J. Trop. Resour. Sustain. Sci. 12 (2024): 141-150
https://doi.org/10.47253/jtrss.v13i2.1488

Journal of Tropical Resources and Sustainable Science

journal homepage: jtrss.org

Effects of silicon treatments on *Nilaparvata lugens* and rice yield under field conditions

NurulNahar Esa* and Maisarah Mohamad Saad

Paddy and Rice Research Centre, MARDI Seberang Perai, 13200 Kepala Batas, Pulau Pinang, Malaysia

Received 29 February 2024
Accepted 23 April 2024
Online 23 December 2024

Keywords:
brown planthopper; fertiliser; grain yield; agronomic efficiency; rice pest

⌧*Corresponding author:
NurulNahar Esa
Paddy and Rice Research Centre, MARDI Seberang Perai, 13200 Kepala Batas, Pulau Pinang, Malaysia
Email: naharesa@mardi.gov.my

Abstract

The brown planthopper, *Nilaparvata lugens* (Stål), is a destructive pest of rice crops. In the present work, experiments were conducted to study the impact of an ideal Si rate of 200 kg/ha applied at different splits on brown planthopper infestation and rice yield components under natural field conditions. Results showed that application at a two-equal split of 100 kg Si/ha at 7 and 45 days after transplanting (DAT) significantly controlled the brown planthopper infestation by an average of 59.2% compared to control. However, the fertilisation time did not contribute to giving maximum rice grain yield. The maximum rice grain yield was achieved with 200 kg Si/ha applied once at 25 days after transplanting. The agronomic efficiency of these two methods were 3.79 kg/ha and 4.25 kg/ha, respectively. This may help to explain why a single application of Si during the maximum tillering-reproductive stages (25 DAT) is critical for producing rice grain yield. The application of Si effectively increased the uptake of N, P, and K in rice plants. An increase in these macronutrients in rice plants may be the reason why rice plants effectively hindered the brown planthopper infestation and also provided greater nutrients for sustaining the rice grain yield. Overall, the application during the early vegetative (7 DAT) and reproductive (45 DAT) stages sheds light on how Si application influences the rice plants' defence mechanisms against brown planthoppers but sacrifices the grain yield. Future research on silicon applications and integration with biological control for ecologically sustainable pest management in rice should be considered.

1. INTRODUCTION

Chemical fertilisers are critically used to increase agricultural output. Applying the right nutrient source at the right time can increase crop yields and maximise profits. Therefore, applications of fertiliser, especially at the right time, are a must to ensure plant growth at an optimal growth rate with sufficient nutrients (Hussain et al., 2017). The timing of fertiliser applications significantly affected plant performance. Early response of the root system in crops is an important factors for proper crop establishment, which shows that the time frame of roots response to fertiliser is an important aspect for improving nutrient use efficiency (van Duijnen et al., 2021). This is necessary because supplying nutrients to plants requires a more seamless integration of the physiological and ecological processes involved in nutrient absorption, transportation, and metabolic mechanisms. These need to be in line with the amount and timing of nutrients needed for plants to go through physiological growth processes. Plants absorb, move, distribute, and assign nutrients to various organs in diverse ways (Bindraban et al., 2015).

A number of reports revealed that by giving split nutrients at different growth stages produce benefits for plants. The application of nitrogen (N) at different growth stages was found to improve high N fertiliser uptake and has a low potential for N losses via nitrification and denitrification, which appear to be the best option to achieve a high maize grain yield (Momesso et al., 2022). While, tobacco plants with two splits of fertilisation increased root establishment, therefore increasing the capability of the fibrous roots to absorb nutrients both horizontally and vertically from the soil at the optimum rate, consequently increasing leaf yield (Lisuma et al., 2023). Nitrogen fertiliser applied at planting, emergence, and tuber initiation maximised the N uptake, and minimised N leaching, thus increasing the potato tuber yield (Silva et al., 2023). Nitrogen application at planting and at knee height increased agronomic nutrient use efficiency (NUE) and consequently improved maize grain yield. Nitrogen use efficiency is a key issue for sustainable and profitable nitrogen use in high-input agriculture (Tadesse et al., 2013). Application of N fertiliser by splitting the dose at sowing, at knee height and at the tasseling stage of the maize improved the total nitrogen uptake and agronomic efficiency, consequently promoting the highest biomass yield and grain yield (Negash et al., 2021). The growth parameters and rice grain yield increased significantly with the application of potassium in three splits (50% basal, 25% tillering, and 25% panicle), because split application significantly increased the

eISSN Number: 2462-2389

number of tillers and panicles per square metre (Nand et al., 2020). In addition, rice has a high rate of N absorption during the jointing-to-booting stage and at the initiation of flag-leaf extension. Therefore, adequate N supply during this critical stage is critical for grain filling and enhancing rice yield, and optimising nitrogen use efficiency (NUE) at these stages is crucial (Shrestha et al., 2022). Applying N at three different stages (20% of nitrogen at the 3-leaf stage, 30% at active tillering, and 50% at 10 days before panicle initiation) is an effective strategy for increasing rice grain yield by increasing the number of panicles per square metre and spikeletes per square metre (NurulNahar, Shajarutulwardah, et al., 2023b).

The brown planthopper (*Nilaparvata lugens* Stal.) is a sucking insect pest of rice that can cause "hopperburn," which is the wilting and total drying of rice plants, especially in areas where infestations are severe. In tropical regions, the insect can complete up to 12 generations in a single year (Stout, 2014). Brown plant hopper (BPH), which is estimated to cause a 90,000 tonne loss per season, is worth approximately RM 72 million (Dorairaj and Govender, 2023). In 1967, Malaysia experienced an outbreak that affected over 5,000 hectares and resulted in revenue losses of up to RM 4 million (Mohammad Aufa et al., 2022). Throughout rice cultivation history, there have been brown planthopper outbreaks. Pest outbreaks could happen more frequently, especially after prolonged droughts and intense rains (Sharma and Prabhakar, 2014). Certain flavonoids, plant sterols, oxalic and silicic acid can prevent brown planthoppers from feeding (Stout, 2014). The naturally occurring bioavailable form of silicon is silica acid. Silica bodies, or solid amorphous silica, are formed when silicic acid accumulates spontaneously in shoots and leaves. These silica bodies are mostly deposited in the cell walls of various tissues and provide structure and mechanical stability (van den Berg et al., 2021). Crop plants are known to benefit from silicon (Si) in terms of minimising biotic and abiotic stressors. Silicon can increase a plant's resilience to insect pests and help attract natural foes by emitting more volatile chemicals. Compared to synthetic pesticides, they are safer to use and more environmentally friendly in the wild (Saw et al., 2023). Besides that, Si is commonly supplied as a fertiliser to assess its impact on crop production. The utilisation of Si fertilisers in rice has resulted in increased plant growth rates and higher productivity, where the effect of increased productivity is also found in vegetable and fruit crops (Tayade et al., 2022). The application of 200 kg Si as an addition to current farmer practices can reduce the survival rate of the nymphs and also inhibit the hatching of brown planthopper eggs (Maisarah et al., 2022). However, effect of split applications of Si on the control of brown planthoppers are rather limited. Besides, there is also limited information whether split applications of Si as a fertiliser can also benefit the productivity of rice plants. Therefore, the aims of this study are to determine the effectiveness of using Si to control brown planthoppers under natural conditions and its effect on rice yield components.

2. MATERIALS AND METHODS

2.1 Site location and soil analysis

The study was conducted during off-season 2022 and main-season 2022/2023 at Kampung Selengkoh, Yan, Kedah. Prior to planting, soil samples at a depth of 0–20 cm for nutrient and mechanical analysis. The samples at each experimental unit were collected and combined as bulk samples. The collected soil samples were air-dried, crushed, and sieved to pass through a 2 mm sieve and stored at room temperature in dark conditions until analysis. Physical and chemical properties of the soil at the study site are presented in Table 1. According to the USDA textural triangle, this soil was classified as clay.

Table 1: Physical and chemical properties of the soil at the study site.

Parameters	Soil (0-20 cm)
pH	5.1
Conductivity (dS/m)	0.12
CEC cmol$_{(+)}$/kg	17.4
Organic matter (%)	12.7
Total Nitrogen (%)	0.18
Available P (mg/kg)	12.8
Exchangeable K cmol$_{(+)}$/kg	0.38
Coarse sand (%)	5.2
Fine sand (%)	9.6
Silt (%)	20.0
Clay (%)	65.2

2.2 Experimental design and treatment application

The standard fertiliser rate of 104 kg N/ha: 42 P_2O_5 kg/ha and 62 K_2O kg/ha was applied for all treatments during off-season 2022 and main-season 2022/23. The first fertilisation was applied at 7 days after transplanting (DAT) with 24.5 kg N/ha, 21.7 kg $P_2O5_/$ha, and 14 kg K_2O/ha followed by second fertilisation at 25 DAT with 36.8 kg N/ha. The third fertilisation was applied at 45 DAT with 34.5 kg N/ha, 18.5 kg P_2O_5/ha, 35 kg K_2O/ha, and 2 kg/ha MgO while the fourth fertilisation was applied at 65 DAT with 8.5 kg N/ha, 1.5 kg P_2O_5/ha, and 12.5 kg K_2O/ha. The treatments consist of a control (T1-standard fertiliser rate) and seven different splits of Si fertiliser, which were T2 (200 kg Si/ha at 7 DAT), T3 (200 kg Si/ha at 25 DAT), T4 (200 kg Si/ha at 45 DAT), T5 (100 kg Si/ha at 7 DAT and 25 DAT), T6 (100 kg Si/ha at 7 DAT and 45 DAT), T7 (100 kg Si/ha at 35 DAT and 45 DAT), and T8 (66.7 kg Si/ha at 7 DAT, 25 DAT, and 45 DAT). The treatments were applied through urea (46%), triple superphosphate (46% P_2O_5), muriate of potash (60% K_2O) and commercial Si fertiliser (25%) and were arranged in a randomised complete block design with three replications.

The plot size was 5 m x 5 m, and in each of the experimental plots, the soil was manually raised to prevent the fertiliser from mixing with other treatments. The high-yielding variety MARDI Siraj 297 was used in this study with 105 maturation days after transplanting. Seeds were soaked for 24 hours in water and left for 36 hours in moist conditions under shade for good establishment. The healthy seedlings with similar plant heights were selected to ensure uniformity. Manual transplanting of the seedlings after 18 days was conducted with a planting distance of 18 cm x 30 cm and three seedlings per point. Data on plant growth, yield, and yield components were collected from the experimental plots.

2.3 Yield and yield components

Four hills per treatment of aboveground biomass were taken as sampling points to determine yield components at maturity. Panicles were hand-threshed, and filled spikelets were separated from unfilled spikelets. The total number of filled and empty spikelets were added to determine the total spikelets per square meter. Meanwhile, the 1000-grain weight was determined from filled spikelets, which were dried to 14% moisture content and weighed on a precision balance (ME3002, Mettler Toledo). The grain moisture content was measured with a digital moisture tester metre (Model SS-7, Satake). Spikelets per panicle, percentage of filled grain (100 x filled spikelets m^{-2} / total spikelets m^{-2}), and 1000-grain weight were also calculated.

The grain yield was calculated based on the weight of 4 m x 4 m in each plot and was converted to per hectare (kg/ha). The final grain yield is based on Dobermann and Fairhurst (2000).

$$\text{Grain yield} = ((\text{PlotGy} \times [(100 - \text{MC})/86])/1000) \times 10000/A$$

PlotGy is grain yield per plot adjusted to 14% moisture content, MC is grain moisture content, and A is harvested area.

Plants were sampled at maturity stage. Four representative plant samples were randomly collected from each treatment plot. Roots, stems (internode plus sheaths), and panicle parts were discarded, and the remainder of the leaves were washed off to remove soil (or dust). Leaf (Y-leaf) samples were dried to a constant weight at 45°C for at least 48 hours in an air-circulating oven (Memmert, UF-110). The concentration of N in leaf samples was determined using the Kjeldahl method, while P, K and Si were determined using flame atomic absorption spectroscopy. The nutrient concentration in leaves multiplied by the dry weight of the aboveground yielded the total uptake of N, P and K in rice leaves.

The agronomic efficiency (AE) of rice for Si was calculated using the following equations (Chuan et al., 2016; Golla, 2021):

$$AE = (Y_{Si} - Y_0) / F_{Si}$$

Where AE is the agronomic efficiency of applied Si (kg yield increase per kg Si applied). Y_{Si} is the rice grain yield with applied Si (kg ha^{-1}), Y_0 is the rice grain yield (kg ha^{-1}) in a control treatment with no Si, and F_{Si} is the amount of Si applied (200 kg ha^{-1}).

2.4 Brown planthopper assessment

The brown planthopper population of each treatment was monitored using a tapping board (18 cm x 23 cm). The population density was taken from three randomly selected hills for each replication. The brown planthopper samplings were done four times throughout the planting season (from tillering to dough ripe stage) for both trials.

2.5 Data analysis

All data were expressed as means ± standard error and analysed using the proc GLM and proc MIXED procedures in the SAS Statistical software package (version 9.4 for Windows). The data of brown plant hopper population density were transformed into Log10 values before the statistical analysis.

3. RESULT AND DISCUSSION

The analysis of variance for the brown planthopper (BPH) population density is presented in Table 2. There was a significant main effect of treatment on the brown plant hopper population per hill under natural conditions. There was also a significant interaction between treatment and season. In addition, a significant interaction between season and time (days after transplanting) was also revealed. Further analysis of the individual seasons on BPH population density is presented in Table 3.

Application of Si significantly shows lower presence of BPH population in off-season 2022 compared to control (T1), except for T7 which does not differ from each other. Still, T7 had a lower BPH population compared to the control. T6 had the lowest BPH population, with an average of 59.2% lower than control. On the other hand, there was no difference in the BPH population in the main-season 2022/23. Increasing the Si level increased the amorphous silica in the rice plants, forming a robust cellulose silicate membrane intertwined with pectin and calcium that provides a mechanically and physically protective barrier against sucking pests. It also increased the hardness of the stems, causing difficultly for BPH to insert their stylets for fluid suction, which results in their inability to extract phloem liquids and ultimately leads to their death (Syamsulhadi et al., 2023). Rice treated with N will accumulate certain amounts of N and soluble protein content in their plant tissue, which in the end influence BPH growth and development (Horgan et al., 2021; Rashid et al., 2017) and also improve all fitness traits of BPH (Horgan et al., 2018). However, the amount of BPH honeydew excretion (a measure of what insects eat) was lower in plants treated with Si than in plants only treated with N, and there was also a notable decrease in N contents in the leaves and stems (Rashid et al., 2016; Wu et al., 2017). The results obtained in the present work provide an insight into how the Si application affects the defensive capabilities of rice plants towards the accumulation of Si that provides mechanical hardness to the rice stems. In addition, Si application could reduce the soluble protein, which hindered the BPH-infested rice plants.

Table 2: Analysis of variance of BPH population density during off-season 2022 and main-season 2022/23

Source	DF	Mean square
		BPH population per hill
Season (S)	1	592.348008ns
Treatment (T)	7	11.710429*
S x T	7	9.671881*
Time (W)	3	85.956271ns
S x W	3	133.571238**
Rep (Season*Time)	16	0.4707344
W x T	21	2.518031ns
S x W x T	21	2.832961ns
Error	112	266.489883

ns, *, ** = non-significant and significant at p = 0.05 or 0.01, respectively. Means with the same letters within a column and each factor are not significantly different at p = 0.05.

Table 3: Analysis of variance on individual seasons in the BPH population density (number of BPH/hill)

Treatment	Off-season 2022	Main-season 2022/23
T1	7.1a	0.24a
T2	3.7b	0.24a
T3	3.9b	0.20a
T4	3.4b	0.18a
T5	4.1b	0.26a
T6	2.9b	0.28a
T7	4.4ab	0.28a
T8	3.1b	0.19a

Treatments consist of a control (T1-standard fertiliser rate) and seven different splits of Si fertiliser (T2-T8)

Male/female ratios, migration patterns, mortality, and the biological traits of the pest itself all have a significant impact on BPH populations. Wind, rain, temperature, and humidity are also additional factors (Sembiring and Mendes, 2023). A rice paddy field is an open environment; hence, the conditions influencing the increase in the BPH population are not constant. Natural enemies, rice resistance, agricultural practices, and climatic and host plant conditions are not the only elements that might impact the dynamics of the BPH population. Therefore, seasonal and environmental factors may be responsible for variations in BPH populations (Skawsang et al., 2019). In this study, the BPH populations varied due to season (Table 4). Generally, during off-season 2022, the population of BPH was higher than in the main-season 2022/23. During the off-season 2022 (dry season), the BPH population was building up and peaking at 55 DAT before the population subsequently declined. On the other hand, during the main-season 2022/23 (rainy season), the BPH was peaking at 45 DAT and 75 DAT. The increase in population in BPH was associated with heavy rainfall, and high relative humidity (Win et al., 2011), which is inconsistent with the present study that high populations of BPH were higher in off-season 2022 (dry season) than in the main-season 2022/23 (wet season). However, heavy rain and floods will wash nymphs and adults off the host plant, and eggs laid in the rice sheath cannot hatch after submersion. These are some of the drawbacks of the wet season (Romadhon et al., 2017). Given that environmental factors have an impact on BPH populations, the present study suggests that these populations fluctuate in response to the dynamic conditions of their surroundings. In addition, rice plants treated with Si may change the source of diet for BPH in the later season, during which BPH may move or migrate for a better food source.

Table 4: Season and days after transplanting (DAT) effects on the population density (number of BPH/hill)

DAT	Season	
	Off-season 2022	Main-season 2022/23
45	1.0d	0.78a
55	7.9a	0.24a
65	4.9b	0.18a
75	2.5c	1.10a
Mean	4.1	0.58

The analysis of variance for yield and yield components is presented in Table 5. The season had no influence on the number of spikelets per panicle, with an average of 126 spikelets per panicle in both seasons. Rice plants treated with Si with different splits methods significantly had a greater number of spikelets per panicle except for T3 and T7, which were comparable to control (T1). However, T3 and T7 had an average of 6.9% higher spikelets per panicle (Figure 1). There was no interaction between season and treatments for the number of spikelets per panicle. Brown planthoppers feeding on rice plants have a significant impact on the rate of photosynthate translocation because they consume a large amount of sugars and nutrients from the phloem, resulting in the physiological disruption of active transportation, and as a result, rice plants have fewer spikelets per panicle (Sogawa and Cheng, 1979). Like other phloem-feeding insects, BPH's mouthparts are made up of a stylet bundle that serves as both the sucking and piercing organs. In order to locate the phloem tissue and control the ingestion of the pressurised plant sap, BPH feeds on the plant by inserting the stylet bundle into the plant along with a salivary sheath (Ghaffar et al., 2011). BPHs have a preference for feeding on a soft, smooth area on the surface of rice leaf sheaths. Because of the fortified sclerenchyma observed in a rice

BPH resistance gene, it significantly stopped BPH stylets from reaching the phloem (Shi et al., 2021). Si amendment increased the deposition of callose and mechanical barrier *via* silicification in the sieve tube of the rice leaf sheath, potentially reducing feeding in response to BPH infestation (Tenguri et al., 2023). Si amendment increased the amount of Si in rice stems and prolonged the non-probing event and phloem puncture, followed by sustained phloem ingestion. High Si addition rates reduced the percentage of individuals with BPH that produced sustained phloem ingestion, lengthened the stylet pathway and the time required to reach the first phloem puncture, and shortened the durations of phloem puncture and phloem ingestion (Yang et al., 2017). Based on the current findings, the application of Si could have maintained the rice's physiological state. As a result, more spikelets per panicle were produced than the control (Table 5), thus strengthening the mechanical barrier in the rice stem and leaf sheath which possibly preventing brown planthoppers from feeding on the rice plants. The number of panicles per square metre was not affected by season or treatment (Table 5). Generally, the average number of panicles per square metre was 235.

Table 5: Analysis of variance on rice yield and yield components under natural field conditions and silicon applications.

Source	DF	Mean square					
		Spikelet / panicle	Panicle / square metre	Spikelet / square metre	Filled grain (%)	1000-grain weight (g)	Yield (t/ha)
Season (S)	1	546.75ns	1008.33ns	4180150.52ns	340.80*	0.000675ns	1.51*
Off-season 2022		123a	239a	29287a	85.0a	29.0a	4.75a
Main-season 22/2023		129a	230a	29878a	79.7b	29.0a	4.36b
Rep (Season)	4	240.54	1641.33	20065671.4	11.08	0.59	0.078
Treatment (T)	7	194.90*	1222.81ns	38783490.4*	4.63ns	0.30ns	0.458*
S x T	7	497.92ns	1119.57ns	14392261.3ns	4.89ns	0.28ns	0.329ns
Error	28	63.95	680.19	13978967.5	19.62	0.49	0.157
Corrected Total	47						
Mean		126	235	29582	82.4	29.0	4.56
CV		8.0	11.1	12.6	5.4	2.4	8.7

ns, *= non-significant and significant at $p < 0.05$, respectively. Means with the same letters within a column and each factor are not significantly different at $p = 0.05$.

Plants infested by the BPH before maximum tillering usually have fewer panicles per unit area (Sogawa and Cheng, 1979). A central stem (rachis) with several primary and secondary branches makes up the rice panicle (Yamburenko et al., 2017). Thirty days before flowering, panicle primordia begin to form at the tip of the vegetative stem apex, inside the boot of the flag leaf sheath (Mohapatra et al., 2011). The present study suggests that under natural conditions and low BPH infestation at the vegetative to reproductive stages, as long as the main primary stem is not damaged, the formation of panicles will not be disturbed. The present study also suggests that Si application at different times does not seem to benefit rice panicle formation.

The total number of spikelets per square metre (spikelet number per panicle x panicles per unit area) did not influence by season but was significantly influenced by treatments. Since there was no difference in the number of spikelets per panicle and the number of panicles per square metre, it can be expected that there will be no change in the number of spikelets per square metre due to the influence of the season. All rice treated with Si, regardless of the application timing, shows a greater number of spikelets per square metre except T8 (Figure 2). However, T8 had an average of 17.4% higher total number of spikelets per unit area compared to control.

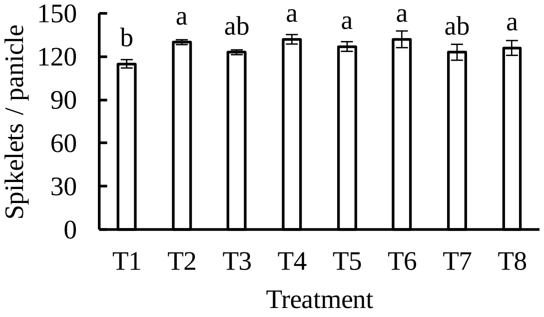

Figure 1: The number of spikelets per panicle as a result of silicon treatments.

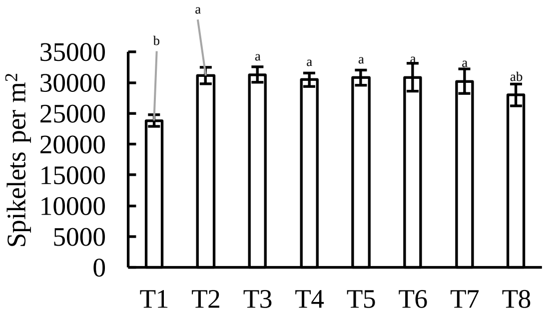

Figure 2: The number of spikelets per square metre as a result of silicon treatments.

Meanwhile, environmental variations have significant impacts on the grain-filling process. Specifically, variations in temperature and solar radiation can affect carbohydrate accumulation in the leaves and stems and affect photosynthetic parameters. This can also affect the transportation of non-structural carbohydrate from leaves and stems to spikeletes and sugar-starch metabolism in grains (Teng et al., 2023). In the grain-filling process, when the solar radiation is greater, it improves the grain filling (Mai et al., 2021). Overcast conditions during the rainy season would significantly block solar radiation in the atmosphere, lowering exposure at the earth's surface (Vun Teong et al., 2017). It is believed that a higher filled grain in off-season 2022 (85.0%) compared to main-season 2022/2023 (79.7%) could be due to seasonal effects related to greater solar radiation, which benefits carbohydrate accumulation in rice plant parts and improves non-structural carbohydrate that can be used for grain filling formation. In this study, all treatments received the same amount of nitrogen, phosphorus, and potassium, and additional Si at the rate of 200 kg/ha for treatments T2 to T8 did not influence on filled grain (%) (Table 5). The present study suggests that the optimal NPK received by the rice plants could somehow be sufficient for optimum grain filling or that the application of Si at different splits methods did not coincide with the needs of rice plants for the grain filling process. This is because the application of fertiliser at the right time, especially at the young panicle differentiation stage, could promote sink strength and grain filling in rice. However, at certain points, it also reduced the grain filling rate and quality of rice grain if the amount are greater than the requirements (Teng et al., 2023).

Nutrients had no effect on the 1000-grain weight or grain size, but significant genetic factors did (Borrell et al., 1999), were relatively stable (Zhou et al., 2017), and remained constant because hull size controls grain size (Yoshida, 1981). It is therefore possible to state that Si fertilisation does not affect the 1000-grain weight (Table 5). Nonetheless, the average grain weight of 29 g in the current study was comparable to the findings of NurulNahar et al., (2023a) and NurulNahar et al., (2023b) using the same variety and under normal conditions. Thus, the results of this study may also indicate that grain weight was unaffected by BPH infestation under natural conditions and low population density.

There are several ways for different rice varieties to achieve a high yield. When the number of spikelets per panicle and grain weight remained constant, some of them achieved a high yield with more panicles per unit area and a high number of filled grains. Some achieved a high yield while maintaining a high grain weight and filling the grains with the same number of spikelets. Others that had the same grain weight and filled grains also had a high yield with a high total number of spikelets (Liu et al., 2024). The results of this study showed that, with the exception of T8 (Figure 3), all rice plants treated with Si had significantly higher grain yields (Table 5) when compared to the control. The higher number of spikelets per panicle and spikelets per square metre were primarily responsible for the higher yield. Even though all Si treatments were applied to the rice plants at a rate of 200 kg/ha, only T8 at the equal amount of splits at seven, 25, and 45 days after transplanting did not benefit the rice plant. The grain yield increased only by 9.5% over the control treatment. In addition, the highest yield was recorded by T3, where Si fertilisation was given only once, 25 days after planting. The average yield was 21.3% higher compared to the control. The present study suggests that early (vegetative) fertilisation was more beneficial to the rice plant. A more optimal early stage of growth may provide benefits at the reproductive and ripening stages. However, based on the results on the BPH population, the application of T3 was seen to be high in the population of BPH, although it was not different with T6, which was the lowest recorded of BPH populations. Based on the data from this study, the selection of fertilisation time is important. Either by prioritising the increase in yield by ignoring the risk of BPH outbreak or prioritising the control of BPH, the increase in yield can still be obtained, but not to the maximum. In addition, the study shows that the rice yield was higher in the off-season 2022 compared to the main-season 2022/23 by 8.9%. This difference may be due to a higher difference in filled grain (%) in the 2022 off-season (Table 5).

Figure 4 shows the correlation between the Si uptake and the N, P, and K uptake tends to be positive. In other words, an increase in Si uptake significantly increases the uptake of N (r = 0.66), P (r = 0.63), and K (r = 0.38) in rice plants. In different plants and plant organs, Si affects the absorption and accumulation of multiple macro- and micronutrients. On the other hand, variations in the uptake and distribution of distinct elements and plants suggested that Si had an impact on the macro- and micronutrients in individual plant tissues (Greger et al., 2018). The application of Si fertiliser significantly increased the total uptake of N, P, K, and Si in the wet season but did not influence in the dry season, in which the significant uptake could be due to increased nutrient availability in the solution form in the soils (Swe et al., 2021). Silicon application, under ideal conditions, improves nutrient uptake by maize crops in tropical soils. The role of Si in improving nutrient availability was suggested through soil acidity correction, modification of certain gene expressions that are responsible for plant nutrient uptake, and improvement of the uptake of the roots (da Silva et al., 2023). According to Ali et al., (2020) the function of Si is more noticeable under stressful conditions because Si application may alter the physico-chemistry of the soil and may have an impact on the composition of nutrients; however, Si may also affect the uptake and translocation of macronutrients under normal conditions.

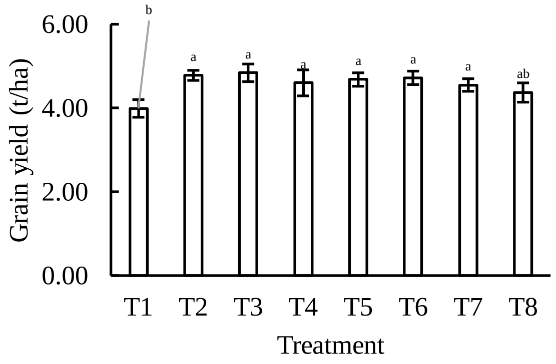

Figure 3: The rice grain yield (t/ha) as a result of silicon treatments.

Singh et al., (2006) suggested that the Si levels that influence N uptake by grain and straw up to the highest level might be due to the synergistic effect of silicon with other nutrients. It has been demonstrated that Si improves plant performance overall in situations with low, ideal, and excessive N supplies. There have been reports of Si having a mitigating effect on a variety of crops when P is limited. Although many studies have reported that Si can affect K concentration under stress conditions such as salinity, drought, or N excess, the interaction of Si with potassium (K) in plants has not been as thoroughly studied as that with N and P (Pavlovic et al., 2021). The current study shows that, in the case of an ideal supply of the macronutrients (N, P, and K), there is a clear tendency for an increase in Si uptake to also increase N, P, and K uptake. The rice panicle formation is a vegetative ending process, therefore more N accumulates in the leaves at the reproductive stage (Patti et al., 2013) while the largest P capacity is kept in vegetative tissue at the reproductive stage before being remobilized to panicle during grain filling (Julia et al., 2016). It shows that the rice plant required sufficient nutrients at an early stage to increase the rice grain yield. This agrees with the current work that, the highest rice grain yield was achieved by early application of Si 25 days after planting with a single application. K deficiency is always associated with lower cell-membrane resistance, increasing the risks of pest and disease attacks (Sardans and Peñuelas, 2021). K provides strength to plant cell walls and is involved in the lignification of sclerenchyma tissues (Dobermann and Fairhurst, 2000). In rice, an increase in K fertilisation significantly improved rice blast resistance by strengthening rice panicles' cell walls to prevent the fungus from penetrating the plant tissue (NurulNahar et al., 2023c). In wheat, an increase in Si content in the root and stem increased the K content in the reproductive parts, which shows a synergistic effect (Mukhomorov and Anikina, 2011). In this study, the application of Si increased the uptake of K in rice plants. Therefore, the application of Si could also contribute to rice grain yield production. In addition, the mechanical strength and stability of the rice cell wall might be enhanced, thereby increasing resistance to BPH infestation. The increase in these nutrient uptakes could be due to the nutritional status of the soil, and Si supply affects the expression of transporter genes in certain ways to increase root absorption.

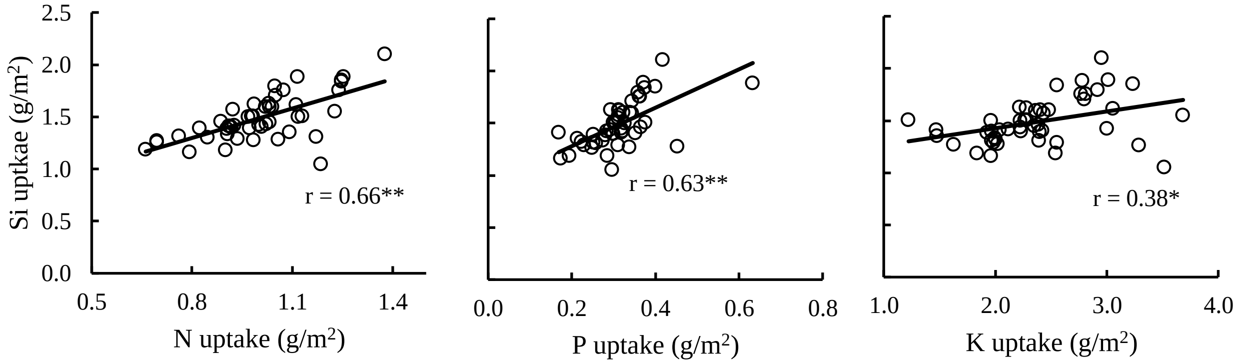

Figure 4: Correlation between silicon uptake with nitrogen, phosphorus and potassium uptake in above ground rice plant

Agronomic efficiency (AE) is the kg unit of crop yield increase per kg of nutrient applied (Roberts, 2008). In Figure 5, the highest AE was recorded in T3. This implies that for every increase of one unit of Si, the grain yield increased by 4.25 kg. The lowest AE, which was in T8, could explain the reason the grain yield was the lowest, which was also comparable to the control. However, there was no significant difference between these treatments, but the present study could indicate that the three-split application of Si at 7 DAT, 25 DAT, and 45 DAT could not be used better by the rice plants compared to single and twice-split applications. Higher-rate of fertiliser application trials with relatively high soil fertility typically produced lower AE values, whereas optimal nutrient management practices typically produced higher AE values (Chuan et al., 2016). The variability of AE depends on climatic conditions and management practices, and most of the time, low AE indicates that higher nutrient losses occur under higher fertiliser rate applications (Li et al., 2023).

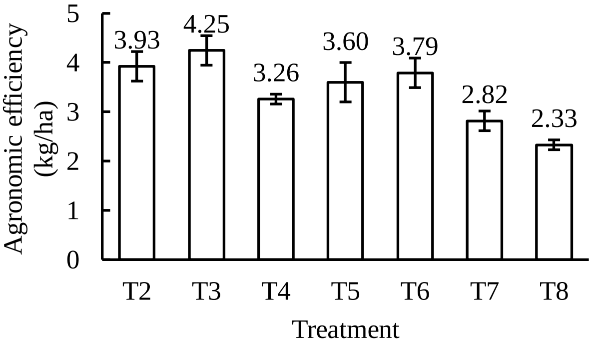

Figure 5: Si fertiliser agronomic efficiency under different splits at the amount of 200 kg/ha of each treatment

Silicon fertilisation has the potential to replace the extensive use of NPK fertilisers in order to maintain sustainable agriculture (Guntzer et al., 2012). Although Si is not an essential element for plant growth, extensive research has identified it as a valuable fertiliser in crop production because it promotes the healthy growth and development of various crops and plays an important role in plant resistance to biotic and abiotic stresses by promoting several plant physiological processes. Silicon fertilisation can help reduce the use of pesticides and fungicides (Kovács et al., 2022). The increased use of chemical fertilisers and pesticides degrades the environment and ecosystems, reduces biodiversity, and poses public health risks, ultimately leading to massive economic losses and sustainability crises (Tayade et al., 2022). The use of Si is a step towards overcoming the problems and challenges that farmers face in the rice cultivation industry. Its use can reduce pesticide dependence while also indirectly minimising the risk of soil nutrient degradation and environmental pollution. Next, the use of Si can reduce pesticide costs while maintaining rice quality and production.

4. CONCLUSION

An optimal Si rate of 200 kg/ha at various splits was studied for BPH infestation in natural conditions as well as its effect on rice yield components. Application at a two-equal split of 100 kg Si/ha at 7 and 45 days after transplanting (DAT) significantly controlled the BPH infestation by an average of 59.2% in off-season 2022. Under natural conditions of very low BPH populations, the effect of Si was not observed in main-season 2023. Although it could increase resistance to BPH attack, the fertilisation time was not seen to give maximum rice yield. The maximum grain yield was achieved with 200 kg Si/ha applied once at 25 days after transplanting. The agronomic efficiency of these two methods was 3.79 kg/ha and 4.25 kg/ha, respectively. This explains why early vegetative and late reproductive applications of Si are beneficial for BPH control; however, a single application at the maximum tillering (25 DAT) stage appears to be critical for maximising grain yield. As a result, determining the optimal timing for Si application for pest and disease control and/or increasing rice grain yield is critical. The application of Si effectively increased the uptake of N, P, and K in rice plants. An increase in these macronutrients in rice plants might be the reason why rice plants effectively hindered the BPH infestation and also provided greater nutrients for sustaining the rice grain yield. Silicon fertilisation promotes the healthy growth and development of rice plants and plays an important role in plant resistance to BPH infestation. Chemical pesticides have a negative impact on the environment and ecosystems, as well as public health. The use of Si is a step towards overcoming the challenges that farmers face in the rice cultivation industry. Its use can reduce pesticide dependence while also indirectly minimising the risk of soil nutrient degradation and environmental pollution. Overall, the application during the early vegetative (7 DAT) and reproductive (45 DAT) stages sheds light on how Si application influences rice plants' defence mechanisms against brown planthoppers but sacrifices the grain yield.

References

AB Ghaffar, M. B., Pritchard, J., Ford-Lloyd, B., (2011). Brown planthopper (*N. lugens* stal) feeding behaviour on rice germplasm as an indicator of resistance. PLoS ONE., 6 (7):E22137

Ali, N., Réthoré, E., Yvin, J. C., Hosseini, S. A., (2020). The regulatory role of silicon in mitigating plant nutritional stresses. Plants., 9(12), 1779.

Bindraban, P. S., Dimkpa, C., Nagarajan, L., Roy, A., Rabbinge, R., (2015). Revisiting fertilisers and fertilisation strategies for improved nutrient uptake by plants. Biology and Fertility of Soils., 51, 897–911.

Borrell, A. K., Garside, A. L., Fukai, S., Reid, D. J., (1999). Grain quality of flooded rice is affected by season, nitrogen rate, and plant type. Australian Journal of Agricultural Research., 50, 1399–1408.

Chuan, L., He, P., Zhao, T., Zheng, H., Xu, X., (2016). Agronomic characteristics related to grain yield and nutrient use efficiency for wheat production in China. PLoS ONE., 11 (9), e0162802.

da Silva, A. P. R., da Silva, L. J. R., Deus, A. C. F., Fernandes, D. M., Büll, L. T., (2023). Silicon application methods influence the nutrient uptake of maize plants in tropical soil. Silicon., 15 (17), 7327–7334.

Dobermann, A., Fairhurst, T., (2000). *Rice: Nutrient Disorders & Nutrient Management. Hanbook Series.* (1st ed.) Potash & Phosphate Institute (PPI), Potash & Phosphate Institute of Canada (PPIC) and International Rice Research Institute (IRRI).

Dorairaj, D., Govender, N. T., (2023). Rice and paddy industry in Malaysia: governance and policies, research trends, technology adoption and resilience. Frontiers in Sustainable Food Systems., 7 (1093605).

Golla, B., (2021). Nitrogen response and agronomic use efficiency of N fertilizer in diverse commercial maize hybrids at Bako, Western Ethiopia. International Journal of Agriculture Science and Food Technology., 7 (2), 245–248.

Greger, M., Landberg, T., Vaculík, M., (2018). Silicon influences soil availability and accumulation of mineral nutrients in various plant species. Plants (Basel). 7(2) : 41.

Guntzer, F., Keller, C., Meunier, J. D., (2012). Benefits of plant silicon for crops: A review. Agronomy for Sustainable Development., 32 (1), 201–213.

Horgan, F. G., de Freitas, T. F. S., Crisol-Martínez, E., Mundaca, E. A., Bernal, C. C., (2021). Nitrogenous fertilizer reduces resistance but enhances tolerance to the brown planthopper in fast-growing, moderately resistant rice. Insects., 12(11), 989.

Horgan, F. G., Peñalver Cruz, A., Bernal, C. C., Ramal, A. F., Almazan, M. L. P., Wilby, A., (2018). Resistance and tolerance to the brown planthopper, *Nilaparvata lugens* (Stål), in rice infested at different growth stages across a gradient of nitrogen applications. Field Crops Research., 217, 53–65.

Hussain, S., Hussain, M. B., Gulzar, A., Zafar-ul-Hye, M., Aon, M., Qaswar, M., Yaseen, R., (2017). Right time of phosphorus and zinc application to maize depends on nutrient–nutrient and nutrient–inoculum interactions. Soil Science and Plant Nutrition., 63 (4), 351–356.

Julia, C., Wissuwa, M., Kretzschmar, T., Jeong, K., Rose, T., (2016). Phosphorus uptake, partitioning and redistribution during grain filling in rice. Annals of Botany., 118, 1151–1162.

Kovács, S., Kutasy, E., Csajbók, J., (2022). The multiple role of silicon nutrition in alleviating environmental stresses in sustainable crop production. Plants., 11(9), 1223.

Li, B., Ma, X., Zhao, B., Wang, L., Ata-Ul-Karim, S. T., (2023). In-season assessment of agronomic nitrogen use efficiency and its components in winter wheat using critical nitrogen dilution curve. Frontiers in Plant Science., 14, 1128799.

Lisuma, J. B., Semoka, J. M., Mbwambo, A. F., (2023). Effect of timing fertilizer application on leaf yield and quality of tobacco. Heliyon., 9, e19670.

Liu, K., Zhang, K., Zhang, Y., Cui, J., Li, Z., Huang, J., Li, S., Zhang, J., Deng, S., Zhang, Y., Huang, J., Ren, L., Chu, Y., Zhao, H., (2024). Optimizing the total spikelets increased grain yield in rice. Agronomy., 14(1), 152.

Mai, W., Abliz, B., Xue, X., (2021). Increased number of spikelets per panicle is the main factor in higher yield of transplanted vs. direct-seeded rice. Agronomy., 11(12), 2479.

Maisarah, M. S., NurulNahar, E., Mohd Fitri, M., Siti Norsuha, M., (2022). Kombinasi nutrien seimbang yang dapat merencat pertumbuhan populasi benah perang. Kelestarian Padi Dan Beras Untuk Kemakmuran Bersama., 136.

Mohammad Aufa, M. B., Mohd Fitri, M., S., N. A. A., Arina, M. N., Nurul Syakira, S., Badril Hisham, A. B., Mohd Khusairy, K., (2022). Evaluation of light trap system in monitoring of rice pests,brown planthopper (*Nilaparvata lugens*). Advances in Agricultural and Food Research Journal., 3 (1), a0000187.

Mohapatra, P. K., Panigrahi, R., Turner, N. C., (2011). Physiology of Spikelet Development on the Rice Panicle: Is Manipulation of Apical Dominance Crucial for Grain Yield Improvement? In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 110, pp. 333–359) Academic Press.

Momesso, L., Crusciol, C. A. C., Cantarella, H., Tanaka, K. S., Kowalchuk, G. A., Kuramae, E. E., (2022). Optimizing cover crop and fertilizer timing for high maize yield and nitrogen cycle control. Geoderma., 405 (115423).

Mukhomorov, V., Anikina, L., (2011). Interrelation of chemical elements content in plants under conditions of primary soil formation. Open Journal of Soil Science., 01 (01), 1–7.

Nand, M. M., Singh, S. P., Kishor, K., Kumar, A., Alam, M. M., Kumar, V., (2020). Impact of split application of potassium on inbred and hybrid rice yield and its attributes in calcareous Soil. International Journal of Current Microbiology and Applied Sciences., 9 (3), 3279–3286.

Negash, H., Wondimu, W., Abraham, A., Belay, Z., (2021). Maize yield improvement by optimal rate and timing of nitrogen fertilizer application in Southwest Ethiopia. AGBIR., 37 (3), 127–138.

NurulNahar, E., Shajarutulwardah, M. Y., Hartinee, A., (2023a). Improving rice grain yield in KADA by site-specific nutrient management. Journal of Tropical Agriculture and Food Science., 51 (1), 7–14.

NurulNahar, E., Shajarutulwardah, M. Y., Hartinee, A., (2023b). Increasing rice grain yield by split application of nitrogen rates. Journal of Agricultural and Food Science., 51 (1), 21–28.

NurulNahar, E., Siti Norsuha, M., Maisarah, M. S., Mohd Fitri, M., (2023c). Nitrogen, potassium, and silicon fertilization to achieve lower panicle blast severity and improve yield components of rice using response surface methodology. Jurnal Teknologi., 85 (5), 81–91.

Patti, P. S., Kaya, E., Silahooy, C., (2013). Analisis status nitrogen tanah dalam kaitannya dengan serapan N oleh tanaman padi sawah di desa Waimital, Kecamatan Kairatu, Kabupaten Seram bagian barat. Agrologia., 2 (1), 51–58.

Pavlovic, J., Kostic, L., Bosnic, P., Kirkby, E. A., Nikolic, M., (2021). Interactions of silicon with essential and beneficial elements in plants. Frontiers in Plant Science., 12 (697592).

Rashid, M. M., Ahmed, N., Jahan, M., Islam, K. S., Nansen, C., Willers, J. L., Ali, M. P., (2017). Higher fertilizer inputs increase fitness traits of brown planthopper in rice. Scientific Reports., 7 (4719).

Rashid, M. M., Jahan, M., Islam, K. S., (2016). Impact of nitrogen, phosphorus and potassium on brown planthopper and tolerance of its host rice plants. Rice Science., 23 (3), 119–131.

Roberts, T. L., (2008). Improving nutrient use efficiency. Turkish Journal of Agriculture and Forestry., 32, 177–182.

Romadhon, S., Koesmaryono, Y., Hidayati, R., (2017). Influence of climate variability on brown planthopper population dynamics and development time. Earth Adn Environmental Science., 58 (012042).

Sardans, J., Peñuelas, J., (2021). Potassium control of plant functions : Ecological and agricultural implications. Plants., 10 (419).

Saw, G., Nagdev, P., Jeer, M., Murali-Baskaran, R. K., (2023). Silica Nanoparticles Mediated Insect Pest Management. Pesticide Biochemistry and Physiology., 194 (105524).

Sembiring, J., Mendes, J. A., (2023). Population density of brown planthoppers (Nilaparvata Lugens Stall) and green planthoppers (*Nephotettix Virescens*) in rice varieties in Merauke, South Papua province. International Journal of Life Science and Agriculture Research., 2 (5), 89–94.

Sharma, H. C., Prabhakar, C. S., (2014). Impact of Climate Change on Agriculture and Food Security. In D. P. Abrol (Ed.), *Integrated Pest Management* (pp. 24–40) Academic Press.

Shi, S., Wang, H., Nie, L., Tan, D., Zhou, C., Zhang, Q., Li, Y., Du, B., Guo, J., Huang, J., Wu, D., Zheng, X., Guan, W., Shan, J., Zhu, L., Chen, R., Xue, L., Walling, L. L., He, G., (2021). Bph30 confers resistance to brown planthopper by fortifying sclerenchyma in rice leaf sheaths. Molecular Plant., 14, 1714–1732.

Shrestha, J., Karki, T. B., Hossain, M. A., (2022). Application of nitrogenous fertilizer in rice production: A review. Journal of Nepal Agricultural Research Council., 8, 16–26.

Silva, A. L. B. R. da, Zotarelli, L., Dukes, M. D., van Santen, E., Asseng, S., (2023). Nitrogen fertilizer rate and timing of application for potato under different irrigation methods. Agricultural Water Management., 283 (108312).

Singh, K. K., Singh, K., Singh, R., Singh, Y., Singh, C. S., (2006). Response of nitrogen and silicon levels on growth , yield and nutrient uptake of rice (*Oryza sativa* L.). Crop Production., 43 (3), 220–223.

Skawsang, S., Nagai, M., Tripathi, N. K., Soni, P., (2019). Predicting rice pest population occurrence with satellite-derived crop phenology, ground meteorological observation, and machine learning: A case study for the Central Plain of Thailand. Applied Sciences., 9 (4846).

Sogawa, K., Cheng, C. H., (1979). Economic thresholds, nature of damage, and losses caused by the brown planthopper. In *Brown planthopper: Threat to rice production in Asia* (p. 125) International Potash Institute.

Stout, M. J., (2014). Host-Plant Resistance in Pest Management. In D. P. Abrol (Ed.), *Integrated Pest Management* (pp. 1–21) Academic Press.

Swe, M. M., Mar, S. S., Naing, T. T., Zar, T., Ngwe, K., (2021). Effect of silicon application on growth, yield and uptake of rice (*Oryza sativa* L.) in two different soils. Open Access Library Journal., 8 (e7937).

Syamsulhadi, M., Taufiqurrahman, A. F., Rahardjo, B. T., (2023). Induced resistance of rice plants to brown planthoppers (*Nilaparvata lugens* Stal.) through the application of compost. Plantropica Journal of Agricultural Science., 8 (2), 181–188.

Tadesse, T., Assefa, A., Liben, M., Tadesse, Z., (2013). The effect of nitrogen fertilizer split application on the nitrogen use efficiency , grain yield and economic benefit of maize production. International Journal of Agriculture Policy and Research., 1 (4), 109–115.

Tayade, R., Ghimire, A., Khan, W., Lay, L., Attipoe, J. Q., Kim, Y., (2022). Silicon as a smart fertilizer for sustainability and crop improvement. Biomolecules., 12 (1027).

Teng, Z., Chen, Y., Meng, S., Duan, M., Zhang, J., Ye, N., (2023). Environmental stimuli: A major challenge during grain filling in cereals. International Journal of Molecular Sciences., 24 (2255).

Tenguri, P., Chander, S., Ellur, R. K., Yele, Y., Sundram, P. A., Nagaraju, M. T., Subramanian, S., Suroshe, S. S., (2023). Effect of silicon application to the rice plants on feeding behaviour of the brown planthopper, *Nilaparvata lugens* (Stål) under elevated CO2. Silicon., 15, 5811–5820.

van den Berg, B., Pedebos, C., Bolla, J. R., Robinson, C. V., Baslé, A., Khalid, S., (2021). Structural basis for silicic acid uptake by higher plants. Journal of Molecular Biology., 433 (21), 167226.

van Duijnen, R., Uther, H., Härdtle, W., Temperton, V. M., Kumar, A., (2021). Timing matters: Distinct effects of nitrogen and phosphorus fertilizer application timing on root system architecture responses. Plant-Environment Interactions., 2, 194–205.

Vun Teong, K., Sukarno, K., Hian Wui Chang, J., Pien Chee, F., Mun Ho, C., Dayou, J., (2017). The monsoon effect on rainfall and solar radiation in Kota Kinabalu. Transactions on Science and Technology., 4 (4), 460–465.

Win, S. S., Muhamad, R., Ahmad, Z. A. M., Adam, N. A., (2011). Population fluctuations of brown plant hopper Nilaparvata lugens stal. and white backed plant hopper *Sogatella furcifera* Horvath on rice. Journal of Entomology., 8 (2), 183–190.

Wu, X., Yu, Y., Baerson, S. R., Song, Y., Liang, G., Ding, C., Niu, J., Pan, Z., Zeng, R., (2017). Interactions between nitrogen and silicon in rice and their effects on resistance toward the brown planthopper Nilaparvata lugens. Frontiers in Plant Science, 8, 28.

Yamburenko, M. V., Kieber, J. J., Schaller, G. E., (2017). Dynamic patterns of expression for genes regulating cytokinin metabolism and signaling during rice inflorescence development. PLoS ONE., 12 (4), 1–18.

Yang, L., Han, Y., Li, P., Wen, L., Hou, M., (2017). Silicon amendment to rice plants impairs sucking behaviors and population growth in the phloem feeder *Nilaparvata lugens* (Hemiptera: Delphacidae). Scientific Reports., 7 (1101), 1–7.

Yoshida, S., (1981). Fundamentals Of Rice Crop Science. In *Plant Production Science* International Rice Research Institute, 269.

Zhou, W., Lv, T., Yang, Z., Wang, T., Fu, Y., Chen, Y., Hu, B., Ren, W., (2017). Morphophysiological mechanism of rice yield increase in response to optimized nitrogen management. Scientific Reports., 7 (17226).