INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
ISSN Print: 1560–8530; ISSN Online: 1814–9596
17–0755/2018/20–3–669–675
DOI: 10.17957/IJAB/15.0543
http://www.fspublishers.org

***Full Length Article***

# Silicon Nutrition and Distribution in Plants of Different Thai Rice Varieties

**Nanthana Chaiwong[1], Sittichai Lordkaew[2], Narit Yimyam[3], Benjavan Rerkasem[4] and Chanakan Prom-u-thai[1*]**
[1]*Department of Plant and Soil Sciences, Faculty of Agriculture, Chiang Mai University, Chiang Mai, 50200, Thailand*
[2]*Center for Agricultural Resource Systems Research, Faculty of Agriculture, Chiang Mai University, Thailand 50200*
[3]*Department of Highland Agriculture and Natural Resources, Faculty of Agriculture, Chiang Mai University, Chiang Mai, 50200, Thailand*
[4]*Plant Genetic Resource and Nutrition Laboratory, Chiang Mai University, Chiang Mai, 50200, Thailand*
[*]For correspondence: chanakan15@hotmail.com; chanakan.p@cmu.ac.th

## Abstract

Rice grain yield benefits from silicon (Si) accumulation in sufficient concentration in the plant, but too much Si in the husk and straw can impede their usefulness as biofuel and animal feed. This study consisted of four experiments. The first experiment evaluated genotypic variation in Si distribution in different parts of the rice grain from farmers' fields in northern Thailand, parts of grain to compare tall plant type and semi-dwarf varieties. The result showed that there were significant differences among the rice varieties in Si concentration of their husk and straw, but without clear distinction between the tall and semi-dwarf plant type or between wetland and upland ecotype. The second experiment evaluated Si distribution in different plant parts among 29 Thai rice varieties, and found significant variation in Si concentration among different parts of the rice plant parts, with the husk Si almost twice the straw, and among the rice ecotypes. The third experiment determined the effect of Si fertilizer on Si distribution in a pot experiment on 3 rice varieties with and without of Si application. The fourth experiment evaluated the effect of different growing locations on Si concentration in different plant parts of the 3 rice varieties. These last 2 experiments showed that rice varieties responded differently to Si fertilizer and location in the Si concentration in their husk and straw. Grain yield was significantly correlated with the Si concentration in the husk but not in the straw. The genotype by environment and management interaction effect on Si concentration in the rice husk and straw together with their relationship to grain yield suggested that further investigation of the relationship between husk Si and grain yield. The underlying processes should make Si management for rice production more effective, for the potential energy to be recovered from the husk and straw as well as grain yield. 

**Keywords:** *Oryza sativa*; Rice silicon; Husk silicon; Silicon distribution; Silicon fertilizer

## Introduction

The conditions for a mineral element to be essential for plant growth proposed by Arnon and Stout (1939) were that it must be required for the completion of the life cycle of the plant and directly involved in plant metabolism by having a specific physiological function but not replaceable by another element. Silicon (Si), while not having been shown to meet any of these conditions, accounts for more than half of the minerals that accumulate in the rice plant and is well established in its roles in rice production. Early work at the International Rice Research Institute summarized by Yoshida (1981) found Si to be largely associated with protection against fungi, insects, and mites, and improvement in light interception by the contribution to holding the leaves up at more erect angle and the stem against lodging. Silicon also increases the resistance of rice to abiotic stresses including chemical stresses such as salt and metal toxicity (Ma and Yamaji, 2006; Moussa, 2006). Reports on the efficacy of Si fertilizer in decreasing the incidence and severity of rice leaf diseases have continued to come from wide ranging systems of rice production, from wetland rice in the US (Datnoff *et al*., 1991) and China (Ning *et al*., 2014), to upland rice in Colombia (Seebold *et al*., 2000) and organic rice in Thailand (Wattanapayapkul *et al*., 2011). Grain yield of field grown rice in Japan in a previous study was shown to respond to silicate fertilizer application when the Si in the straw fell below 5.1% (Inaizum and Yoshida, 1958).

In addition to the rice grain, value from the rice crop has been increasing from new usages of the rice husk and straw, which are among the most reliable sources of bioenergy (Lim *et al*., 2012). However, while increasing Si supply may benefit the rice grain yield, too much Si may be detrimental to the quality of the husk and straw. Burning and pyrolysis of the rice husk and straw can be impeded by the Si they contain (Raveendran *et al*., 1995; McKendry, 2002; Bharadwaj *et al*., 2004). High Si content in the rice straw may also have adverse effect on its quality as feed (Van Soest, 2006). Balancing the positive effect of Si on rice grain yield on the one hand and negative effect on value of the husk and straw on the other should benefit from understanding how Si distribution in different parts of the rice plant is influenced by genetics, environment, management and the interactions. The information on these is limited among the rice varieties of major rice producing countries in the tropics such as Thailand. Distribution of Si among different parts of the rice plant is also rarely considered in rice breeding. We therefore hypothesize significant variation may exist among Thailand's commercial and promising new rice varieties in the concentration of Si in their different plant parts, which may also be modified by Si application and where the rice is grown. This paper reports on Si distribution in different rice varieties and the effect of location and Si fertilizer application, following a preliminary survey of Si in farmers' rice grain. Understanding how genotype and environmental condition affect silicon concentration in different parts of the plant belonging to different rice verities will contribute to the management of Si for better grain as well as energy yield through the management of Si fertilizer and rice breeding.

## Materials and Methods

### Preliminary Survey of Silicon in Farmers' Rice (Exp. 1)

Twenty-four samples of unhusked rice from the wet season crop of 2015 were collected from farmers in northern Thailand, where the rice was grown as a wetland crop on sandy loam soil texture with pH 5.0–7.0. These included 10 samples each of a traditional variety with tall plant type KDML105 and a modern semi-dwarf variety PSL2, and 4 samples of SPT1, another modern semi-dwarf variety. The samples were air-dried to moisture content of 14%, 1 kg subsample of each was de-husked in with a laboratory husker (model P-1, Ngek Seng Huat, Thailand). The brown rice (endosperm enclosed in pericarp, with embryo attached) was polished for 30 s in a laboratory milling machine (model K-1, Ngek Seng Huat) to produce white rice (endosperm) and bran (mixture of pericarp, seed coat, aleurone layer and sub-aleurone layer). The weight of brown rice, husk, white rice and bran were determined. Analysis for Si was conducted in triplicates for unhusked grain, brown rice, husk, white rice and bran, and Si concentration of the tissues measured by spectrophotometer at 650 nm after digesting in 50% NaOH by the method of Dai *et al.* (2005).

### Genotypic Variation in Si Distribution of Wetland and Upland Rice

One pot experiment (Exp. 2) determined how Si is distributed among the tissues of 29 rice varieties. Seventeen varieties of the wetland ecotype (RD 6, Hom Nil, Khao Dawk Mali 105 (KDML105), Kum Chao 2, Kum Na, Kum Payao, Kum Doi Saket (KDK), Bue Nermu, Cho Cham Pa, Sang Yod and Hom Mali Daeng), 6 with the modern semi-dwarf (RD 21, Phitsanulok 2 (PSL2), San Pah Tawng 1 (SPT1), Chainat 1 (CNT1), Pathumthani 1 (PTT1) and Suphanburi 1 (SPR1)), and 11 with the traditional, tall plant type (Khao Pong Krai (KPK), Khao Rai Khao chao, Khao Rai Khao Na, Sew Mae Jun, Nam Roo, Pa Ai Go, Asa, Abang, Pi Ei Zu 1, Pi Ei Zu 2, Kum Hom CMU (KH CMU) and Laem Pua) were grown in plastic undrained pots (28 cm in diameter, 30 cm deep) containing a sandy loam soil of Sansai series with pH 6.4. Another 12 varieties of the upland ecotype were grown aerobically in the same soil and similar containers. The pot experiment was arranged in a completely randomized design (CRD) with three replications. One experimental unit consisted of one pot containing 5 plants of each rice variety. Fertilizer was applied in 4 equal doses at planting, tillering, booting and flowering, each pot receiving 135 g N, 59 g P and 112 g K in total. The soil in the pots was kept flooded to 5 cm above the surface for the varieties of wetland ecotype, and watered as needed and allowed to drain for those of the upland ecotype. At maturity plants were harvested for determination of grain and straw dry weight and Si concentration of the grain, straw and husk as in Exp. 1.

### Effects of Silicon Fertilizer and Location

The effect of Si fertilizer on Si distribution was examined in a factorial experiment (Exp. 3) with 3 rice varieties grown with or without Si application, conducted in June to September 2014 at Chiang Mai University. The rice varieties were Suphanburi 1 (SPR1, a wetland rice variety), grown in soil flooded to 3–5 cm of water above the surface and two upland rice varieties of Kum Hom CMU (KHCMU) and Sew Mea Jun were grown under aerobic condition with soil moisture content maintained at field capacity. Silicon was applied as calcium silicate ($Ca_2SiO_4$) at 2 g $kg^{-1}$ soil (Si+) in comparison with no Si application (Si-). One experimental unit consisted of 5 plants of each rice variety, transplanted as 2-week old seedlings into a plastic pot (28 cm in diameter, 30 cm deep) containing 12 kg sandy loam soil of Sansai series with pH 6.4, with or without Si application. The pots were arranged in a completely randomized design (CRD) with three replications. A combined fertilizer (15-15-15, % N, P and K) was applied in 4 equal doses, at 7 days after transplanting, tillering, booting and flowering stage, totaling 0.9 g $pot^{-1}$. Samples were harvested at maturity and separated into stems, leaf sheath, leaf blades, flag leaves and grain. The grain was sun-dried for 2-3 days to reach 14% moisture content. The vegetative plant parts, paddy rice, brown rice and husk were oven-dried at 70˚C for 72 h and ground for Si analysis (Dai *et al.,* 2005).

In the field experiment (Exp. 4), 3 of Thailand's mega rice varieties (KDML105, CNT1 and PTT1) were grown as wetland rice on the sandy loam soil of Sansai series at 2 locations (Chiang Mai University main campus and Mae Hia Research Station, designated CMU and Mae Hia) in a completely randomized block design with 3 replicates. Seedlings were raised in seedbeds and transplanted into the field after one month at 0.25 x 0.25 m spacing. Basal fertilizer applied included 60 kg N $ha^{-1}$ and 20 kg P $ha^{-1}$ at planting and 60 kg N $ha^{-1}$ at panicle initiation. The field was kept flooded to approximately 10 cm above the soil surface until 2 weeks before harvest. At maturity grain and dry matter yield were determined on 1 $m^2$ internal quadrats. Plants from additional 3 hills were harvested for determination of dry weight and Si contents of seven separate parts of the rice plant at maturity, namely, leaves, leaf sheath, stem, peduncle + rachis, brown rice and husk. Separation of husk and brown rice and Si analysis were done as described in the study of farmers' rice samples.

### Statistical Analysis

Statistical analysis of all the data was performed by using the Statistic 9 (analytical software SX). Analysis of variance (ANOVA) was used to detect difference among treatments and least significant difference (LSD) at $P < 0.05$ was used to compare means. Significance of the correlation coefficient was analyzed by linear regression.

## Results

### Partitioning of Dry Weight and Silicon in Farmers' Rice Grain (Exp. 1)

The three common rice varieties grown by farmers in northern Thailand varied significantly in the partitioning of dry weight and the Si concentration in different parts of the rice grain (Table 1). One kg dry weight of unhusked rice was comprised of 0.26 kg to 0.30 kg of husk and 0.70 to 0.74 kg of brown rice, which was milled into 0.59 to 0.64 kg of white rice and 0.08 kg to 0.11 kg of bran. The Si concentration of the unhusked rice, at 1.81% to 2.01%, did not differ significantly among the varieties. However, the rice varieties were differentiated in the husk Si, being lowest in KDML105 at 6.96%, followed by SPT1 at 7.52% and PSL2 at 7.81%. There were also significant differences among the varieties in the Si concentration of the brown rice, white rice and bran, although the Si concentration in these parts of the rice grain were extremely low compared with the husk, which accounted for 98–99% of the 17–20 g of Si in one kg of the unhusked rice grain.

### Silicon Distribution in Different Wetland and Upland Rice Varieties (Exp. 2)

Significant variation was found among the 29 rice varieties in the Si concentration and partitioning in different parts of the plant and grain, and the harvest indices in dry matter and Si (Table 2). Variation in the Si concentration was associated with individual varieties and not with the grouping by ecotype or plant type. The varieties belonging to the wetland and upland ecotypes were not distinguishable by the Si concentration of their seed, straw, brown rice and husk, neither were those with semi-dwarf and tall plant type.Compared with the straw and husk, there was very little Si in the brown rice. The semi-dwarf varieties accumulated more Si in the seed than the tall varieties, but less in the straw. This was in agreement with the higher harvest indices in both dry matter and Si in the semi-dwarf varieties. The relative concentration among the plant parts followed the same order in all varieties, with very little Si in brown rice, and the highest concentration of Si in the husk, which averaged 1.8 times that of the straw. The straw and husk Si concentration were only weakly related (r = 0.35, $NS_{0.05}$).

### Effects of Environment and Management (Exp. 3, 4)

Grain yield and the straw Si concentration of all 3 rice varieties, wetland grown wetland variety SPR1 as well as aerobically grown upland varieties KHCMU and Sew Mae Jun were increased by Si application, and so were the husk Si concentration in SPR1 and Sew Mae Jun but not in the variety KHCMU (Fig. 1). Grain yield correlated significantly with the Si concentration in the husk (r = 0.62, $P < 0.01$), but not in the straw (r = 0.11, $NS_{0.05}$) (Table 3). The straw Si concentration was closely correlated with the Si in its components, i.e., the leaves, flag leaf and stem. The husk Si was also correlated with the straw Si, although there was much weaker correlation between the husk Si and the Si concentration of individual components of the straw. The Si application increased the Si concentration most strongly in the leaf sheath (by 30–40%), and to smaller extent in the stem (by 10–20%) of all three rice the varieties, and also in the leaves of SPR1 and KHCMU, but much less in the leaves of Sew Mae Jun which accumulated more Si in the flag leaf with Si application (Fig. 2). Location had significantly different effect on the grain yield and grain Si content of different rice varieties, but not on the yield and Si content of the straw (Fig. 3). While location had no effect on the grain yield and grain Si content of KDML105 and PTT1, the lower grain yield and grain Si content were produced by the variety CNT1 at Mae Hia station. Much larger proportion of Si was found in the straw of KDML105 with traditional, tall plant type than in the modern, semi-dwarf varieties CNT1 and PTT1. Location had different effect on Si concentration in different parts of the plant in different varieties (Fig. 4). Location effect on the Si concentration was significant in KDML105 for the husk and in CNT1 for the straw and husk, but not significant in PTT1 for the straw, grain and husk. The rice varieties also differed in their response to location in the concentration of Si in the vegetative tissues (Table 4).

**Table 1:** Distribution of dry matter, silicon concentration and silicon content in different parts of the grain in 3 rice varieties from farmer's fields in northern Thailand (Exp. 1)

| Variety | KDML105 (n=10) | | PSL2 (n=10) | | SPT1 (n=4) | | Variety effect† |
|---|---|---|---|---|---|---|---|
| (a) Dry weight (kg in 1 kg dry weight of unhusked rice) | | | | | | | |
| Husk | 0.28 | ab | 0.26 | a | 0.30 | b | $P$< 0.01 |
| Brown rice | 0.72 | ab | 0.74 | b | 0.70 | a | $P$< 0.01 |
| White rice | 0.64 | b | 0.63 | b | 0.59 | a | $P$< 0.01 |
| Bran | 0.08 | a | 0.11 | b | 0.11 | b | $P$< 0.01 |
| (b) Silicon concentration (% dry weight) | | | | | | | |
| Unhusk rice | 1.81 | | 2.01 | | 1.90 | | $NS_{0.05}$ |
| Husk | 6.96 | a | 7.81 | b | 7.52 | ab | $P$< 0.001 |
| Brown rice | 0.06 | b | 0.04 | a | 0.04 | a | $P$< 0.001 |
| White rice | 0.04 | b | 0.03 | a | 0.03 | a | $P$< 0.001 |
| Bran | 0.12 | b | 0.09 | a | 0.08 | a | $P$< 0.001 |
| (c) Silicon content (g Si in 1 kg dry weight of rice) | | | | | | | |
| Unhusk rice | 16.98 | | 17.32 | | 19.56 | | $NS_{0.05}$ |
| Husk | 16.63 | | 17.05 | | 19.33 | | $NS_{0.05}$ |
| Brown rice | 0.35 | c | 0.27 | b | 0.22 | a | $P$< 0.001 |
| White rice | 0.20 | | 0.14 | | 0.14 | | $NS_{0.05}$ |
| Bran | 0.08 | | 0.08 | | 0.08 | | $NS_{0.05}$ |

†By analysis of variance; difference between varieties within row by $LSD_{0.05}$ indicated by different letters

**Table 2:** Variation of silicon concentration and content in different parts of the plant and seed, and harvest indices in dry matter and silicon of rice varieties belonging to wetland ecotype with semi-dwarf and tall plant type and of upland ecotype with tall plant type (Exp. 2)

| Ecotype/cultivation | Wetland/wetland | | | | Upland/aerobic | | Variety effect† |
|---|---|---|---|---|---|---|---|
| Plant type | Semi-dwarf (n=6)† | | Tall (n=11) | | Tall (n = 12) | | |
| | Silicon concentration (% dry weight ±SE§) | | | | | | |
| Straw | 3.75 | ±0.21 | 3.72 | ±0.28 | 4.03 | ±0.21 | $P$< 0.05 |
| Seed | 1.81 | ±0.36 | 1.66 | ±0.17 | 1.42 | ±0.17 | $P$< 0.05 |
| Husk | 7.14 | ±0.34 | 6.81 | ±0.54 | 6.51 | ±0.66 | $P$< 0.05 |
| Brown rice | 0.10 | ±0.01 | 0.06 | ±0.02 | 0.06 | ±0.02 | $P$< 0.05 |
| | Silicon content (g pot$^{-1}$) ±SE§ | | | | | | |
| Straw | 0.99 | ±0.06 | 1.32 | ±0.14 | 1.19 | ±0.13 | $P$< 0.001 |
| Seed | 0.36 | ±0.09 | 0.28 | ±0.03 | 0.21 | ±0.03 | $P$< 0.001 |
| | Harvest index ±SE§ | | | | | | |
| Dry weight | 0.41 | ±0.03 | 0.35 | ±0.03 | 0.32 | ±0.02 | $P$< 0.001 |
| Silicon | 0.23 | ±0.02 | 0.19 | ±0.05 | 0.15 | ±0.02 | $P$< 0.001 |

† By analysis of variance; ‡ number of entries in each group; § standard error for group means

**Table 3:** Correlation between grain and dry matter yield and silicon concentration and among the silicon concentration in different plant parts (Exp. 3)

| Variables | Silicon concentration | |
|---|---|---|
| | Straw | Husk |
| | Correlation coefficient (r)† | |
| Yield | | |
| Grain | $0.11^{NS}$ | 0.62** |
| Total dry matter | $-0.23^{NS}$ | $0.36^{NS}$ |
| Silicon concentration | | |
| Leaves | 0.91*** | $0.34^{NS}$ |
| Flag leaf | 0.77*** | $0.34^{NS}$ |
| Leaf sheath | 0.94*** | $0.44^{NS}$ |
| Stem | 0.60*** | $0.43^{NS}$ |
| Husk | 0.51** | |

† With significance of linear regression by F-test: * $P$ < 0.05; ** $P$ < 0.01; *** $P$ < 0.001; NS not significant at $P$ < 0.05

Location effect was significant for Si concentration in the peduncle + rachis, stem, leaves and leaf sheath of CNT1, in the peduncle + rachis, leaves and leaf sheath of KDML105, but only in the peduncle + rachis and the stem of PTT1. Differentiation in the Si concentration among the different tissues was similar among the 3 rice varieties at both locations. The lowest concentration of Si was in brown rice and highest in the husk, followed by the peduncle + rachis, the stem, and highest in the leaves and leaf sheath.

## Discussion

The genotypic variation in husk Si concentration found in farmers' rice survey was confirmed in subsequent experiments with more rice varieties, which also varied significantly in Si concentration in the straw and in the different vegetative parts making up the straw. It is well established that the husk Si concentration is highest among the various parts of the rice plant (Yosahida *et al*., 1962). However, the significant effect of variety x Si application on straw Si ($P$< 0.05) and husk Si ($P$< 0.01) (Exp. 3) and the effect on Si concentration of variety x location x plant part ($P$< 0.001) (Exp. 4), suggest a level of variation in distribution of Si among rice varieties that would be crucial for Si management for grain and energy yield. While the biological function that would satisfy the requirement for Si to be described as an essential element for plants (Arnon and Stout, 1939) is as yet to be definitively proved, the beneficial effects of Si in preventing yield loss by enhancing resistance of biotic and abiotic stresses in rice are well recognized (Epstein, 1999; Ma, 2004; Ma and Yamaji, 2006). The 17–20 g of Si in one kg of unhusked grain from farmers' rice (Exp. 1) illustrated the potential value of Si in the rice harvest that can be recovered with advanced usages of the rice husk Si, e.g. in vulcanization process of natural rubber (Sae-Oui *et al*., 2002), additive to enhance strength and permeability of concrete (Ganesan *et al*., 2008). However, too high Si concentration may hamper energy recovery from the rice husk and straw as biofuel (Raveendran *et al*., 1995; McKendry, 2002; Bharadwaj *et al*., 2004) or animal feed (Van Soest, 2006).

Based on the critical husk Si concentration defined in South America for deficiency at < 3%, marginal at 3–6%, and sufficiency at > 6% (Winslow *et al*., 1997), sufficiency was indicated by the husk Si in the farmers' rice from northern Thailand. The often quoted critical straw Si value of 5% dry weight (11% $SiO_2$) (e.g., Reuter *et al*., 1997; Koyama, 2014), below which responses to Si fertilizer can be expected, came from an early work in Japan (Imaizumi and Yoshida, 1958 cited by Yoshida, 1981). Extensive field trials have led to a suggestion that yield responses to Si fertilizer in japonica rice could be expected in Japan and Korea with straw Si at < 6% in Japan and Korea and < 5% in Taiwan (Lian, 1976).

**Table 4:** Variation in silicon concentration in different plant parts of 3 rice varieties grown at two locations (Exp. 4)

| Location/Variety | Leaves | | Leaf sheath | | Stem | | Peduncle + rachis | | Husk | | Brown rice | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Silicon concentration (% dry weight) | | | | | | | | | | | |
| CMU | | | | | | | | | | | | |
| KDML105 | 6.54 | dBC | 6.11 | dB | 2.45 | cA | 1.62 | bA | 6.79 | dA | 0.02 | aA |
| CNT1 | 5.41 | dA | 5.51 | dA | 2.31 | cA | 1.53 | bA | 7.55 | eB | 0.01 | aA |
| PTT1 | 6.23 | dB | 6.25 | dB | 2.25 | cA | 1.91 | bB | 6.32 | dA | 0.07 | aA |
| Mae Hia | | | | | | | | | | | | |
| KDML105 | 5.45 | dA | 5.36 | dA | 2.37 | bA | 1.96 | bB | 6.66 | eA | 0.04 | aA |
| CNT1 | 6.84 | dC | 6.93 | dC | 3.21 | cB | 2.38 | bC | 9.85 | eC | 0.05 | aA |
| PTT1 | 6.41 | dBC | 6.41 | dBC | 3.23 | cB | 2.32 | bC | 7.90 | eB | 0.02 | aA |
| Mean | 6.15±0.59 | | 6.10±0.58 | | 2.64±0.46 | | 1.95±0.35 | | 7.51±1.29 | | 0.04±0.02 | |

Significant effects by analysis of variance, after $\log_{10}(X+1)$ transformation

Plant part (P), $P< 0.001$ Variety (V), NS ($P< 0.05$) Location (L), $P< 0.01$

P x V, $P< 0.001$ P x L, $P< 0.01$ L x V, $P< 0.001$ P x V x L, $P< 0.01$

Significant difference by $LSD_{0.05}$ within row indicated by different lowercase letters, within column by uppercase letters

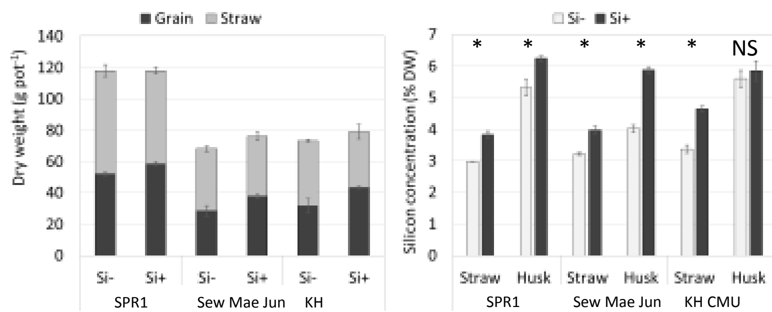


**Fig. 1:** Grain and straw KH CMU of 3 rice varieties with (+Si) and without (-Si) silicon application (left) and the silicon concentration in their straw and husk, with significant effect of silicon on each plant part and variety indicated by * above each pair of bars, NS not significant at $P< 0.05$ (right). (Exp. 3)

| Significant effects by analysis of variance | Dry weight | | Silicon concentration | |
|---|---|---|---|---|
| | Grain | Straw | Straw | Husk |
| Variety (V) | $P< 0.001$ | $P< 0.001$ | $P< 0.001$ | $P< 0.001$ |
| Silicon (Si) | $P< 0.001$ | NS ($P< 0.05$) | $P< 0.001$ | $P< 0.001$ |
| V x Si | NS ($P< 0.05$) | NS ($P< 0.05$) | $P< 0.05$ | $P< 0.01$ |

A claim that indica rice may respond to Si with lower Si concentration in the straw was based on work in India and Sri Lanka that showed responses to Si fertilizer when the straw Si was lower than 4.7% (Savant *et al*., 1997).

Three rice varieties in the present study with straw Si at 2.98–3.37% and husk Si at 4.03–5.60% when grown without Si application (Exp. 4) were apparently deficient in Si, as Si application significantly increased both their straw Si to 3.83–4.65% and husk Si to 5.85–6.25% as well as the grain yield. In the present study significant positive correlation was found between grain yield and the husk Si, but not with the straw Si. Low husk Si has been reported to be associated with depression in grain filling and thus grain yield, in a study comparing a rice mutant with defective Si uptake and a wild type (Tamai and Ma, 2008). This reported effect of husk Si on grain filling and grain yield was relate to the Si concentration that may be said to be abnormally low, at < 1% in the mutant compared with >8% in the wild type. The consistently significant positive correlation between husk Si concentration and grain yield suggested that similar effect may operate at higher Si concentrations,

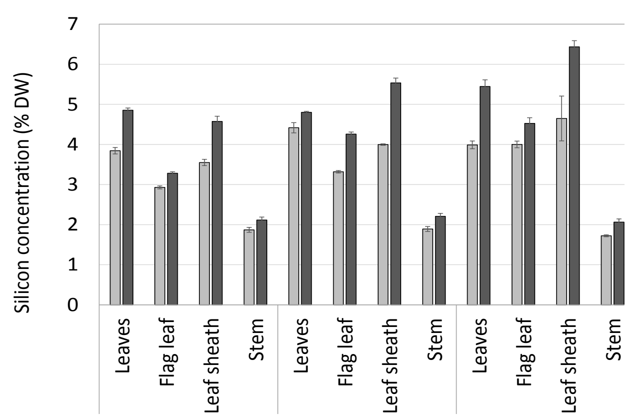


**Fig. 2:** Silicon concentration in different tissues of 3 rice varieties grown with two levels of Si application (with ■; and without ■), with standard error bars (Exp. 4)

Significant effects by analysis of variance: Variety (V) $P< 0.001$; Si application (Si) $P < 0.001$; Plant part (P) $P< 0.001$; V x Si $P< 0.05$; V × P $P< 0.001$; Si × P $P< 0.001$; V × Si x P $P< 0.001$

Significant location effect on each variety indicated by * above each pair of bars

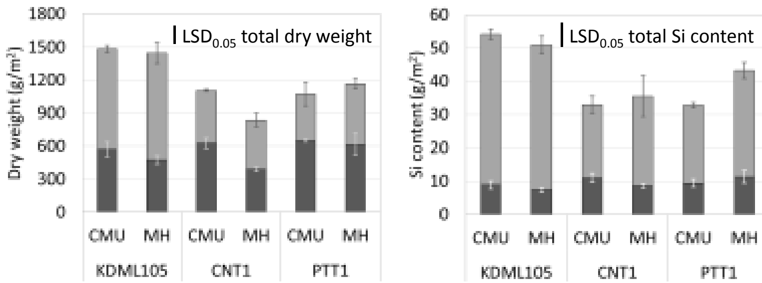


**Fig. 3:** Partitioning of dry weight and silicon content (grain ■ and straw ■) in 3 rice varieties grown at Chiang Mai University (CMU) and Mae Hia Station (MH), with standard error bars (Exp. 4)

| Significant effects by analysis of variance | Dry weight | | Silicon content | |
|---|---|---|---|---|
| | Grain | Straw | Grain | Straw |
| Variety (V) | $P< 0.01$ | $P< 0.001$ | $P< 0.05$ | $P< 0.001$ |
| Location (L) | $P< 0.001$ | NS ($P< 0.05$) | NS ($P< 0.05$) | $P< 0.05$ |
| V × L | $P< 0.05$ | NS ($P< 0.05$) | $P< 0.05$ | NS ($P< 0.05$) |

as found in the present study and also those encountered in the field. In addition, responses of Si concentration in plant parts can be affected by the location where the rice is grown due to variation in the availability of Si to the rice plants paddy soil as influenced by factors such as soil pH and soil type (He, 1993).

## Conclusion

The Si concentration in various parts of the rice plant and grain can vary significantly under interacting influences of genotype, location and Si application. Further investigation of the relationship between husk Si and grain yield and the underlying processes should make Si management for rice production more effective, for the potential energy to be recovered from the husk and straw as well as for grain yield.

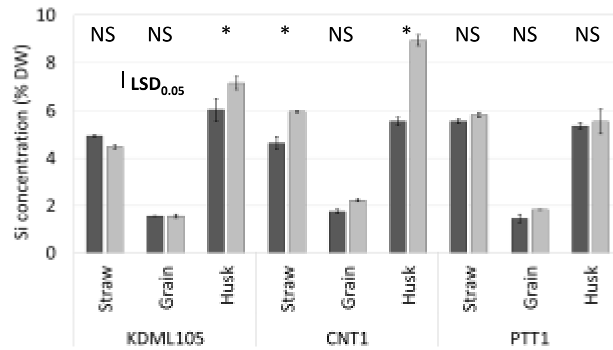


**Fig. 4:** Silicon concentration in the grain, straw and husk of 3 rice varieties grown at for Chiang Mai University (■) and Maehia station (■) with standard error bars (Exp. 4)
Significant effects by analysis of variance: Variety (V) $P< 0.001$; Plant part (P) $P < 0.001$; Location (L) $P< 0.001$; V × P, $P< 0.001$; V × L $P< 0.001$; P × L $P< 0.001$; V × P × L $P< 0.001$
Significant location effect on each variety indicated by * above each pair of bars, NS not significant at $P< 0.05$

## Acknowledgements

We are grateful to the Royal Golden Jubilee Ph.D. Program (Grant No. PHD/0153/2557) for financial support.

## References

Arnon, D.I. and P.R. Stout, 1939. The essentiality of certain elements in minute quantity for plant with special reference to copper. *Plant Physiol*., 14: 371–375
Bharadwaj, A., Y. Wang, S. Sridhar and V.S. Arunachalam, 2004. Pyrolysis of Rice Husk. *Curr. Sci*., 87: 981–986
Dai, W., K. Zhang, B. Duan, C. Sun, K. Zheng, R. Cai and J. Zhuang, 2005. Rapid determination of silicon content in rice. *Rice Sci*., 12: 145–147
Datnoff, L.E., R.N. Raid, G.H. Snyder and D.B. Jones, 1991. Effect of calcium silicate on blast and brown spot intensities and yields of rice. *Plant Dis*., 75: 729–732
Epstein, E., 1999. Silicon. *Annu. Rev. Plant Physiol. Plant Mol. Biol.,* 50: 641–664
Ganesan, V., K.A. Rosentrater and K. Muthukumarappan, 2008. Flowability and handling characteristics of bulk solids and powders – a review with implications for DDGS. *Biosyst. Eng*., 101: 425–435
He, D.Y., 1993. Form, content and availability of silicon in main farmland of Hunan province and research on furnace slag fertilizer. *Res. Agric. Mod*., 14: 43–47
Inaizum, K. and S. Yoshida, 1958. Edaphological studies on silicon supplying power of paddy soils. *Bull. Nat. Inst. Agric. Sci*., B: 261–304
Koyama, O., 2014. Achievement in JIRCAS Presented at 2014 meeting of the Oversight Committee of the Global Rice Science Partnership, November 2014, Bangkok, Thailand
Lian, S., 1976. *Silica fertilization of rice in The Fertility of Paddy Soils and Fertilizer Applications for Rice*. Food and Fertilizer Technology Center, Taipei, Taiwan
Lim, J.S., Z.A. Manan, S.R.W. Alwi and H. Hashim, 2012. A review on utilisation of biomass from rice industry as a source of renewable energy. *Renew. Sustain. Energy Rev*., 16: 3084–3094
Ma, J.F., 2004. Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. *Soil Sci. Plant Nutr*., 50: 11–18
Ma, J.F. and N. Yamaji, 2006. Silicon uptake and accumulation in higher plants. *Trends Plant Sci*., 11: 392–397
McKendry, P., 2002. Energy production from biomass (part 1): overview of biomass. *Bioresour. Technol*., 83: 37–46
Moussa, H., 2006. Influence of exogenous application of silicon on physiological response of salt-stressed maize (*Zea mays* L.). *Int. J. Agric. Biol*., 8: 293–297
Ning, D., A. Song, F. Fan, Z. Li and Y. Liang, 2014. Effects of slag-based silicon fertilizer on rice growth and brown-spot resistance. *PLoS One. 9*, e102681

Raveendran, K., A. Ganesh and K.C. Khilar, 1995. Influence of mineral matter on biomass pyrolysis characteristics. *Fuel*., 74: 1812–1822

Reuter, D.J., D.G. Edwards and N.S. Wilhelm, 1997. Temperate and tropical crops. *In*: *Plant Analysis: An Interpretation Manual*, pp: 83–284. 2nd edition. Reuter, D.J. and J.B. Robinson (eds.). CSIRO Publishing, Collingwood, Victorai, Australia

Sae-Oui, P., C. Rakdee and P. Thanmathorn, 2002. Use of rice husk ash as filler in natural rubber vulcanizates: In comparison with other commercial fillers. *J. Appl. Polym. Sci.*, 83: 2485–2493

Savant, N.K., G.H. Snyder and L.E. Datnoff, 1997. Silicon management and sustainable rice production. *Adv. Agron*., 58: 151–199

Seebold, K.W., L.E. Datnoff, F.J. Correa-Victoria, T.A. Kucharek and G.H. Snyder, 2000. Effect of silicon rate and host resistance on blast, scald and yield of upland rice. *Plant Dis.*, 84: 871–876

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

Van Soest, P.J., 2006. Rice straw, the role of silica and treatments to improve quality. *Anim. Feed Sci. Technol*., 130: 137–171

Wattanapayapkul, W., A. Polthanee, B. Siri, N. Na-Bhadalung and V. Promkhambut, 2011. Effects of silicon in suppressing blast disease and increasing grain yield of organic rice in northeast Thailand. *Asian J. Plant Pathol*., 5: 134–145

Winslow, M.D., K. Okada and F. Correa-Victoria, 1997. Silicon deficiency and the adaptation of tropical rice ecotypes. *Plant Soil*., 188: 239–248

Yoshida, S., 1981. *Fundamentals of Rice Crop Science*. International Rice Research Institute, Los Banos, Philippines

Yosahida, S., Y. Ohnishi and K. Kitagishi, 1962. Chemical forms, mobility and deposition of silicon in rice plant. *Soil Sci. Plant Nutr*., 8: 15–21

**(Received 12 July 2017; Accepted 25 November 2017)**