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# RELEASE OF SILICON FROM SILICATE MATERIALS AND ITS UPTAKE BY RICE PLANT

## *Pelepasan Silika dari Bahan Silikat dan Penyerapannya oleh Tanaman Padi*

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## ABSTRACT

Plants absorb silicon (Si) from soil solution in the form of monosilicic acid, also called orthosilicic acid ($H_4SiO_4$). Application of organic and inorganic materials containing readily soluble Si can increase Si supply in the soil and its uptake by plant. The study aimed to evaluate the release of Si from organic and inorganic material sources and its uptake by rice plant. The released phosphorus (P) from those materials was also evaluated. The inorganic materials evaluated included fly ash, steel slag, silica gel and Japanese silica gel (JSG), while the organic materials consisted of rice husk ash (RHA), rice husk burnt (RHB), media of mushroom (MM), cacao shell biochar (cacao SB) and rice straw compost (RSC). The dynamics of Si and P were observed by periodical samplings at 7, 17, 24 and 34 days after transplanting (DAT). Tiller number and plant height were measured at 16, 21 and 36 DAT. The results showed that Si concentration in solution derived from inorganic material was highest for JSG followed by silica gel (1.107 and 0.806 mmol $L^{-1}$, respectively). The release of Si from organic material was higher for RHB and RHA (0.618 and 0.539 mmol $L^{-1}$, respectively). Cacao SB, silica gel, JSG and RHB significantly increased plant height at 36 DAT. Meanwhile, Si materials did not significantly affect the tiller number. Of the materials used, steel slag and JSG significantly affected Si uptake by rice plant.

[***Keywords***: rice, silicate materials, silicon, silicon uptake]

## ABSTRAK

*Tanaman menyerap silikon dari larutan tanah dalam bentuk asam monosilikat, yang juga disebut asam ortosilikat ($H_4SiO_4$). Penggunaan bahan organik dan anorganik yang mengandung Si yang cepat tersedia bagi tanaman dapat meningkatkan ketersediaan Si dalam tanah dan penyerapannya oleh tanaman. Penelitian ini bertujuan untuk mengevaluasi pelepasan Si dari bahan organik dan anorganik dan penyerapannya oleh tanaman padi. Pelepasan fosfor (P) dari bahan-bahan sumber Si tersebut juga dievaluasi. Bahan anorganik yang diteliti meliputi abu terbang (*fly ash*), terak baja, silika gel, dan silika gel Jepang, sedangkan untuk bahan organik terdiri atas abu sekam padi (RHA), sekam padi bakar (RHB), media jamur (MM), biochar kulit buah kakao (cacao SB), dan kompos jerami padi (RSC). Pengamatan dinamika Si dan P dilakukan secara berkala pada 7, 17, 24, dan 34 hari setelah tanam (HST), sementara jumlah anakan dan tinggi tanaman padi diamati pada 16, 21, dan 36 HST. Hasil penelitian menunjukkan bahwa konsentrasi Si dalam larutan yang berasal dari bahan anorganik paling tinggi untuk JSG dan diikuti oleh silika gel, masing-masing 1,107 dan 0,806 mmol $L^{-1}$. Pelepasan Si dari bahan organik tertinggi terdapat pada RHB dan RHA (0.618 dan 0.539 mmol $L^{-1}$). Biochar kulit buah kakao, silika gel, JSG, dan RHB nyata meningkatkan tinggi tanaman padi pada 36 HST. Sumber Si tidak memengaruhi jumlah anakan tanaman. Dari bahan yang digunakan, terak baja dan silika gel Jepang (JSG) nyata memengaruhi serapan Si oleh tanaman padi*

[***Kata kunci****: bahan silikat, padi, penyerapan silika, silika*]

## INTRODUCTION

Silicon (Si) is the second most common element of the earth's crust (Wedepohl 1995). Silica minerals undergo chemical and physical weathering which release Si into soil solution, followed by combination with other elements to form clay minerals or release toward the streams and oceans or to be absorbed by vegetation (Guntzer et al. 2012).

The form of Si absorbed by plant root is silicic acid (Datnoff et al. 2001). According to Matichenkov and Bocharnikova (2001), monosilicic acid, polysilicic acid, organo-silicon compound and complex compounds with organic and inorganic substances are the mobile forms of Si. By replacing phosphorus (P) from calcium (Ca), aluminum (Al) and magnesium (Mg) phosphates, monosilicic acid can control the mobility of phosphates and transform plant-unavailable P into plant-available P (Matichenkov and Ammosova 1996).

Silica as a beneficial element for plant may reduce biotic and abiotic stresses. Si has been recognized for reducing rice blast caused by fungus *Magnaporthe grisea* (Winslow et al. 1997; Meena et al. 2014) and enhancing wheat resistance to freezing stress (Liang et al. 2008)

The release of Si has a larger interaction with P and other nutrients (Meena et al. 2014). The beneficial effects of Si application on increasing available soil P was confirmed by several researchers. According to Raleigh (1953), application of Si increased P uptake in P-deficient soil. Si is also beneficial to the plant when available P is high, by reducing P uptake and thereby reducing inorganic P within the plant (Ma and Takahashi 1990). Although inorganic P is necessary for metabolism and storage, its high concentrations inhibit enzyme reactions leading to creation of abnormal osmotic pressure in the cell (Yoneyama 1988). According to Tubana and Heckman (2015), Si fertilizer increased the amount of released Si in the soil solution. Furthermore, Si is adsorbed onto the slightly soluble phosphates of Al, Ca, Fe and Mg by desorption of the phosphate anion. It seems possible to reduce the amount of P fertilizer by application of Si.

Currently, many materials are being evaluated as Si sources for use in agriculture, and the most important properties of those materials must have much Si readily soluble in the soil solution (Gascho 2001). Rice straw contains about 86% of the total Si storage in rice plants (Klotzbucher et al. 2015). However, farmers commonly burn or take out rice straw from rice fields after the harvest for animal feed. As Si continuously removed through harvested products, the Si status of agricultural soil becomes low. Furthermore, if soil nutrients were not replenished by fertilizer application, the Si may possibly decrease from season to season.

Silicon from natural sources has a potential to mitigate environmental stresses and soil nutrient depletion thereby maintaining sustainable agriculture (Guntzer et al. 2012). Rice is a Si-accumulator plant that has physical-chemical functions for plant growth (Nguyen et al. 2014). Wollastonite ($CaSiO_3$) is the best known as a Si fertilizer source. However, it is relatively expensive (Haynes et al. 2013). Silicon sources such as slag, fly ash and bottom ash from industrial waste are of great interest for Si fertilizer in paddy field. Haynes et al. (2103) reported that industrial waste materials such as slag, processing mud and fly ash increased soil pH and EC. Steel slag is a non-metallic by-product from iron and steel manufacturing that consists of Ca, Mg and Al silicates in various combinations. At high temperatures, slag is formed when limestone reacts with silicon dioxide and other impurities of iron ore (Teir et al. 2007). The purpose of this study was to evaluate the release of Si from organic and inorganic material sources and Si uptake by rice plant. The released P from those materials was also evaluated.

## MATERIALS AND METHODS

### Silicon Sources

Two kinds of Si sources namely organic and inorganic materials were collected from Indonesia and Japan. The organic materials included rice husk ash (RHA), rice husk burnt (RHB), media of mushroom (MM), cacao shell biochar (cacao SB) and rice straw compost (RSC). The inorganic materials included fly ash, steel slag, silica gel and Japanese silica gel (JSG).

### Greenhouse Experiment

The soil sample was air dried and passed through a 2-mm sieve. Exchangeable potassium (K), sodium (Na), calcium (Ca) and magnesium (Mg) were extracted with 1 M ammonium acetate pH 7.0 and measured by Inductively Coupled Plasma Spectroscopy (ICPE-9000 Shimadzu, Kyoto Japan). Available Si was extracted by acetate buffer (pH 4.0) at a ratio of 1:10, for intermittent shaking for 5 hours at 40$^o$C, determined using the silicate molybdenum blue method (Imaizumi and Yoshida 1958). Soil pH ($H_2O$) was determined in 1:2.5 (w/v) soil : water suspensions with pH meter (D-51, Horiba). Total carbon (C) and nitrogen (N) were measured using dry combustion methods (Sumigraph NC-22 Analyzer).

Seeds of Koshihikari rice variety were sterilized against nematodes, fungi and bacteria with fungicides (suporutakkuu sitaana) and air dried for overnight. The soaked seeds were kept in an incubator for 4 days at 20$^o$C and on the fifth day, the temperature was increased to 32$^o$C to enhance uniform germination. The seeds were then planted in the nursery box, covered with black polythene and put in the growth chamber at 25$^o$C for day time and 20$^o$C for night time during one week. The nursery box was transferred to the pool for the remaining 3 weeks.

A pot experiment was carried out from June to July 2016 in the greenhouse of Shimane University, Japan. The experiment was set up in a completely randomized design with ten treatments and three replicates. The soils used for the experiment were collected from Shimane Prefecture - Japan. Soils of 400 g and 1 g of fine powder Si inorganic materials (fly ash, steel slag, silica gel) and organic materials (RHA, RHB, MM, cacao SB and RSC) were mixed. The exception was JSG application in a granular form. Soil and each material treatment were transferred into the pot of 500 ml size and mixed thoroughly. Basal treatment was 0.88 g $KH_2PO_4$ and 0.95 g $(NH_4)_2SO_4$

per pot. Materials and basal treatments were applied one day before transplanting. One seedling was sown in each pot. Conventional continuous flooding was used during the experiment.

### Solution Sampling and Laboratory Analysis

Silicon and P of solution were measured at 7, 17, 24 and 34 days after transplanting (DAT). The supernatant was obtained after filtration using paper filter Advantec No. 6. Si and P concentrations in the supernatant were determined by colorimetric analysis with spectrophotometer UV 1800 Shimadzu. The wavelength was 810 nm for Si and 720 nm for P measurements.

### Plant Growth Observation and Analysis

Tiller number and plant height were recorded at 16, 21 and 36 DAT. Plant height was measured from the ground to the tip of the highest leaves. Tiller number was calculated from the main stem of rice plants.

Plants were harvested at 37 DAT and separated into straw and root. The dry weight of these tissues was recorded after being dried. Straw samples were oven dried at 60–70°C for one day after and then finely ground using a mixer mill (MM 200, Retsch GmbH, Haan, Germany). Fine samples were oven-dried for 12 hours at 80$^{o}$C. The total Si uptake in straw samples was determined by $HNO_3$ at 160$^{o}$C for 4 hours and HF digestion method using Teflon vessel and measured by spectrophotometer UV 1800 Shimadzu (Koyama and Sutoh 1987).

### Data Analysis

IBM package SPSS 22 was used to analyze the data. A one way ANOVA was carried out to compare the means of different treatments at the 5% level using Duncan multiple range test (DMRT).

## RESULTS AND DISCUSSION

### Soil Properties

The soil used for this study was acidic in reaction and had clay loam texture. The C/N ratio was 15 (C and N content of 15.0 and 1.0 g kg$^{-1}$, respectively) exceeded the mean value of tropical Asia soil (11.5) (Kyuma 2004). The exchangeable Ca and Mg (4.7 and 1.0 cmol$_c$ kg$^{-1}$, respectively) were lower than the mean value of tropical Asia soil (9.3 and 5.6 cmolc/kg, respectively). The available Si concentration (138.1 mg $SiO_2$ kg$^{-1}$) was below the critical level of 300 mg $SiO_2$ kg$^{-1}$ according to Sumida (1992).

### Si and P Release in Solution

The effect of Si and P on the growth of rice plants is shown in Figure 1. The Si uptake was compared among the materials during 37 DAT under the same condition. The Si release pattern during 34 DAT was similar for all the materials (Figure 1a), which was higher at the beginning of observation. Most of the treatments showed the lowest Si concentration in solution at day 34. It is possible due to Si uptake by rice plant.

Si concentration in solution was higher for inorganic materials as compared to organic materials in the first 7 DAT, except for steel slag (< 0.5 mmol L$^{-1}$). It might be possible that decomposition of organic materials (MM, cacao SB and RSC) occurred slowly. Marxen et al. (2016) reported that Si concentrations in soil solution increased when the organic matrix surrounding the phytoliths was decomposed and the surface of phytoliths was exposed to the soil solution. Another possibility is that the available Si in most organic materials (1.47–3.74 g Si kg$^{-1}$) was lower compared to Si in inorganic materials (6.54–16.14 g Si kg$^{-1}$).

Silicon material applications to the soil not only supplied Si, but also increased P concentration. The release pattern of P was similar to that of Si (Figure 1b) which was higher in the first 7 DAT. According to Ma and Takahashi (1991), both Si and P may produce beneficial effects on the growth of rice plants in acid soils with P deficiency. Silicic acid had an indirect effect to improve P on the rice growth by decreasing Mn uptake. In this experiment, although P concentration was 10 times lower compared to Si (Table 3), the Si effect could be held responsible mainly for increasing P supply from the soil.

Si and P concentrations in solution (Table 1) added with Si materials was higher than that of the control, except for MM and cacao SB for Si concentration. It means that almost all materials increased Si and P concentrations in soil solution. For MM and cacao SB, the low Si was not only due to sampling loss, but also to active Si absorption by rice plant (Kato and Owa 1997). Correa-Victoria et al. (2001) reported a positive interaction of Si and P on rice yield in soils with low in Si and P. The highest Si concentration in solution was derived from JSG and RHB application, respectively.

According to Jones and Handreck (1967), the activity of Al ions in solution was reduced by

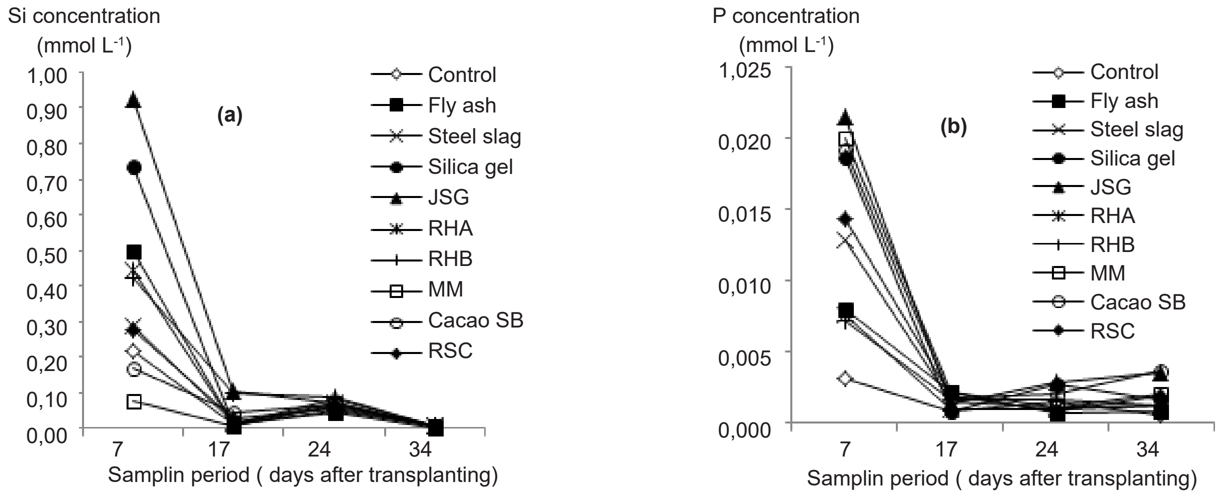


**Fig. 1**. Release pattern of silicon (a) and phosphorus (b) in solution during 39 days of experiment.

monosilicic acid which then preventing those ions from precipitating the phosphate. Silicon fertilizer increased available Si in the soil solution, and the amount of Si adsorbed onto the slightly soluble phosphates of Al and Fe was followed by the desorption of the phosphate anion (Tubana and Heckman 2015). Reaction of P release into soil solution is described as follows:

$$2Al(H_2PO_4)_3 + 2Si(OH)_4 + 5H^+ = Al_2Si_2O_5 + 5H_3PO_4 + 5H_2O$$

$$2FePO_4 + Si\ (OH)_4 + 2H^+ = Fe_2SiO_4 + 2H_3PO_4$$

## Plant Height

The significant difference among treatments in plant height is shown in Figure 2. Cacao SB, silica gel, JSG and RHB significantly increased plant height at 36 DAT. Fallah (2012) reported that plant height increased under Si application. This was corroborated by Pati et al. (2016) who observed a significant increase in plant height due to Si application.

Plant height was similar for silica gel and JSG applications, where Si release in solution was higher than that of other treatments. This clearly shows that application of silica gel and JSG increased plant height. Meanwhile, RHB and cacao SB did not increase plant height as Si concentration in solution was not in line with plant height (Figure 1A).

## Tiller Number

Silica materials did not significantly affect tiller number (Figure 3). However, the highest tiller number was obtained for JSG application at 36 DAT. The tiller number was lower for RHB and RSC than that of the control at day 36. These findings are similar to Ahmad et al. (2013) and Anggria et al (2016), where productive tiller was lower in Si application than the control.

Tamai and Ma (2008) reported that Si did not affect tiller number. Agostinho (2016) also reported no significant increase in tiller number with foliar or soil application of Si. On the other hand, the increased tiller number of rice plant was recorded by Yasari et al. (2012) and Gholami and Falah (2013).

**Table 1. Cumulative concentration of silicon (Si) and phosphorus (P) in solution at 34 days after rice transplanting.**

| Treatments | Cumulative concentration (mmol $L^{-1}$) | |
|---|---|---|
| | Si | P |
| Control | 0.319 | 0.006 |
| Fly ash | 0.565 | 0.012 |
| Steel slag | 0.375 | 0.017 |
| Silica gel | 0.806 | 0.024 |
| Japanese silica gel (JSG) | 1.107 | 0.029 |
| Rice husk ash (RHA) | 0.539 | 0.011 |
| Rice husk burnt (RHB) | 0.618 | 0.012 |
| Media of mushroom (MM) | 0.159 | 0.025 |
| Cacao sheel biochar | 0.290 | 0.027 |
| Rice staw compost (RSC) | 0.371 | 0.019 |

## Plant Biomass and Si Uptake

Application of all Si-materials did not significantly affect dry matter yield compared with the control (Figure 4). These results were in contrast to those

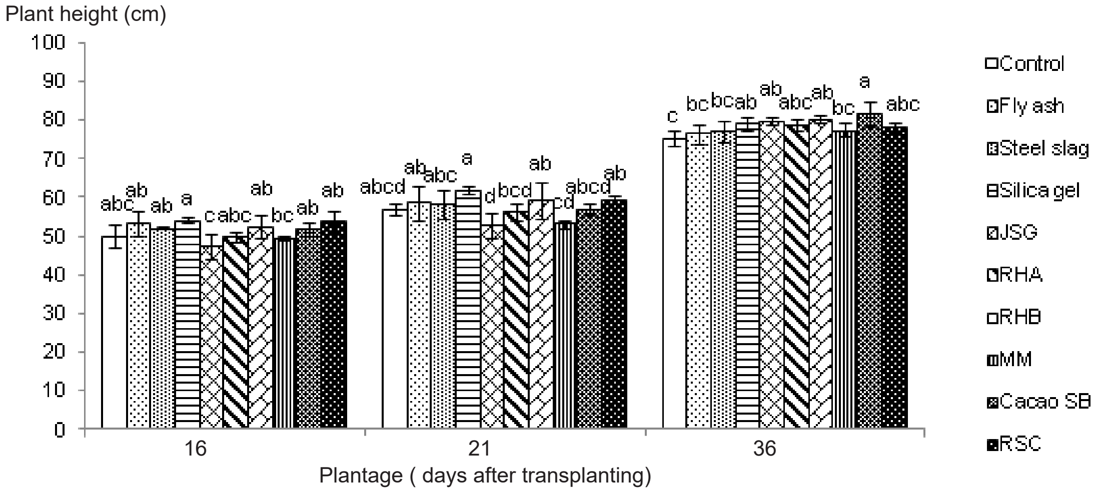


**Fig 2.** Effect of inorganic and organic material applications on rice plant height; different letters indicate significant difference at P < 0.05 by DMRT.

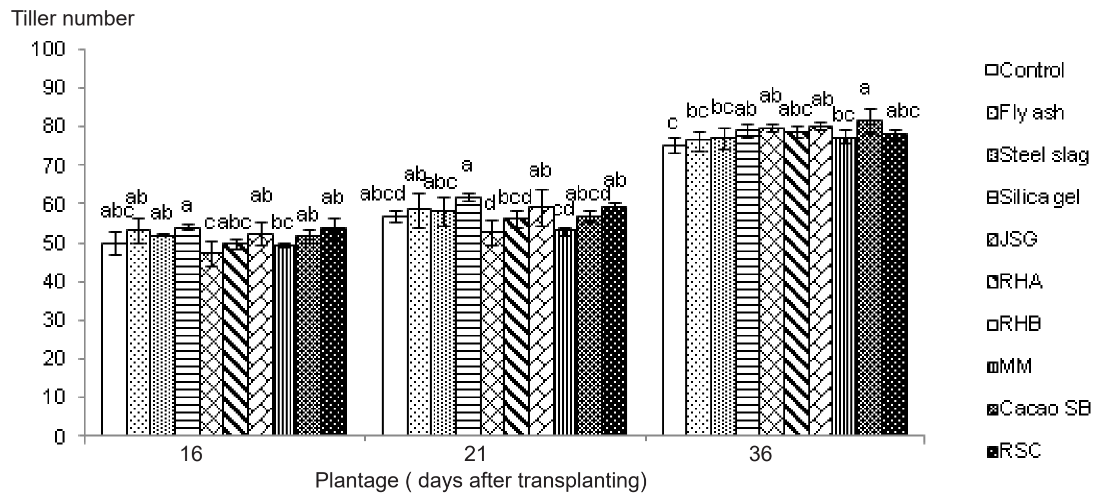


**Fig 3**. Effect of inorganic and organic material applications on rice tiller number; different letters indicate significant difference at P < 0.05 by DMRT.

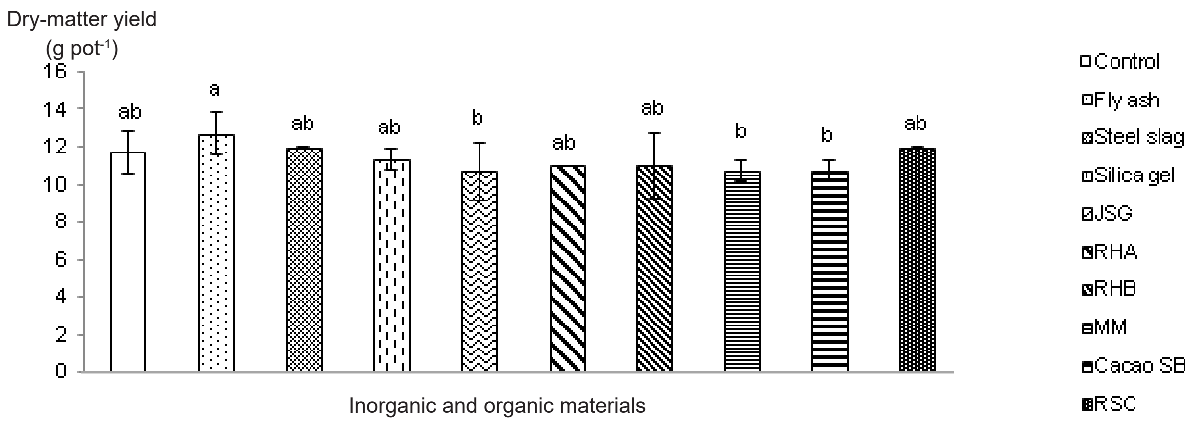


**Fig 4.** Rice dry matter yield as affected by silicon-derived organic and inorganic materials; different letters indicate significant difference at P < 0.05 by DMRT.

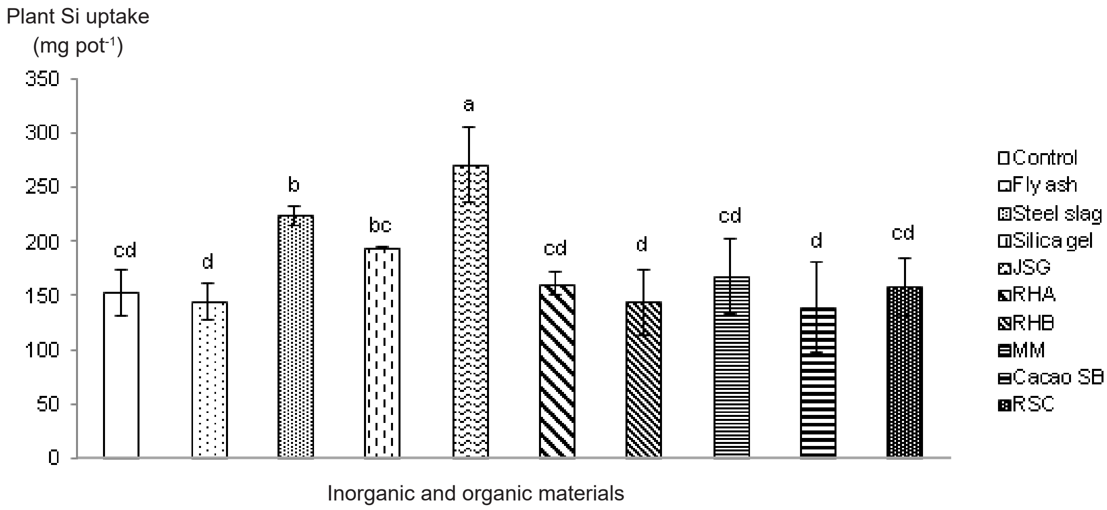


**Fig 5.** Plant silicon uptake as affected Si-derived organic and inorganic materials; different letters indicate significant difference at $P < 0.05$ by DMRT.

reported by Gerami et al. (2012) that plant dry weight increased by the increase in Si levels. An explanation for our result is that Si from the materials was not dissolved all in solution at 37 DAT.

As Si accumulates at the places of respiratory water losses and consequently Si concentrates in the leaves (Gocke et al. 2013), thus we analyze Si concentration in above ground biomass. The effect of JSG and steel slag on increasing Si uptake is presented in Figure 5.

The greatest Si uptake by rice plant occurred for JSG application. Silica gel and MM also increased plant Si uptake but were not significant compared to the control. Silica gel and JSG easily dissolve Si into solution (Table 1), resulted in more Si uptake by plants. These data suggest that the plant Si uptake accelerated the release of dissolved Si from both silica gels and soil. These results agree with the observation reported by Marxen et al. (2016) in which the decreased Si concentrations in soil solutions would accelerate the release of Si from rice straw and soils.

Rice plant was able to uptake Si in a high amount, although Si was low in solution for basic steel slag from Indonesia. On the other hand, rice could uptake Si in the high amount from silica gel having high Si solubility. It might be because Si release from steel slag was slow. In addition, steel slag contains calcium silicate that increases solution pH up to 6.7 at day 34 (data not shown) that organic nitrogen stimulates ammonification of thus, extra nitrogen may dilute the Si content and then it is possible that application of steel slag as silicate fertilizer affects the formation of Si bodies indirectly through nitrogen nutrition (Ma and Takahashi 1993).

## CONCLUSION

Inorganic and organic materials vary widely in Si and P concentration in soil solution. Japanese silica gel (JSG) and steel slag were effective to be used as a source of Si for improving Si uptake by plant. The plant Si uptake accelerated the release of dissolved Si from both JSG and soil. The use of steel slag increased solution pH that stimulates the ammonification of organic nitrogen. The extra nitrogen may dilute the Si content.

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