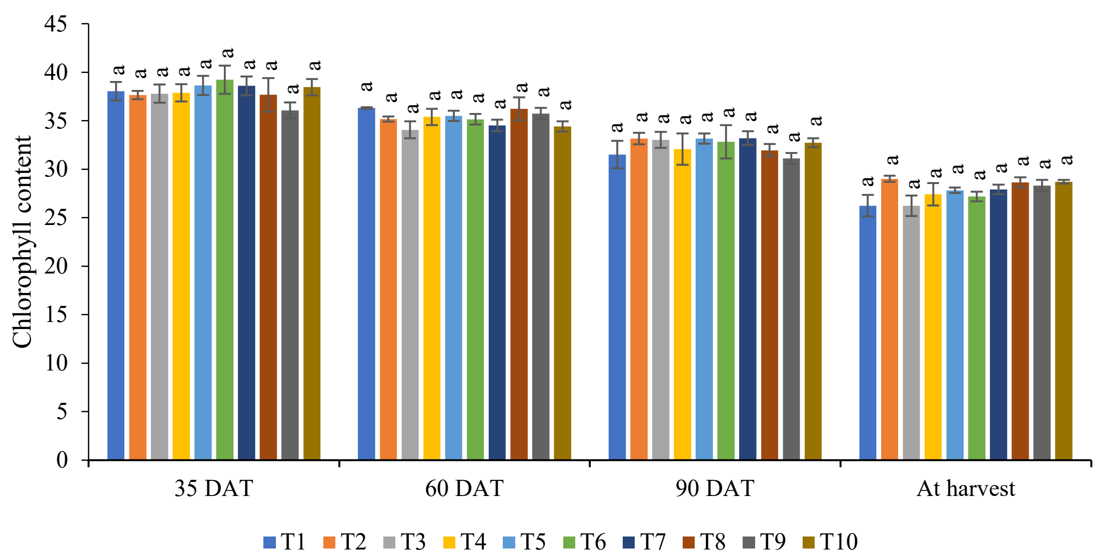

Figure 8. Effects of treatments on SPAD value of the paddy plants during off season 2020. Note: Same alphabet indicates insignificant difference between treatment means using DNMRT test at $p \leq 0.05$.

CONCLUSIONS

The combined use of organic Si, between rice straw (50%) and rice husk ash (50%) as a soil amendment prior to transplanting, along with the application of $CaSiO_3$ (100%) as an inorganic Si source during panicle initiation, with additional NPK fertiliser (17:3:25:2MgO) at the heading stage (T7), and without application of additional NPK fertiliser (17:3:25:2MgO) at the heading stage (T8), improved paddy plant height and tillers number per meter square. The study suggests that the combined use of (50%) rice straw and (50%) rice husk ash as organic Si, along with 100% $CaSiO_3$ as an inorganic silicate material, can be a beneficial approach to boost paddy crop growth and ultimately improve paddy productivity.

AUTHORS CONTRIBUTION

All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interests with regard to the publication of this paper.

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REFERENCES

Berahim, Z., Omar, M. H., Zakaria, N. I., Ismail, M. R., Rosle, R., Roslin, N. A. and Che'Ya, N. N. (2021). Silicon improves yield performance by enhancement in physiological responses, crop imagery, and leaf and culm sheath morphology in new rice line, PadiU Putra. *BioMed Research International*, 2021, 6679787.

Cuong, T. X., Ullah, H., Datta, A. and Hanh, T. C. (2017). Effects of silicon-based fertilizer on growth, yield and nutrient uptake of rice in tropical zone of Vietnam. *Rice Science*, 24(5), 283-290.

Dobermann, A. and Fairhurst, T. H. (2000). Nutrient disorders and nutrient management. *Potash and Phosphate Institute, Potash and Phosphate Institute of Canada and International Rice Research Institute, Singapore*, 191.

Dorairaj, D., Ismail, M. R., Sinniah, U. R. and Tan, B. K. (2017). Influence of silicon on growth, yield, and lodging resistance of MR219, a lowland rice of Malaysia. *Journal of Plant Nutrition*, 40(8), 1111-1124.

Duwayri, M., Tran, D. V. and Nguyen, V. N. (2000). Reflections on yield gaps in rice production: how to narrow the gaps. In: Papademetriou, M. K., Dent, F. J. and Herath, E. M. (Eds.) *Bridging the Rice Yield Gap in the Asia-Pacific Region*. Rome: FAO. pp. 26-46.

Elawad, S. H. and Green, V. E. (1979). Silicon and the rice plant environment: a review of recent research. *II Riso*, 28, 235-253.

Gong, D., Zhang, X., Yao, J., Dai, G., Yu, G., Zhu, Q., Gao, Q. and Zheng, W. (2021) Synergistic effects of bast fiber seedling film and nano-silicon fertilizer to increase the lodging resistance and yield of rice. *Scientific Reports*, 11, 12788.

Gowariker, V., Krishnamurthy, V. N., Gowariker, S. Dhanokar, M. and Paranjape, K. (2009). *The Fertilizer Encyclopedia*. John Wiley, New York.

Hernandez-Apaolaza, L. (2014). Can silicon partially alleviate micronutrient deficiency in plants? A review. *Planta*, 240(3), 447-458.

Hosseini, S. Z., Babaeian Jelodar, N. A. and Bagheri, N. A. (2011). Effect of silica on morphological traits and resistance of rice to striped stem borer (*Chilo suppressalis* Walker). *Plant Ecophysiology*, 3(2), 95-100.

Hu, Y., Javed, H. H., Asghar, M. A., Peng, X., Brestic, M., Skalický, M., Ghafoor, A. Z., Cheema, H. N., Zhang, F. F. and Wu, Y. C. (2022). Enhancement of lodging resistance and lignin content by application of organic carbon and silicon fertilization in *Brassica napus* L. *Frontiers in Plant Science*, 13, 217.

IRRI. (2002). *Standard Evaluation System for Rice (SES)*. Manila: IRRI Press

Ismail, C. H., Shajarutulwardah, M. Y., Ahmad Arif, I., Shahida, H., Mohamad Najib, M. Y. and Helda, S. (2013). The need for rice cultivation is high. *Paper presented at the National Rice Conference 2013, 10-12 December 2013, Seberang Jaya, Pulau Pinang*.

Klotzbücher, T., Leuther, F., Marxen, A., Vetterlein, D., Horgan, F. G. and Jahn, R. (2015). Forms and fluxes of potential plant-available silicon in irrigated lowland rice production (Laguna, the Philippines). *Plant and Soil*, 393(1), 177-19.

Kowalska, J., Tyburski, J., Jakubowska, M. and Krzymińska, J. (2021). Effect of different forms of silicon on growth of spring wheat cultivated in organic farming system. *Silicon*, 13, 211-217.

Li, Y., Xi, K., Liu, X., Han, S., Han, X., Li, G., Yang, L., Ma, D., Fang, Z., Gong, S. and Yin, J. (2023). Silica nanoparticles promote wheat growth by mediating hormones and sugar metabolism. *Journal of Nanobiotechnology*, 21(1), 2.

Mahmad-Toher, A. S., Govender, N., Dorairaj, D. and Wong, M. Y. (2021). Comparative evaluation on calcium silicate and rice husk ash amendment for silicon-based fertilization of Malaysian rice (*Oryza sativa* L.) varieties. *Journal of Plant Nutrition*, 45(9), 1336-1347.

MOA (Ministry of Agriculture and Agro-based Malaysia). (2008). Seksyen Industri Padi dan Beras (IPB). Projek Pembangunan Pertanian Bersepadu (IADP) Jelapang Padi. [Online] Available at: http://agrolink.moa.my/moa/index. [Accessed 20th February 2023].

Navabi, A., Iqbal, M., Strenzke, K. and Spaner, D. (2006). The relationship between lodging and plant height in a diverse wheat population. *Canadian Journal of Plant Science*, 86(3), 723-726.

Okuno, A., Hirano, K., Asano, K., Takase, W., Masuda, R., Morinaka, Y., Ueguchi-Tanaka, M., Kitano, H. and Matsuoka, M. (2014). New approach to increasing rice lodging resistance and biomass yield through the use of high gibberellin producing varieties. *PLoS One*, 9(2), e86870.

Othman, O., Abu Hassan, D., Alias, I., Ayob, A. H., Azmi, A. R., Azmi, M., Badrulhadza, A., Maisarah, M. S., Muhamad, H., Saad, A., Sariam, O., Siti Norsuha, M., Syahrin, S. and Yahaya, H. (2008). *Manual Teknologi Penanaman Padi Lestari*. Serdang: MARDI Press.

Paramanathan, S. (2000). *Soils of Malaysia: Their Characteristics and Identification*. Kuala Lumpur: Academic Science of Malaysia.

Pati, S., Pal, B., Badole, S., Hazra, G. C. and Mandal, B. (2016). Effect of silicon fertilization on growth, yield, and nutrient uptake of rice. *Communications in Soil Science and Plant Analysis*, 47(3), 284-290.

Patil, A. A., Durgude, A. G., Pharande, A. L., Kadlag, A. D. and Nimbalkar, C. A. (2017). Effect of calcium silicate as a silicon source on growth and yield of rice plants. *International Journal of Chemical Studies*, 5(6), 545-549.

Pavlovic, J., Samardzic, J., Maksimović, V., Timotijevic, G., Stevic, N., Laursen, K. H., Hansen, T. H., Husted, S., Schjoerring, J. K., Liang, Y. and Nikolic, M. (2013). Silicon alleviates iron deficiency in cucumber by promoting mobilization of iron in the root apoplast. *New Phytologist*, 198(4), 1096-1107.

Peng, S., Garcia, F. V., Laza, R. C. and Cassman, K. G. (1993). Adjustment for specific leaf weight improves chlorophyll meter's estimate of rice leaf nitrogen concentration. *Agronomy Journal*, 85(5), 987-990.

Restrepo, H. and Garcés, G. (2013). Evaluation of low light intensity at three phenological stages in the agronomic and physiological responses of two rice (*Oryza sativa* L.) cultivars. *Agronomía Colombiana*, 31(2), 195-200.

Sandhya, T. S. and Prakash, N. B. (2017). Evaluation of calcium silicate, rice hull and rice hull ash as silicon sources on wetland rice in acidic and alkaline soils. *Journal of the Indian Society of Soil Science*, 65(4), 428-434.

Savant, N. K., Datnoff, L. E. and Snyder, G. H. (1997). Depletion of plant-available silicon in soils: A possible cause of declining rice yields. *Communications in Soil Science and Plant Analysis*, 28(13-14), 1245-1252.

Stewart, W. M. and Roberts, T. L. (2012). Food security and the role of fertilizer in supporting it. *Procedia Engineering*, 46, 76-82.

Sun, X., Liu, Q., Tang, T., Chen, X. and Luo, X. (2019). Silicon fertilizer application promotes phytolith accumulation in rice plants. *Frontiers in Plant Science*, 10, 425.

Tamai, K. and Ma, J. F. (2008). Reexamination of silicon effects on rice growth and production under field conditions using a low silicon mutant. *Plant and Soil*, 307(1), 21-27.

Tan, B. T., Fam, P. S., Firdaus, R. R., Tan, M. L. and Gunaratne, M. S. (2021). Impact of climate change on rice yield in Malaysia: a panel data analysis. *Agriculture*, 11(6), 569.

Turner, F. T. and Jund, M. F. (1994). Assessing the nitrogen requirements of rice crops with a chlorophyll meter. *Australian Journal of Experimental Agriculture*, 34(7), 1001-1005.

Wang, W., Lai, D. Y., Li, S., Kim, P. J., Zeng, C., Li, P. and Liang, Y. (2014). Steel slag amendment reduces methane emission and increases rice productivity in subtropical paddy fields in China. *Wetlands Ecology and Management*, 22, 683-691.

Xiong, D., Chen, J., Yu, T., Gao, W., Ling, X., Li, Y., Peng, S. and Huang, J. (2015). SPAD-based leaf nitrogen estimation is impacted by environmental factors and crop leaf characteristics. *Scientific Reports*, 5, 13389.

Yasari, E., Yazdpoor, H., Kolhar, H. P. and Mobasser, H. R. (2012). Effect of plant density and the application of silica on seed yield and yield components of rice (*Oryza sativa* L.). *International Journal of Biology*, 4(4), 46-53.

Yoshida, S. (1981). *Fundamentals of Rice Crop Science*. Los Baños: International Rice Research Institute.

Zervoudakis, G., Salahas, G., Kaspiris, G. and Konstantopoulou, E. (2012). Influence of light intensity on growth and physiological characteristics of common sage (*Salvia officinalis* L.). *Brazilian Archives of Biology and Technology*, 55, 89-95.

Zhang, J., Li, G., Song, Y., Liu, Z., Yang, C., Tang, S., Zheng, C., Wang, S. and Ding, Y. (2014). Lodging resistance characteristics of high-yielding rice populations, *Field Crops Research*, 161, 64-74.

Zhang, M., Liang, Y. and Chu, G. (2017). Applying silicate fertilizer increases both yield and quality of table grape (*Vitis vinifera* L.) grown on calcareous grey desert soil. *Scientia Horticulturae*, 225, 757-763.