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RESEARCH ARTICLE
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Three sources of silicon in biomass production of rice (*Oryza sativa* L.) under controlled conditions

Tres fuentes de silicio en la producción de biomasa del arroz (*Oryza sativa* L.) bajo condiciones controladas

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Abstract

A pot experiment was conducted in the campus of La Molina National Agrarian University in order to evaluate the effect of rice husk ash, ladle furnace slag and potassium silicate on the soil chemical properties and biomass of rice (*Oryza sativa* L.) cv. 'Fedearroz 60', using topsoil from a commercial paddy field at Aucayacu, Huanuco, Peru. Doses were calculated taking into consideration each product available Si (SiA), for reaching concentrations of 100, 200 and 400 ppm (w / w) of SiA in soil before sowing. Control pots without any silicon amendment were considered as well. A completely randomized design with factorial arrangement (3 × 4) was used to assess the Si absorption by plant tissues, final SiA in soils, roots volume, whole plant's dry weight, tillering capacity, panicles per plant and average spikelets per panicle. Salinity and pH of the growing media were registered weekly. Also were environmental temperature, and light intensity on a daily basis. Results showed that potassium silicate 200 ppm sustainably increased SiA in soils and Si in plant tissue, however the yield components were not positively influenced. Ladle furnace slag increased SiA in soils too, nonetheless for doses of 200 ppm and 400 ppm, symptoms of severe nutritional problems appeared. Rice husk ash did not show statistical significance on SiA in soils, Si in plant tissue, nor yield components. It was concluded that for such soil and weather conditions involved in this experiment, silicon increases in soil and tissues had no influence on rice yield components. In spite of this, ladle furnace slag exhibited an outstanding liming capacity and rice husk ash, a great amount of P, K and micronutrients.

Keywords: *silicon nutrition, rice yield components, ladle furnace slag, potassium silicate, rice husk ash.*

Resumen

Un ensayo en macetas fue realizado en el campus de la Universidad Nacional Agraria La Molina, para evaluar el efecto de la ceniza de cascarilla de arroz, escoria básica de horno cuchara y silicato de potasio, en las propiedades químicas del suelo y en la biomasa del arroz (*Oryza sativa* L.) cv. 'Fedearroz 60', usando material de

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suelo procedente de un campo arrocero en Aucayacu, Huánuco, Perú. Las dosis fueron calculadas en base a la concentración de silicio biodisponible (SiA) de cada enmienda para lograr 100, 200 y 400 ppm (p / p) de SiA en suelo antes de la siembra, además de testigos sin aplicación de silicio. Se empleó un diseño completo al azar con arreglo factorial de 3 × 4 en el que se evaluó la absorción de Si en tejidos, disponibilidad de SiA al final de la campaña, volumen radicular, habilidad de macollamiento, panículas por planta y espiguillas por panícula promedio. Se registraron las variaciones semanales de salinidad y pH en el material de suelo empleado como sustrato, así como las variaciones diarias de temperatura e intensidad luminosa. Se encontró que el silicato de potasio a 200 ppm incrementó sostenidamente el SiA en suelos y el Si en tejido; sin embargo, no hubo influencia en los componentes del rendimiento. La escoria básica también incrementó el SiA en suelos, pero presentó reacciones tóxicas severas en las dosis de 200 ppm y 400 ppm. La ceniza de cascarilla de arroz no influyó significativamente en los parámetros de silicio, ni en los componentes de rendimiento. Se concluyó que para las condiciones de suelo y clima en la que se desarrolló el experimento, el incremento en la concentración de silicio en suelo y tejidos, no influyó en los componentes del rendimiento del arroz. Pese a ello, la escoria presenta una extraordinaria capacidad encalante y la ceniza una gran cantidad de P, K y micronutrientes.

Palabras clave: *nutrición con silicio, componentes rendimiento arroz, escoria básica, silicato de potasio, ceniza cascarilla arroz.*

Introduction

Rice (*Oryza sativa* L.) is one of the main food crops in the world (Food and Agriculture Organization of the United Nations [FAO], 2021). Not only is it important at a food security level, but it also represents a substantial source of income for farmers in the northern coast and rainforest areas of Peru (Ministerio de Desarrollo Agrario y Riego del Perú [MIDAGRI], 2021). Although the highest rice yields are obtained in the coast, this cereal's production should be encouraged mainly at the Amazon basin. There are two situations which back up this statement. In first place, Peruvian coastal valleys have constant threat of water shortage, due to their desert-like climate and a increasing expansion of farming land for export products (Drenkhan et al., 2015). Secondly, paddy fields tillage causes physical and chemical degradation which limits the use of these areas only to rice monoculture (Sione et al., 2017). This line of investigation involves silicon as part of a strategy for increasing yields at the Amazon basin, looking forward to making this crop more attractive for this area. This element, historically considered "non-essential" within the majority of nutritional programs, has gained importance in research which highlights its ability to indirectly increase yields, by alleviating conditions of biotic and abiotic stress (Meharg & Meharg, 2015). For this pot experiment, available silicon concentration in soil (SiA) was raised in order to verify whether or not %Si in tissue increased as well. Subsequently, this variable was correlated with some parameters associated with yield components, in order to check if higher silicon levels could have resulted in higher yields. For such purpose, three sources of silicon were used: potassium silicate, rice husk ash and ladle furnace slag. These last two amendments are materials considered as residues with potential to be used in agriculture. Rice husk is a residue obtained from rice mills. It has been used as a component of growing substrates in nurseries and different crops' plantations. According to (Della et al., 2002), its ashes contain up to 94.9% of SiO_2. Ladle furnace slag is a by-product of steel plants. Encina (2017) studied its properties, finding good liming power in this material. Apart from that, its SiO_2 concentration varies from 10 % to 19 %. This amendment is a good candidate for Amazonian acidic soils, where it is known that high precipitation quickly leaches silicon.

Methodology

Location

The experimental part of this research was conducted in the Soil Fertility Laboratory, belonging to the Soil Academic Department, at the campus of Universidad Nacional Agraria La Molina (UNALM), which is located at 12º 4' 46" S, 76º 56' 45" W and an altitude of 244 m.a.s.l. The experimental field part took place from February 16th 2018 to August 17th 2018.

Supplies, materials and tools

Topsoil samples from a commercial rice paddy field, located in river Huallaga's floodplain in Aucayacu (Leoncio Prado province, Huánuco region, Peru) was used for the experiment. This rainforest area has a tropical climate, with an annual mean temperature of 24.67 □ and precipitation of 2866 mm. The sources of available silicon (SiA) were ladle furnace slag (SiderPeru-Gerdau, Chimbote, Peru), rice husk ash (Feedcor EIRL, Lima, Peru) and potassium silicate (commercial name Klaida, Feedcor EIRL, Lima, Peru). Ammonium sulfate, potassium sulfate and diammonium phosphate were the regular soil fertilizers for the nutritional program. Irrigation water (pH 7.83; E.C. 0.5 dS / m; SAR 0.57) was classified C2-S1 according to Wilcox (1955), meaning low risk of sodium hazard, and medium salinity hazard. Rice seeds cv. 'Fedearroz 60' were brought from Aucayacu. Reagents for silicon analysis were considered following the reference of Parra et al. (2004) and Pereira et al. (2007). Regarding tools, 7.5 L plastic pots were used as growing containers. The equipment used for the measurements were scale, electric stove, potentiometer, conductivity meter, thermo-hygrometer with data logger (Elitech, California, USA), lux meter (Benetech, Guandong, China), thermal plate, muffle-type oven and a UV spectrophotometer (ThermoScientific, Massachusetts, USA).

Experimental design

A completely randomized design with factorial arrangement (3 × 4) was used. Factors under study were: (1) soluble silicon sources and (2) Initial SiA concentrations. Levels for factor one – (i) ladle furnace slag – "Slag", (ii) rice husk ash – "Ash" and (iii) potassium silicate – "KSi". Levels for factor two – (a) 0 ppm, (b) 100 ppm, (c) 200 ppm and (d) 400 ppm. The experimental unit was defined as a pot with a rice plant with 5.8 kg of air-dried soil previously sieved, homogenized and partially fertilized. Total: 72 experimental units. The experiment begun with six replicates per treatment, however due to the identification of other cultivars which were not 'Fedearroz 60', some experimental units had to be removed. As a consequence, all treatments suffered a reduction in the number of replicates and three of them had to be discarded from the experiment because were left with only two replicates (Slag 100ppm, KSi 400ppm, Ash 200ppm). Collected data was analyzed using the free software, R (RcoreTeam, 2014). A linear model was used to obtain the residuals for each quantitative variable and then were subjected to the Shapiro-Wilk test, in order to verify the assumption of residuals' normal distribution (). Breutsch-Pagan test was also carried out to corroborate the assumption of homogeneity of variances in the residuals (). In the event of non-compliance with any of the assumptions, specific mathematical transformations were carried out for each variable. They will be indicated individually in the tables. After verifying that data fit into the statistical assumptions, ANOVAs were carried out. Subsequently, Tukey tests were performed () in which all treatments were contrasted at the interaction level.

Variables

The evaluated variables were grouped into three groups: (1) Edaphoclimatic - electrical conductivity of the soil, soil reaction (pH), environmental temperature and light intensity. (2) Morphological - tillers per plant, panicles per plant, average spikelets per panicle, whole plant's dry weight and root volume. (3) Analytical - Si concentration in tissues and available silicon in soils (SiA).

Experiment installation

The collected topsoil was air dried and passed through a 2 mm sieve. Three samples were taken to the laboratory in order to perform a soil characterization analysis (Table 1). The results indicated the textural class as Loam, with 40 % of sand and 41 % of silt, as expected for an area next to a river, where constant sediments are brought with water. Electrical conductivity was measured in 0.25 dS · m^{-1}, and pH in 5.14. The nature of river water, very low in salts caused

Table 1. Physical and chemical properties of the experimental topsoil collected from Aucayacu, Huanuco, Peru.

PARAMETER		I	II	III	Mean	S.D.
Granulometric analysis (%)	Sand	40	42	40	40.67	1.15
	Silt	43	39	41	41.00	2.00
	Clay	17	19	19	18.33	1.15
Textural class		Loam	Loam	Loam		
pH (1:1) (w / w)		5.04	5.15	5.23	5.14	0.10
CaCO3 (%)		0.00	0.00	0.00	0.00	0.00
E.C. (1:1) (w / w)($dS.m^{-1}$)		0.25	0.26	0.24	0.25	0.01
Organic matter (%)		1.97	1.95	2.02	1.98	0.04
Available P (ppm)		5.60	5.40	5.80	5.60	0.20
Available K (ppm)		105	116	111	110.67	5.51
Total CEC ($cmol_c.kg^{-1}$)		11.2	10.4	12.72	11.44	1.18
Exchangeable cations ($cmol_c.kg^{-1}$)	Ca^{2+}	5.51	4.17	4.35	4.68	0.73
	Mg^{2+}	0.85	0.78	0.87	0.83	0.05
	K^{+}	0.15	0.29	0.3	0.25	0.08
	Na^{+}	0.12	0.15	0.12	0.13	0.02
	Al^{3+} / H^{+}	0.10	0.10	0.10	0.10	0.00
Effective CEC ($cmol_c.kg^{-1}$)		6.73	5.49	5.74	5.99	0.66
% Acid saturation		1.49	1.82	1.74	1.68	0.17
% Base saturation		98.51	98.18	98.26	98.32	0.17
% Na saturation		1.78	2.73	2.09	2.20	0.48
Initial available silicon – SiA (ppm)*		11.19	10.85	13.29	11.78	1.32

Source: Laboratory of Analysis of Soils, Plants, Water and Fertilizers, UNALM (2017).
Laboratory of silicon, UNALM (2018)*.

low salinity levels. This soil can be considered as strongly acidic, which relates to the big annual precipitation and consequently, lacks calcium carbonate. Organic matter content remained at 1.98 %, which is considered high in relation to the 18 % of clay. This indicates that lack of oxygen is delaying processes of organic matter degradation, which correlates with a paddy field in constant state of saturation. This analysis was considered as the basis for designing the fertilization plan together with the nutrients' absorption curves provided by Bertsch (2009). The initial availability of silicon in the soil (Table 1) and amendments (Table 2) were also analyzed. This information was used to calculate how much of each amendment had to be mixed with the soil in the pots: Slag 100 ppm – 92.82 g per pot. Slag 200 ppm – 185.65 g per pot. Slag 400 ppm – 371.3 g per pot. Ash 100 ppm – 99.95 g per pot, Ash 200 ppm – 199.92 g per pot, Ash 400 ppm – 399.83 g per pot. KSi 100 ppm – 16.05 g per pot, KSi 200 ppm – 32.1 g per pot, KSi 400 ppm – 64.21 g per pot. Additionally, a chemical profile analysis of these same amendments was carried out. (Table 2). The seeds received a heat treatment at 40 □ for 48 hours to break the dormancy prior to sowing in order to ensure uniform germination. The pots' drainage holes were covered with duct tape. A total of 5.7 kg air-dried fine soil was separated for each pot in mixture with the diammonium phosphate and the correspondent treatment of rice husk ash and ladle furnace slag. One day before sowing, the pots were watered until saturation point. Potassium silicate treatments got their first doze with this first watering. Subsequently, sowing was carried out by placing 30 seeds per pot at a depth of approximately 1.5 cm. After ten days, only three plants per pot were left and after 20 days, only the most vigorous plant was left in the pot. The main agronomic activity was irrigation. A total of 57 L of water per pot was needed for finishing all crop cycle. Nitrogen fertilization was separated into five moments and potassium fertilization into one single application. Additionally, corrective measures had to be taken when some leaks appeared in the pots by placing patches with duct tape, plastic bags and paraffin wax. Apart from that, plastic cover was used as isolating material when temperatures went below of those recommended for rice development (18 □).

Table 2. Complete chemical profile of the three silicon sources (total content) and availability of silicon (SiA).

ELEMENT (ppm)	AMENDMENT Slag*	Ash**	KSi***
P_2O_5	1 100	2 000	100
K_2O	32 300	22 900	170 000
CaO	340 200	45 600	224
MgO	79 900	9 800	42
S	10 700	0	0
Fe	50 000	2 450	31
Cu	224	90	2
Zn	401	290	3
Mn	13 950	1 200	3
Pb	1 551	2	26
Cd	10	8	1
Cr	862	3	18
SiA	6 248	5 802	36 130

Source: Laboratory of Analysis of Soils, Plants, Water and Fertilizers, UNALM (2018) and Laboratory of silicon, UNALM (2018).

Note: Slag* stands for ladle furnace slag; Ash**, for rice husk ash and KSi*** for potassium silicate.

Assessment of variables

One pot per treatment was chosen for electrical conductivity and soil pH assessment. At the end of the experiment, all pots were evaluated for these variables. The first two weeks of the experiment, the samples were obtained using a spoon within the upper 2 cm from the surface. From week three onwards, a cylindrical sampler (15 cm x Ø 2.5 cm) was used to reach more depth in the pots' profile. Benchtop potentiometers and conductivity meters were used for sample analysis on a 1:1 (w / w) dilution rate methodology with deionized water (Mass & Hoffman, 1977). Temperature was measured every 15 minutes (from sowing until day 173 after sowing). Data was stored in the thermohygrometer memory for further processing. Light intensity was measured using the lux meter and data was manually registered in a data base. The daily light integral was calculated according to the methodology of Torres and Lopez (2012) with the support of the transformation constants from McCree (1981). Morphological parameter evaluations were performed after harvest, between day 171 and day 182 after sowing. Roots were separated from aerial organs using a band saw, in order to assess root volume, by the water displacement methodology using a beaker and a graduated cylinder. Samples were placed in labeled paper bags and placed in an electric stove at 65 □ for 72 hours. After this period, whole plant's dry weight was obtained. The number of tillers per plant, panicles per plant and spikelets per plant were manually counted. From these data, the average number of spikelets per panicle was calculated as well as the estimated grain yield per plant. Root samples and aerial parts samples were grounded separately in a laboratory mill and passed through a 1 mm sieve, in order to carry out the chemical analyzes. Silicon concentration in plant tissue was analyzed taking into consideration the NaOH fusion methodology detailed by Parra et al. (2004). Available silicon in soil (SiA) samples were measured according to the $CaCl_2$ 0.01 M methodology, detailed by Pereira et al. (2007).

Results and discussions

Effect of the silicon amendments in the chemical properties of the soil samples

It is necessary to clarify that, despite silicon is the second most abundant element in the earth's crust after oxygen - 28.8 % (w / w) – (Wedepohl, 1995), most of this element is not available to plants. According to Matichenkov and Bocharnikova (2001), silicon is found in three fractions in soils: (a)the solution fraction, (b) weakly adsorbed fraction and (c) the solid phase. The solution fraction and the slightly adsorbed fraction involve monosilicic acids, polysilicic acids and organosilicate compounds. On the other hand, the solid fraction is composed of biogenic amorphous forms, such as phytoliths; or non-biogenic forms such as amorphous silica, as well as crystalline forms, which can be finely dispersed (micas, kaolinite, illite, smectite) or minerals dispersed in large pieces such as feldspars and quartz. The predominant form of silicon between pH 4.5 and 8 is H_4SiO_4 (Elgawhary & Lindsay, 1972), which is also the available form to plants, according to Epstein (1994). It fluctuated from 0.1 mM to 0.6 mM (9.6 ppm to 57.6 pm) under conditions of pH range of

4.5 to 8. This is 375 times higher than the 0.0016 mM phosphorous concentration, according to the same author. Nonetheless, solubility depends on type of mineral, temperature, pH, texture, organic matter and land usage history (Struyf et al., 2010). For this experiment, the resulted initial SiA was 11.78 ppm (Table 1), which is located very close to the lower limit stablished by Epstein (1994). In order to raise silicon availability to 100 ppm, 200 ppm and 400 ppm, it was necessary to analyze SiA for rice husk ash, ladle furnace slag and potassium silicate (Table 2). Both two pieces of information were useful to calculate the amount of each silicon amendment for every treatment. Apart from that, all three silicon amendments were subjected to a complete chemical characterization (Table 2). It is necessary to clarify that such dozes were not commercial, therefore salinity and acidity variations were monitored for the entire crop's cycle. Figure 1, Figure 2 and Figure 3 show electrical conductivity changes taking into consideration the days after sowing and phenology. Salinity assessment took place for 14 weeks. It is possible to see that all control treatments (0 ppm) experienced increases since the first week of evaluation, because of pre-sowing fertilization and irrigation water. Within the treatments, all curves behaved similarly, corroborating that maintenance labors were the same for all. Higher dozes portrayed the higher values of electrical conductivity. Changes in the sampling method explained in the previous section tell why E.C. levels during first two weeks seems higher than the third one. Surface soil is always richer in salt content because of evaporation. Same material was used for keeping track of soil pH variations. Figure 4, Figure 5 and Figure 6 show pH behavior during the crop's cycle. Rice husk ash treatments remained almost invariable in relation to the control unit. Potassium silicate treatments showed high values for first and second week because of the sampling methodology formerly explained, however all its dozes kept higher than the control. Ladle furnace slag showed a consistent rise in pH since the first week. At the end of the field stage, all experimental units were analyzed for electrical conductivity and pH. Table 3 summarizes E.C. data showing that all treatments were statistically similar to the control units, except for 200 ppm and 400 ppm slag treatments, which portrayed significant differences. In spite of this, average of 2.25 dS · m^{-1} is not detrimental for rice

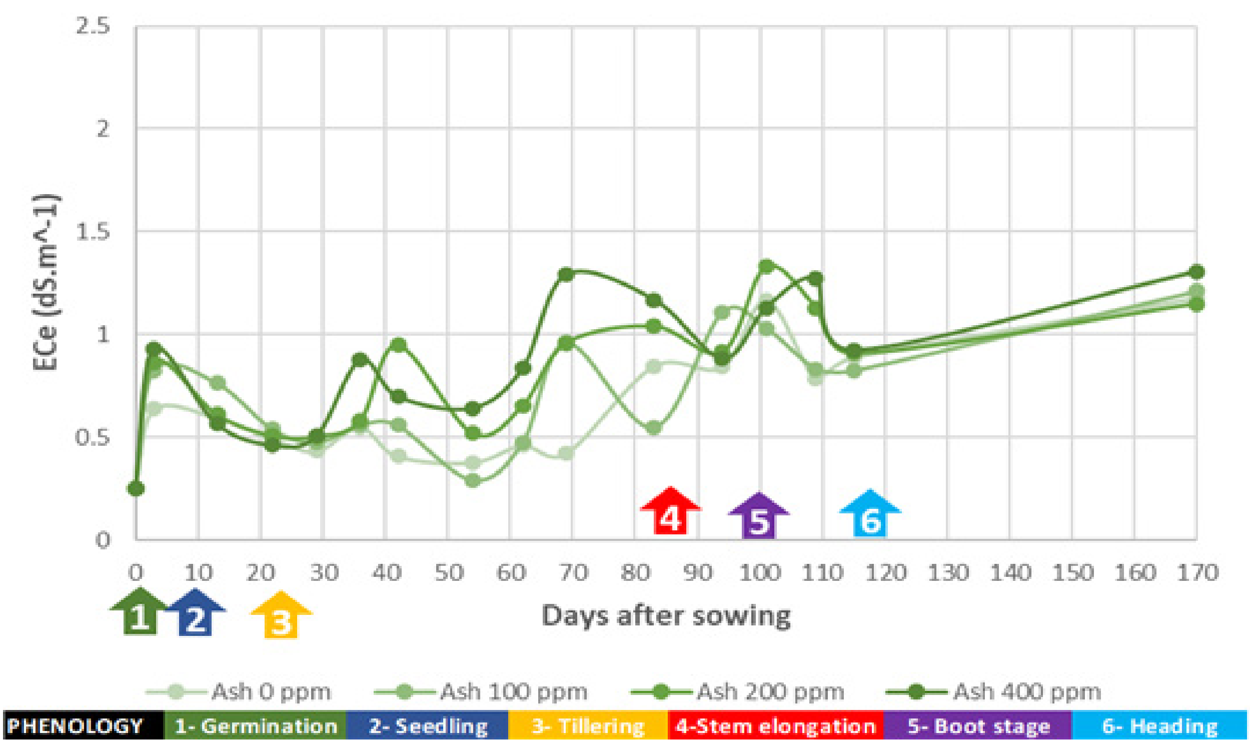

Figure 1. Fluctuation of ECe (*dS.m*$^{-1}$) for all rice husk ash treatments (Ash Xppm) during the field stage of the experiment.

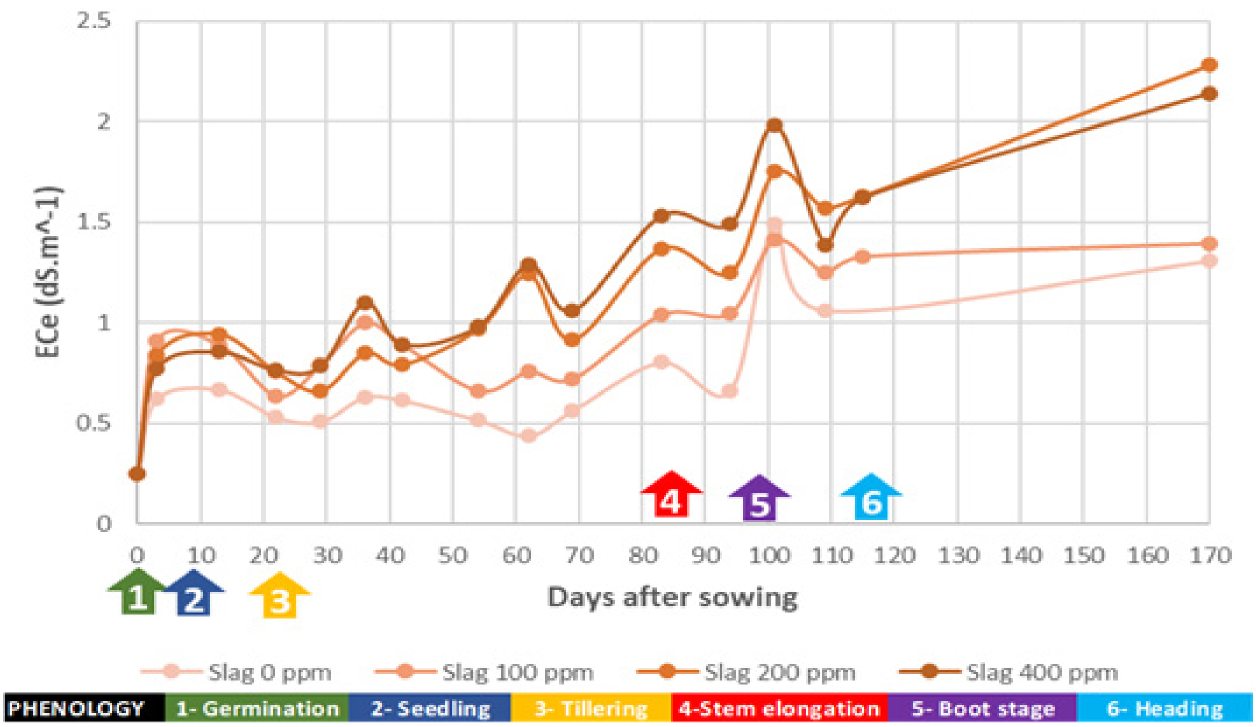

Figure 2. Fluctuation of ECe (*dS.m*$^{-1}$) for all ladle furnace slag treatments (Slag Xppm) during the field stage of the experiment.

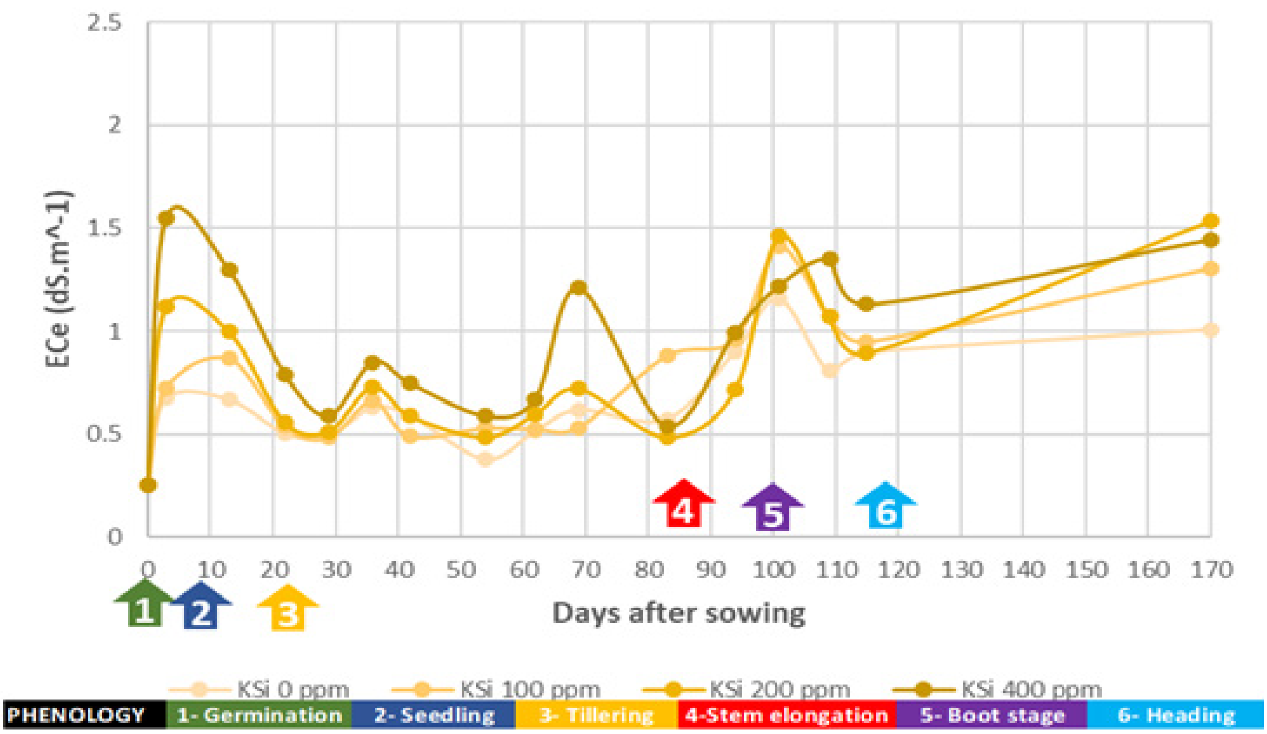

Figure 3. Fluctuation of ECe (*dS.m*$^{-1}$) for all potassium silicate treatments (KSi Xppm) during the field stage of the experiment.

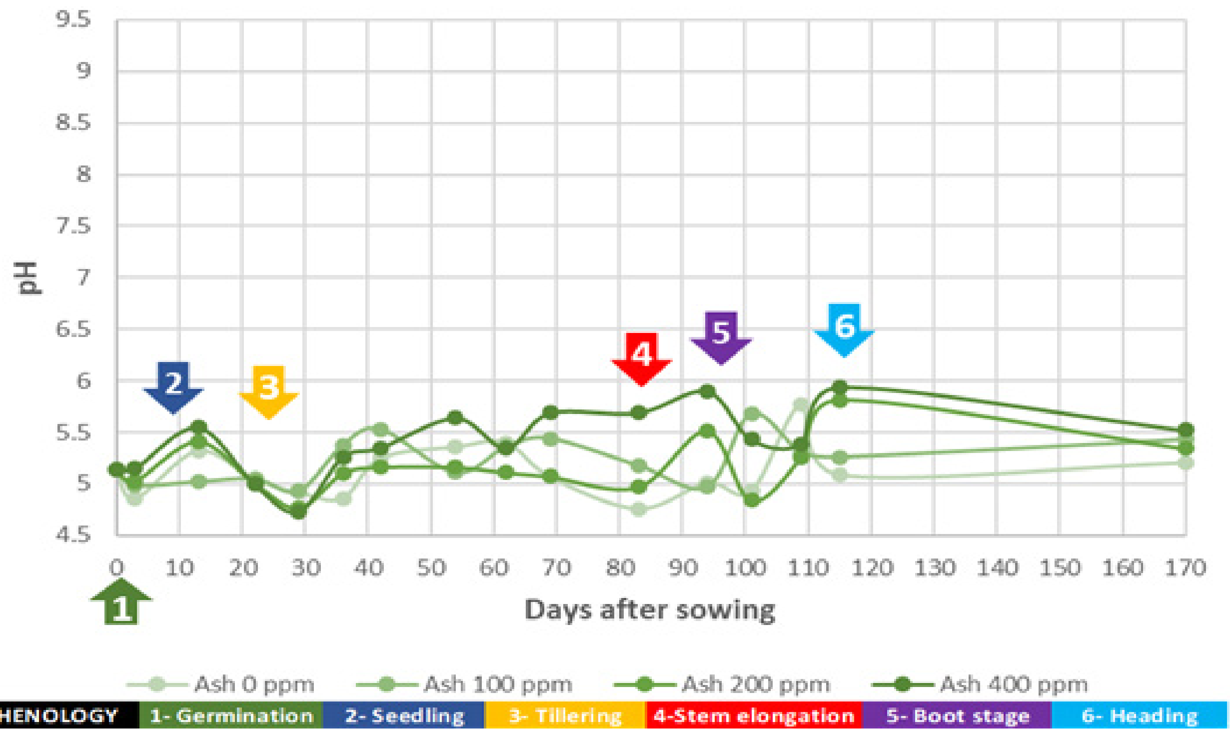

Figure 4. Fluctuation of soil pH for all rice husk ash treatments (Ash Xppm) during the field stage of the experiment.

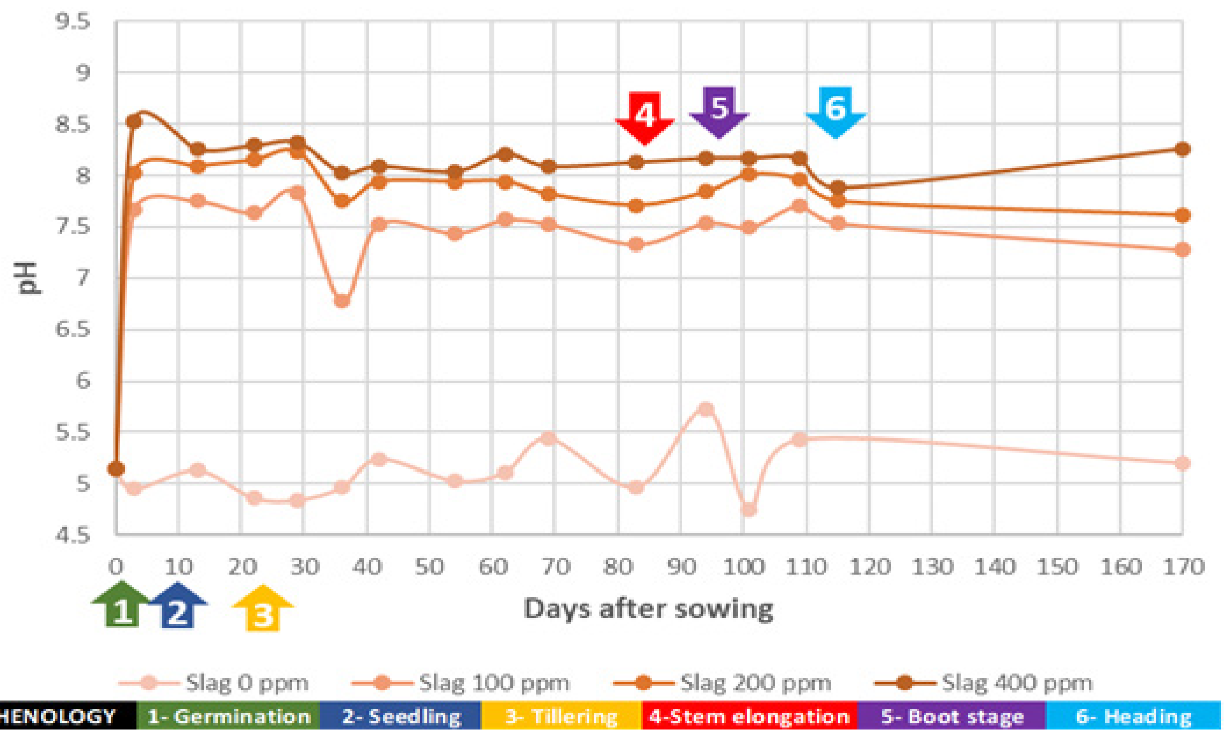

Figure 5. Fluctuation of soil pH for all ladle furnace slag treatments (Slag Xppm) during the field stage of the experiment.

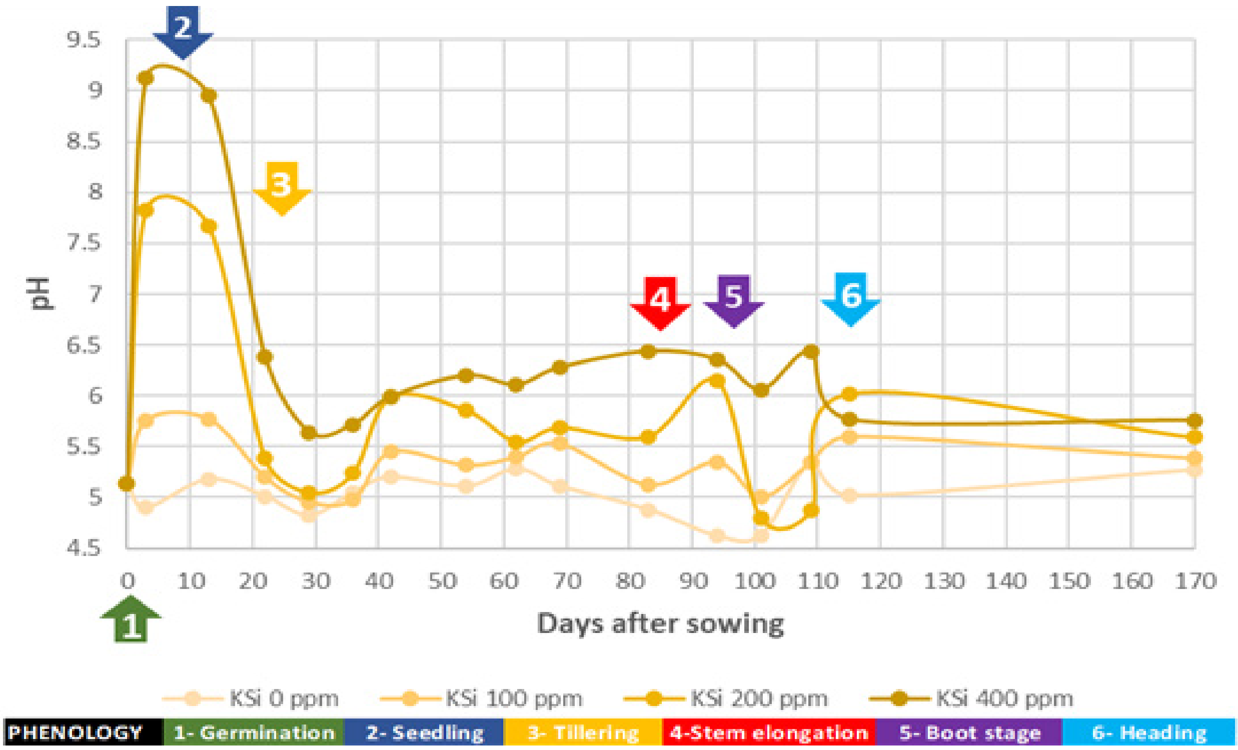

Figure 6. Fluctuation of soil pH for all potassium silicate treatments (KSi Xppm) during the field stage of the experiment.

development, as Yoshida (1981) explained that this crop tolerates up to 4.5 dS · m^{-1}. This indicates that even high dozes of those products will not rise salinity at dangerous levels for rice. Table 4 summarizes soil pH data, showing that slag 200 and 400 ppm treatments were significantly different from the control units and the rest of treatments. Furthermore, 400 ppm doze had the highest values, which goes in accordance with findings from Ning et al. (2016). Average pH of 8.26 made it impossible for rice plants to develop properly. Liang et al. (2015) explained that slags have a high liming property because silicon is found in the form of calcium silicate and magnesium silicate, which are formed due to the high temperature conditions in the steel furnaces. In table 2 is possible to see the chemical composition of the ladle furnace slag. It indicates that concentrations of CaO reached 340,200 ppm and MgO reached 79,900 ppm, the highest among all elements. This explains such high pH values. Table 5 summarizes root volume data. Its information corroborated the lack of plant growth with the poor root growth for 200 ppm and 400 ppm slag treatments, which were significantly smaller than the control units. The rest were statistically similar to the control units.

Effect of treatments on availability and absorption of silicon

Table 6 summarizes silicon availability (SiA) at the end of the field stage of the experiment. Taking into consideration that initial SiA for this soil was 11.78 ppm (Table 1), it is possible to see that after 170 days such value slightly changed in the control pots, which show means of 16.78 ppm, 14.53 ppm and 11.93 ppm (consider the transformation). All those control treatments were statistically similar. Therefore, concluding that without the addition of any silicon amendment, SiA did not change. Regarding rice husk ash treatments, the lowest doze and the highest one ended up with 15.99 ppm, statistically similar to control units. Perhaps, temperatures above 700 □ which take place during the rice husk combustion may have altered silicon forms, making its solubility to last for short periods of time (Le-Blond et al., 2010). Potassium silicate (KSi) 100ppm reached 20.23 ppm SiA (pH 5.38), while KSi 200ppm reached 30.31 ppm SiA (pH 5.59), this goes along with Epstein (1994) who stablished that for pH of 4.5 to 8, SiA fluctuated from 9.6 ppm to 57.6 pm. However, 30.31 ppm is very far from the 200 ppm initially calculated. Liang et al. (2015) explained that higher concentrations cannot be achieved

Table 3. Statistical summary of the soil electrical conductivity - ECe (dS.m^{-1}) data at the end of the campaign, transformed with . Significance levels were obtained from Tukey test, α = 0.05.

SiA Source	ppm	Mean	Min.	Max.	Rep.	S.D. (× 10^{-2})	Sg.
Slag	200	1.24	1.19	1.28	3	4.65	a
Slag	400	1.21	1.16	1.28	5	5.25	a
KSi	200	1.11	1.10	1.15	4	2.27	b
KSi	100	1.07	1.05	1.08	4	1.12	bc
Ash	400	1.07	1.02	1.09	5	3.00	bc
Slag	0	1.07	1.02	1.10	5	3.63	bc
Ash	100	1.05	1.03	1.07	4	1.79	bc
Ash	0	1.04	1.00	1.07	5	3.28	bc
KSi	0	0.99	0.91	1.08	4	7.01	c

Note: Slag stands for ladle furnace slag; Ash, for rice husk ash and KSi, for potassium silicate

Table 4. Statistical summary of soil pH data at the end of the campaign. Significance levels were obtained with Tukey test, α = 0.05.

SiA Source	ppm	Mean	Min.	Max.	Rep.	S.D. (× 10^{-1})	Sg.
Slag	400	8.26	7.86	8.40	5	2.28	a
Slag	200	7.72	7.61	7.87	3	1.32	b
KSi	200	5.59	5.36	5.82	4	2.22	c
Ash	400	5.52	5.32	5.66	5	1.31	c
Ash	100	5.43	5.20	5.57	4	1.62	c
KSi	100	5.38	5.24	5.45	4	1.00	c
KSi	0	5.27	4.99	5.60	4	2.54	c
Ash	0	5.20	4.99	5.40	5	1.51	c
Slag	0	5.20	5.07	5.45	5	1.53	c

Note: Slag stands for ladle furnace slag; Ash, for rice husk ash and KSi, for potassium silicate.

Table 5. Statistical summary of root volume (cm^3) data, transformed with . Significance levels were obtained with Tukey test, α = 0.05.

SiA Source	ppm	Mean	Min.	Max.	Rep.	S.D. (× 10^{-1})	Sg.
Ash	400	6.68	6.35	7.07	5	2.83	a
KSi	200	6.38	6.20	6.56	4	1.49	ab
KSi	0	6.27	5.93	6.73	4	3.71	ab
Ash	0	6.22	5.71	6.49	5	3.00	ab
Ash	100	6.14	6.03	6.32	4	1.23	b
KSi	100	6.13	6.02	6.24	4	1.00	b
Slag	0	5.99	5.66	6.19	5	2.13	b
Slag	200	1.88	1.52	2.17	3	3.31	c
Slag	400	1.51	1.23	1.67	5	1.71	c

Note: Slag stands for ladle furnace slag; Ash, for rice husk ash and KSi, for potassium silicate.

Table 6. Statistical summary of available silicon-SiA (ppm) data at the end of the campaign, transformed with . Significance levels were obtained with Tukey test, α = 0.05.

SiA Source	ppm	Mean	Min.	Max.	Rep.	S.D. ($\times 10^{-2}$)	Sg.
Slag	400	1.88	1.79	1.93	5	5.29	a
Slag	200	1.77	1.74	1.79	3	2.49	a
KSi	200	1.62	1.57	1.66	4	4.47	b
KSi	100	1.53	1.50	1.56	4	3.09	bc
KSi	0	1.49	1.42	1.58	4	7.64	cd
Ash	100	1.48	1.45	1.56	4	5.39	cd
Ash	400	1.48	1.45	1.53	5	3.21	cd
Ash	0	1.46	1.41	1.57	5	5.98	cd
Slag	0	1.42	1.37	1.47	5	4.23	d

Note: Slag stands for ladle furnace slag; Ash, for rice husk ash and KSi, for potassium silicate.

at that pH levels, otherwise silicon polymerizes or precipitates into non-soluble forms. On the other hand, ladle furnace slag treatments resulted in higher pH (Table 4), consequently SiA was higher for all the treatment. Slag 200ppm treatment reached 28.43 ppm SiA (pH 7.72) while the Slag 400ppm treatment, 86.87 ppm (pH 8.26), which agrees with Liang et al. (2015). Table 7 summarizes Si% in roots. All potassium silicate and rice husk ash treatments were statistically similar to the control pots. Even KSi 200 ppm treatment, whose silicon availability was statistically higher than the control units (30.31 ppm SiA - Table 6) remained similar to control units for %Si in roots, showing that such availability did not impact this element's concentration in root tissue. Conversely, both slag treatments showed significant differences from the control units, being the Slag 400ppm treatment the one that portrayed the lowest Si content with 1.94 %. Table 8 summarizes Si% in aerial organs. In general, such concentrations are smaller than Si% in roots. Raven (2003) explains that H_4SiO_4 is a neutral molecule and can defuse through the lipid components of cell membrane of roots. Thus, it is expected to find higher concentrations in roots than in stems and leaves, because aerial organs got their silicon supply from the xylem sap. In the xylem, the raw sap reaches silicic acid concentrations as high as 20 mM (1920 ppm), 36 times higher than the concentration in the soil solution (Nikolic et al., 2007), however this occurs for a very short period of time, due to the fact that, from 2 mM (192 ppm) the silicon begins to polymerize (Mitani et al., 2005). Much of those molecules are deposited in the xylem vessels where they help them to remain rigid when high transpiration rates take place (Balasta et al., 1989). Silicon leaves the xylem vessels through transporter, OsLsi-6. This transfers the H_4SiO_4 via the symplastic pathway into the parenchyma associated to the xylem. This is an inflow transporter similar to OsLsi-1, but it is also expressed in leaves, stems and in the root tips (Yamaji et al., 2008). Silicon that follows this route ends up being deposited inside specialized cells that store silicon called phytoliths. Also, silicon can leave the xylem vessels by the apoplastic pathway, in which case, the silicon ends up deposited in the cell walls of the epidermis, binding with hemicellulose, as a hydrated amorphous polymer (opal), forming a silicate-cuticle association. The surplus can even escape out of the leaves by guttation (Ma et al., 2011). The reason why some rice varieties accumulate more silicon than others depend on the expression of the transporter genes (Ma et al., 2007b). Control units showed mean values of 2.87 %, 2.82 % and 2.76 % for Si concentration in aerial organs. All rice husk ash and ladle furnace slag treatments were statistically similar to control pots. Potassium silicate at 200 ppm doze was the treatment with the highest silicon absorption (significantly different from control units) with 4.75 %. Almost twice the amount found in the control pots. That treatment was the third in terms of silicon availability with 30.31 ppm SiA (Table 6). The silicon content in plants varies in a very wide range that goes from 0.1% to 10% of the dry weight depending on the species (Epstein, 1994). Within the higher plant species, Poaceae family is the group with the highest relative content of

Table 7. Statistical summary of silicon concentration (%) in roots. Significance levels were obtained with Tukey test, α = 0.05.

SiA Sources	ppm	Mean	Min.	Max.	Rep.	S.D.	Sg.
KSi	200	7.33	6.78	7.92	4	0.46	a
KSi	100	7.29	6.87	7.96	4	0.46	a
Ash	0	7.19	6.15	8.82	5	1.17	a
KSi	0	7.08	4.77	8.53	4	1.71	a
Ash	100	7.03	6.31	8.01	4	0.74	a
Ash	400	6.83	5.93	7.49	5	0.65	a
Slag	0	6.49	5.40	8.08	5	1.06	a
Slag	200	2.64	1.67	3.61	3	0.96	b
Slag	400	1.94	0.78	3.39	5	0.94	b

Note: Slag stands for ladle furnace slag; Ash, for rice husk ash and KSi, for potassium silicate.

Table 8. Statistical summary of silicon concentration (%) in aerial organs. Significance levels were obtained with Tukey test, α = 0.05.

SiA Source	ppm	Mean	Min.	Max.	Rep.	S.D. ($\times 10^{-1}$)	Sg.
KSi	200	4.75	4.54	4.94	4	1.87	a
KSi	100	3.88	3.25	4.26	4	4.49	ab
Ash	400	3.65	3.13	4.36	5	5.01	ab
Slag	400	3.04	1.94	3.95	5	9.73	bc
Ash	100	2.89	2.27	3.23	4	4.50	bc
KSi	0	2.87	2.62	3.43	4	3.82	bc
Ash	0	2.82	2.57	3.01	5	2.05	bc
Slag	0	2.76	2.37	3.51	5	5.16	bc
Slag	200	2.24	2.01	2.43	3	2.14	c

Note: Slag stands for ladle furnace slag; Ash, for rice husk ash and KSi, for potassium silicate.

silicon. (Hodson et al., 2005). The essentiality of this element according to the criteria of Arnon and Stout (1939), has not been proven (Ma et al., 2001). For Epstein (1999), silicon is considered a "quasi essential" element, which is defined by this author as an element which is present in plants and should be provided in determined quantities in order to avoid any strongly-enough deficiency to cause abnormalities in growth and development, otherwise in will be detrimental for agronomic performance. Rice is capable of accumulating up to 10 % of the dry weight in the aerial organs. This concentration is considered much higher than that of most macronutrients such as N, P or K. (Liang et al., 2015). This led to Savant et al. (1997) to deduce that large amounts of Si were required for sustainable rice production. According to Desplanques et al. (2006) the average silicon extraction is 270 kg · ha^{-1} · year^{-1}. Table 9 shows the silicon extraction for whole plants. Control units, extracted means of 5 482 mg, 5 220 mg and 4 917 mg, which were statistically similar to all treatments except for Slag 200 ppm and 400 ppm, which extracted only 26 mg and 11 mg respectively. Plants for such treatments did not grow nor developed because of the high pH levels (Figure 5), therefore the biomass production was negatively affected. Apart from that, ladle furnace slag showed big concentrations of Fe, Cu, Zn, Mn, Pb and Cr (Table 2), hence any possible toxicity should not be discarded. There is extensive discussion on how silicon may relieve toxicity stress (Gu et al., 2011), however this beneficial effect depends on the easiness in which H_4SiO_4 is absorbed. Ma et al. (2007a) mentions that high soil pH and low temperatures reduce the effectiveness of OsLsi-2 transporter, which partner OsLsi-1 (Ma et al., 2004) as the two transporters involved in the active silicon uptake by rice. This is the main route which is not influenced by transpiration flow (Nikolic et al., 2007). Further discussion on this point will take place in the following section. Despite the fact that KSi 200 ppm treatment was the only one which had a significantly higher level of SiA (30.31ppm - Table 6), with suitable soil pH (5.59 - Table 4), silicon absorption was not statistically different from control treatments (Table 9). Similar increase in SiA was found by Yalda et al. (2020) for potassium silicate treatments. There is a possibility that control treatments could have received available silicon with the irrigation water, which was not measured. Other possibility is that the topsoil features and the environmental conditions of the experiment made it possible that the substrate could have solubilized enough silicon to satisfy plants' demand. This is supported by Paye et al. (2018), who argues that positive results on silicon fertilization can be seen only when soils have less than 11 ppm of SiA (using the $CaCl_2$ extraction methodology) and the initial available Si for our topsoil samples was 11.78 ppm, therefore they may have provided enough of this element.

The relation between silicon absorption and yield components

There are four components which determine yield in rice crop: (1) number of panicles per square meter, (2) number of spikelets per panicle, (3) % filled spikelets and (4)1000-grain weight (Yoshida,1981). The experimental unit consisted in a 7.5 L pot with one rice plant, therefore, the first yield component was related to the following morphological variables: number of tillers per plant (Figure 7) and number of panicles per plant (Figure 8). Figure 7 shows that all treatments were statistically similar to the control units, except for the Slag 200 ppm and 400 ppm treatments, which had considerably less tillers. This could be explained because of the detrimental soil pH conditions (Table 4) for those two treatments which made it impossible the normal growth of plants. Contrary to this, Das et al. (2020) found that slag treatments improved soil fertility as it enhanced microbiota activity, however dozes tested in that research work were smaller. According to Yoshida (1981) and Heros (2012), Nitrogen is the main element playing a role during the tillering stage, and all experimental units got the same Nitrogen fertilization. This explains why no enhancements were found in the potassium silicate treatments, despite having Si% increases in aerial organs (Table 8). Figure 8, portraying the number of panicles per plant, did not consider treatments of Slag 200 ppm and 400 ppm because none of them produced a single panicle. The rest of treatments were statistically similar to the control unit, except for the Ash 400 ppm treatment which was significantly superior. Rice husk ash, being an organic amendment, might have improved the physical properties in the pots by reducing the bulk density, helping the roots proliferate better, thus it might have helped to produce more panicles. Figure 9 summarizes whole plant's dry weight. This variable indicates

Table 9. Statistical summary of silicon total extraction (mg) data, transformed with . Significance levels were obtained with Tukey test, $\alpha = 0.05$.

SiA Source	ppm	Mean	Min.	Max.	Rep.	S.D.	Sg.
KSi	200	14.89	14.63	15.13	4	0.20	a
KSi	100	14.22	14.08	14.30	4	0.09	ab
KSi	0	13.58	12.32	14.87	4	1.07	ab
Ash	0	13.38	12.97	14.25	5	0.58	b
Ash	400	13.32	12.57	14.03	5	0.58	b
Ash	100	13.24	12.70	13.77	4	0.43	b
Slag	0	13.14	12.53	14.00	5	0.58	b
Slag	200	2.69	1.94	3.54	3	0.80	c
Slag	400	2.08	1.39	2.44	5	0.42	c

Note: Slag stands for ladle furnace slag; Ash, for rice husk ash and KSi, for potassium silicate.

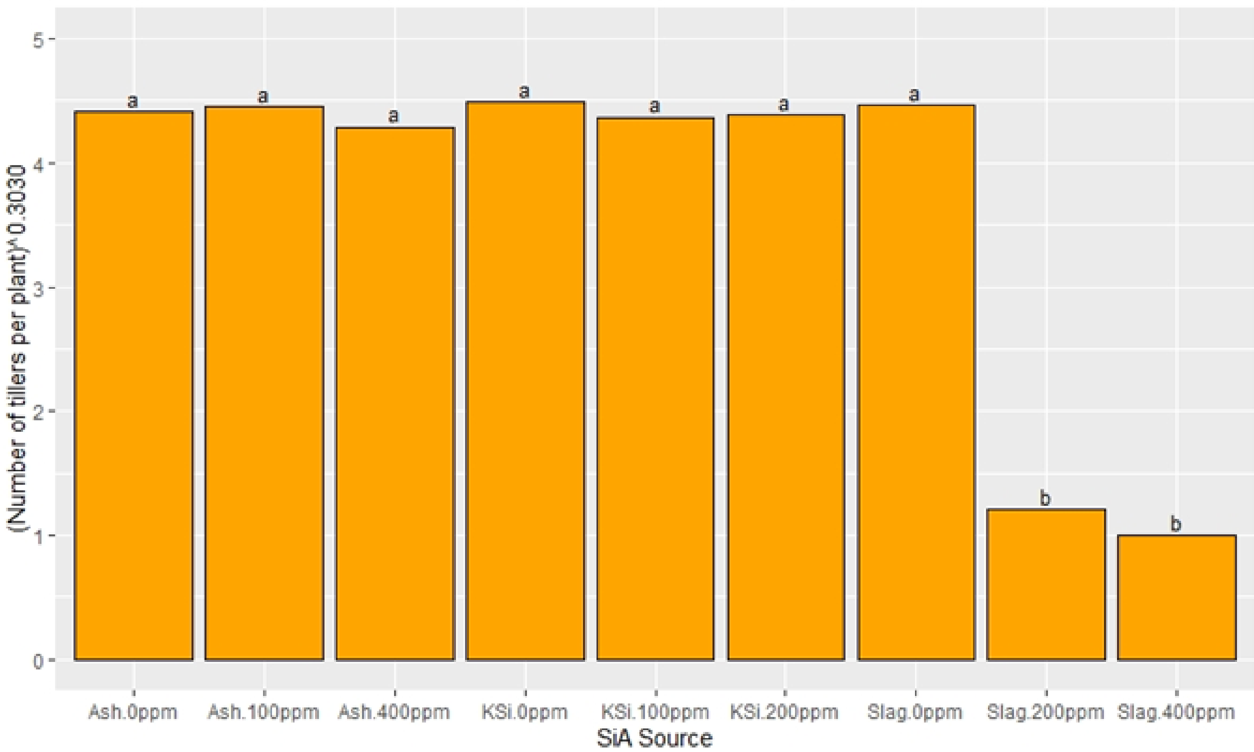

Figure 7. Statistical summary of (*Number of tillers per plant)*$^{0.3030}$. Significance levels were obtained with Tukey test, α = 0.05. Ash stands for rice husk ash; KSi, for potassium silicate and Slag, for ladle furnace slag.

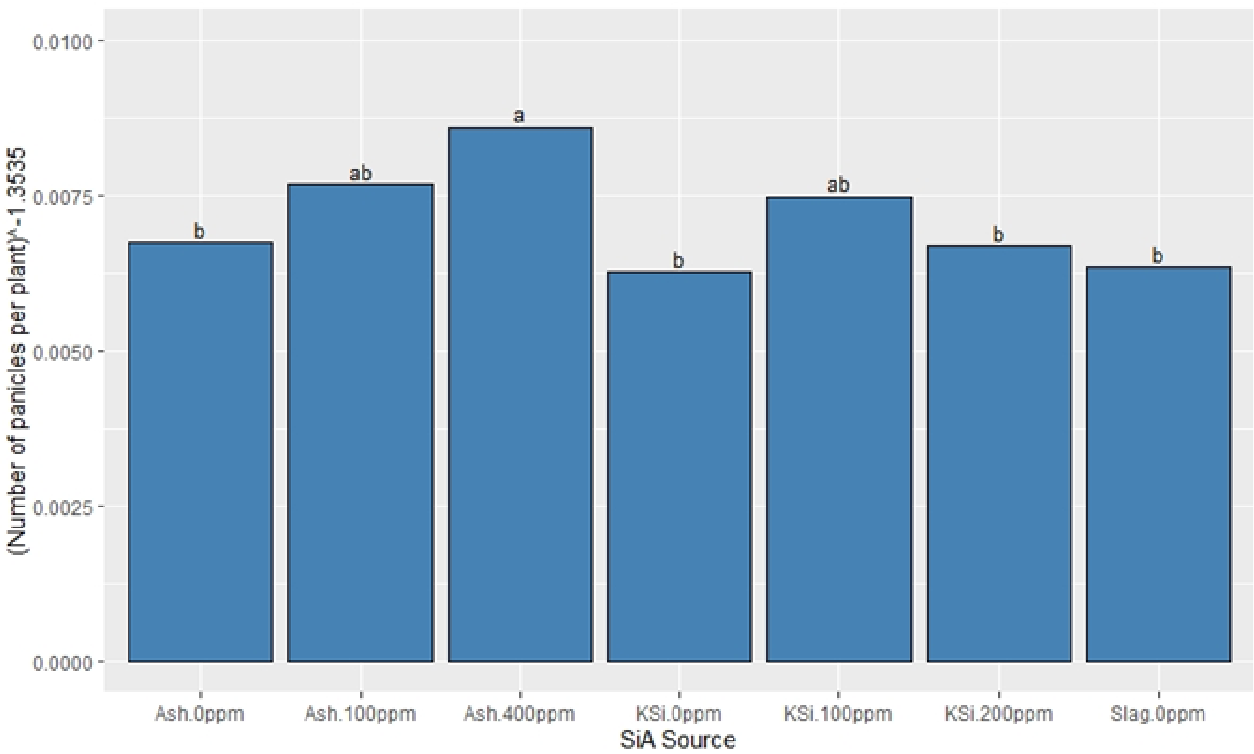

Figure 8. Statistical summary of (*Number of panicles per plant)* $^{-1.3535}$. Significance levels were obtained with Tukey test, α = 0.05. Ash stands for rice husk ash; KSi, for potassium silicate and Slag, for ladle furnace slag.

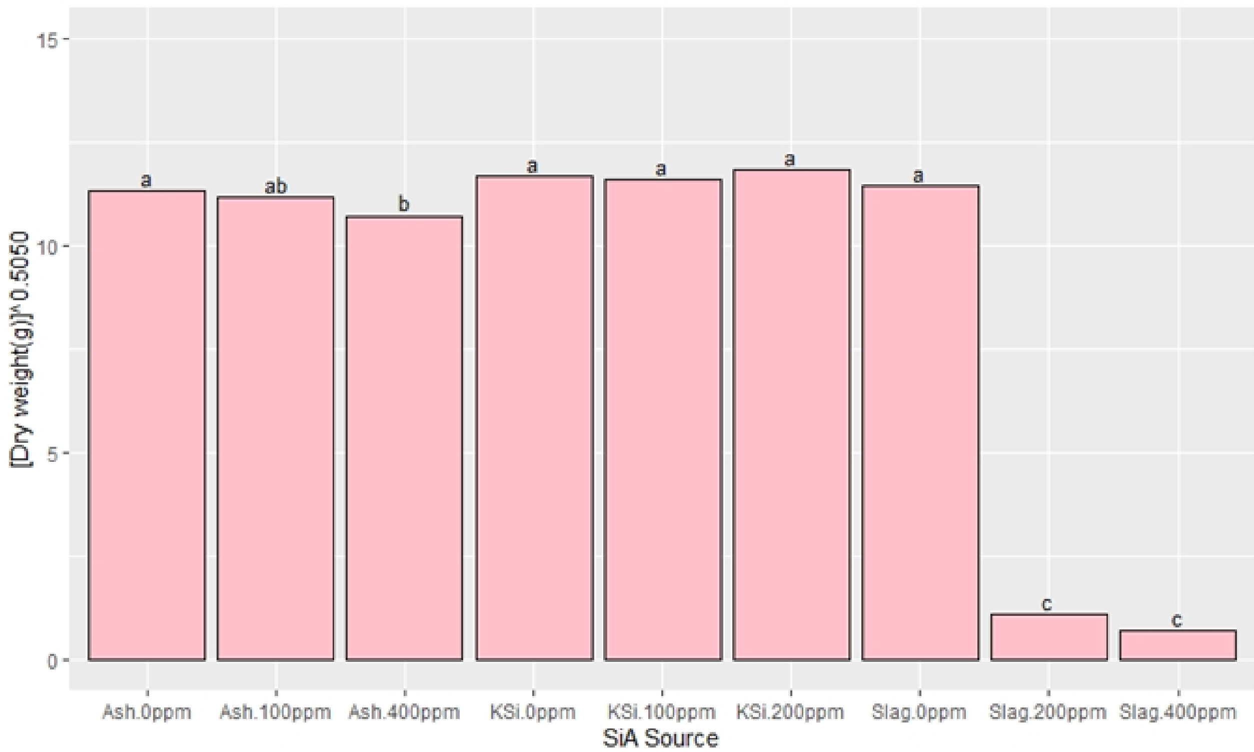

Figure 9. Statistical summary of whole plant's [Dry weigh$_{t(g)}$]$^{0.5050}$. Significance levels were obtained with Tukey test, α = 0.05. Ash stands for rice husk ash; KSi, for potassium silicate and Slag, for ladle furnace slag.

the total amount of photosynthates produced by each plant. It behaved similarly to the number of tillers per plant, however it is possible to see that Ash 400 ppm treatment had significantly lower values for this variable than the control units, despite having the highest amount of panicles (Figure 8). This could be explained because rice husk ash provides large quantities of Ca, Mg and P (Table 2), therefore that reduction in dry weight in comparison with control units could have been attributed to a slight toxicity. Figure 10 summed up the second yield component, average number of spikelets per panicle. No significant differences were found in relation to the control units. Slag 200 ppm and 400 ppm treatments were not considered for this analysis because their experimental units did not produce any panicle. This yield component was not influenced by higher availability of silicon. The third yield component was 0 % because temperatures below 18 □ happened during the beginning of the stem elongation stage, which coincide with the transition to the reproductive stage (Figure 11), also pointed out by Hasanuzzaman et al. (2013), in which case, higher availability of silicon did not alleviate cold stress. The fourth yield component was estimated according to Abad (2017) who tested the same cultivar in the Amazonian region of San Martin and considering 90% of grain set per panicle. Thus, an estimated grain yield per plant was obtained portrayed in Figure 12. All treatments were statistically similar to the control units. Slag 200 ppm and 400 ppm treatments were excluded from this analysis for the reasons formerly explained. According to Table 2, potassium silicate provided mainly silicon and potassium, in contrast with the rice husk ash and ladle furnace slag, which also incorporated big amounts of P, Ca, Mg, Fe and Mn, as well as Pb and Cr. Such big quantities could have played a detrimental role in those treatments' yield components, however further tissue analysis must be executed to discard any toxicity or deficiency. Light intensity was also measured. Results are shown in Figure 13. According to Yoshida (1981), ideal levels of Photosynthetic Active Radiation (PAR) for rice is 300 cal • cm^{-2} • day^{-1} (57 mol • m^{-2} • day^{-1}). It is possible to see that optimal levels were found until the beginning of the reproductive stage (May 10th 2018). Camargo et al. (2007) and Pati et al. (2016) stated that high silicon concentration in rice tissues correlates

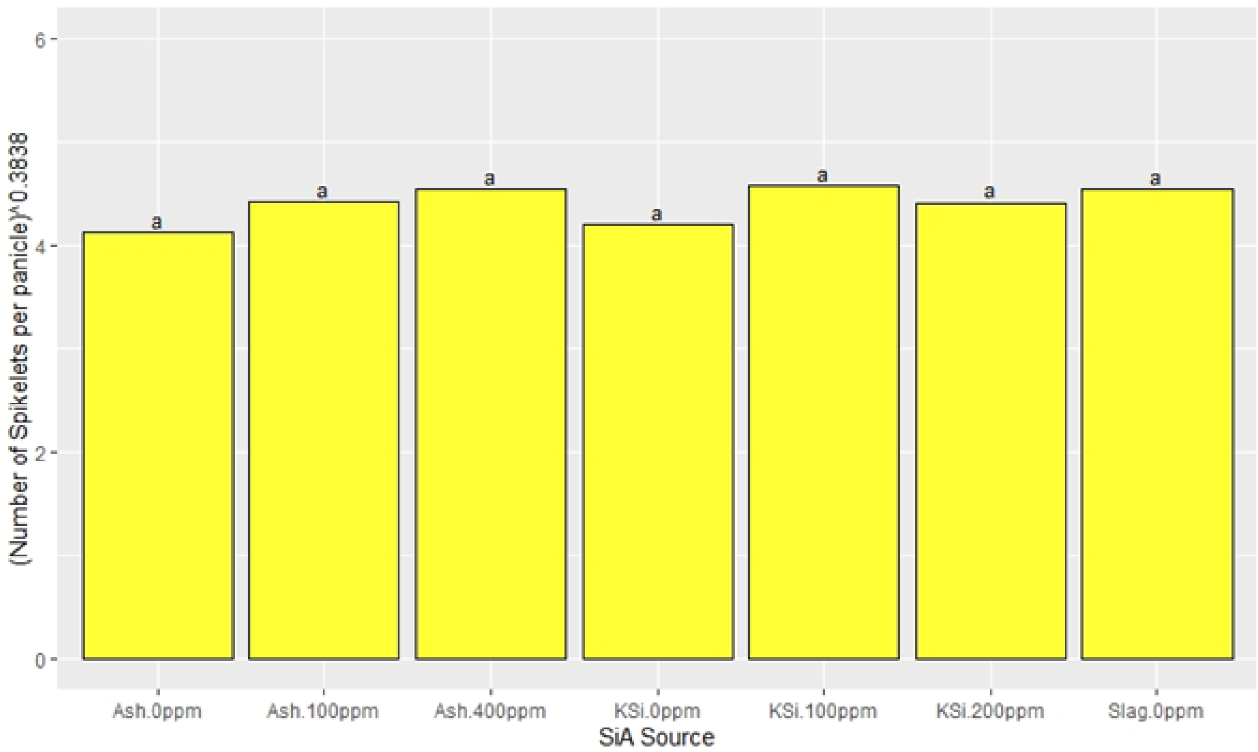

Figure 10. Statistical summary of (*Number of Spikelets per panicle*)$^{0.3838}$. Significance levels were obtained with Tukey test, α = 0.05. Ash stands for rice husk ash; KSi, for potassium silicate and Slag, for ladle furnace slag.

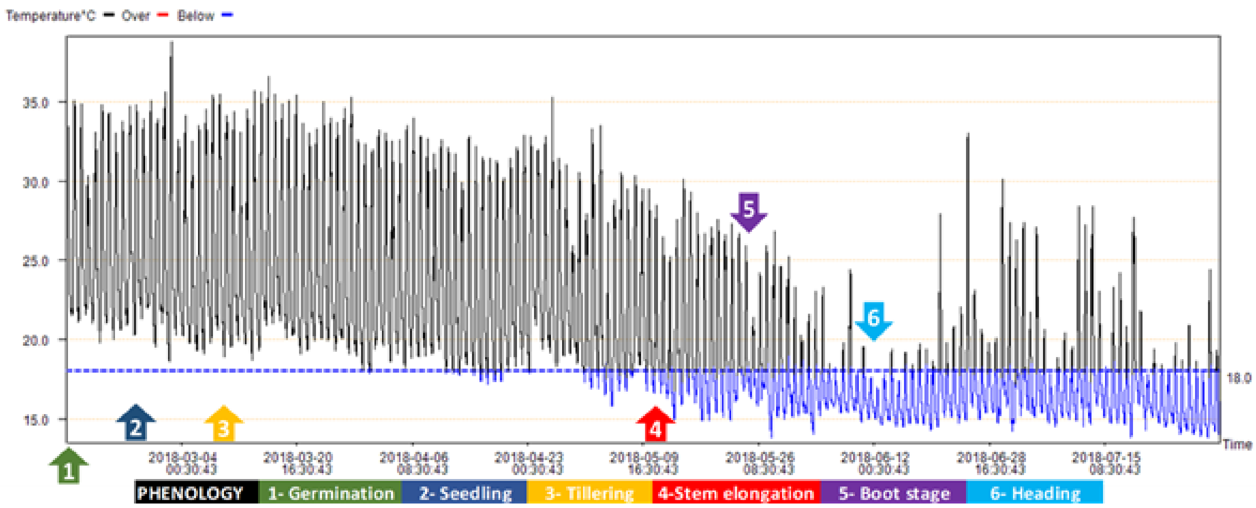

Figure 11. Environmental temperature's fluctuation registered during the field stage of the experiment. Graphic was generated using the Elitech termohigrometer's software.

with yield increasing, however, this experiment did not reflect such findings. All current and past research highlights the benefits of silicon on yield enhancements; however, it focuses on tolerance to various forms of stress, both biotic and abiotic (Meharg & Meharg, 2015) Therefore, it would be incorrect to manage silicon nutrition as if it was nitrogen. Applying higher doses of this element did not improve rice yield components, under this experiment's-controlled conditions. There should be any unfavorable condition, such as presence of pests, diseases, water stress or deficit SiA, in order to see silicon fertilization's beneficial effects. Further research in other areas of Peru, where available silicon in soils is depleted, should be considered.

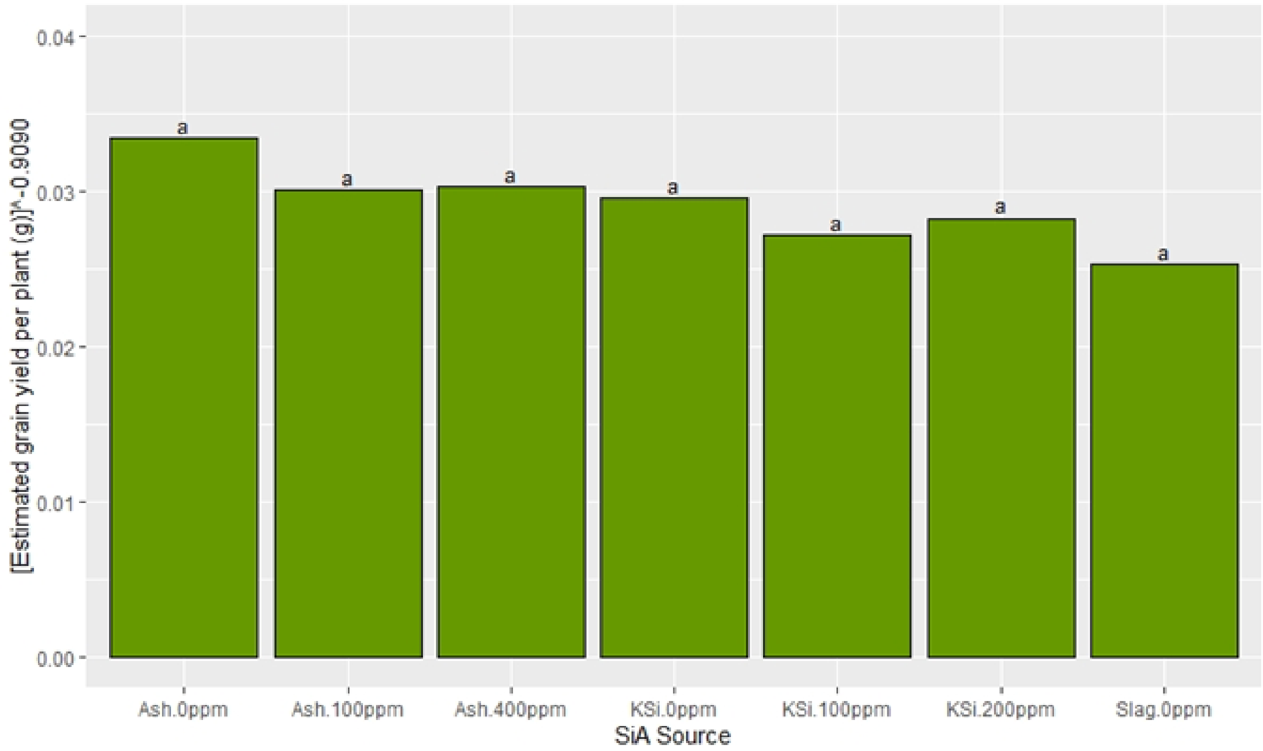

Figure 12. Statistical summary of [*Estimated grain yield per plant* $_{(g)}$] $^{-0.9090}$. Significance levels were obtained with Tukey test, α = 0.05. Ash stands for rice husk ash; KSi, for potassium silicate and Slag, for ladle furnace slag.

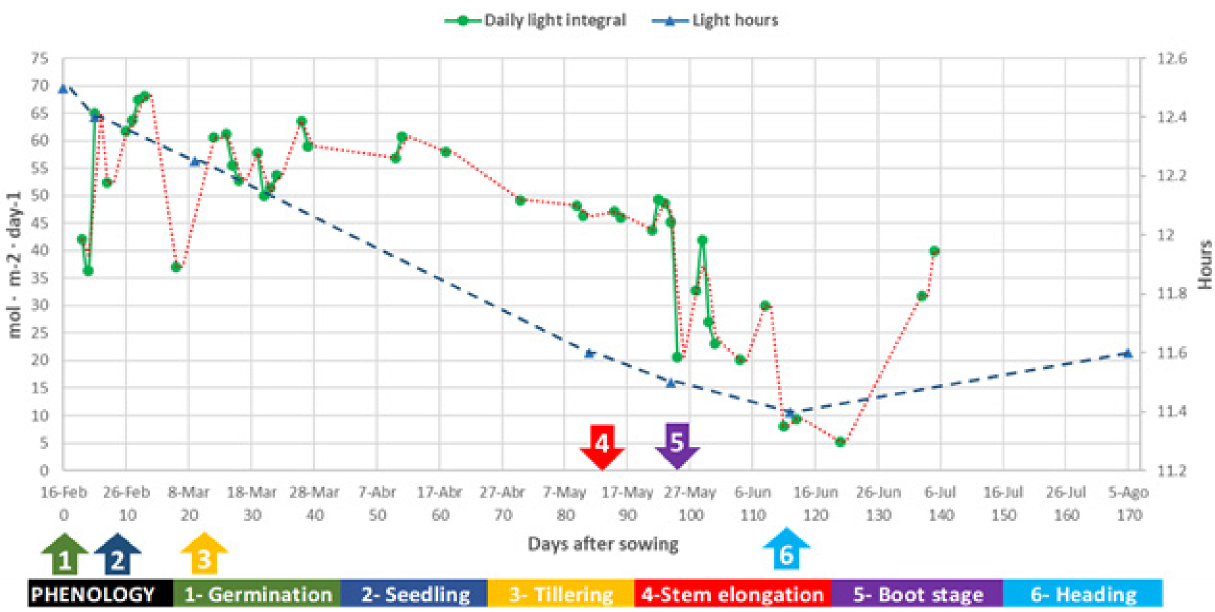

Figure 13. Fluctuation of the Photosynthetic Active Radiation-PAR, expressed as the Daily Light Integral (*mol·m*$^{-2}$ *day*$^{-1}$) and Light hours during the field stage of the experiment.

Conclusions

- Despite having two treatments with a significantly higher level of salinity, all of them remained within the tolerance limits for rice crops.
- Soil pH changed according to the treatment. Rice husk ash and potassium silicate treatments kept soil pH statistically similar to control units, however ladle furnace slag treatments significantly raised this variable. 200 ppm and 400 ppm ladle furnace slag treatments detrimentally affected growth and development of rice plants. Further tissue analysis should determine any deficiency or toxicity.
- Rice husk ash and ladle furnace slag have considerable amounts of other nutrients, nonetheless, ladle furnace slag demands further attention as it also contains some heavy metal elements such as Cr, Cd, Pb, Cu and Zn.
- Silicon availability did not keep the original concentration of 100 ppm, 200 ppm and 400 ppm. Possibly such high concentrations forced silicon polymerization. Control units variated varied from 11.78 ppm to 15 ppm at the end of the campaign.
- Potassium silicate treatments were considered as the base point for contrasting the silicon effects in the yield components, due to the fact that this amendment supplied predominantly silicon and potassium, while other elements' concentration were insignificant.
- Treatments which kept the higher levels of silicon availability without causing growing problems, were the potassium silicate treatments. In the same fashion, they had the higher silicon concentration in tissues.
- Higher silicon concentration in tissues did not correlate with any yield component's enhancement, for the given test conditions.

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Conflicts of interest

The signing authors of this research work declare that they have no potential conflict of personal or economic interest with other people or organizations that could unduly influence this manuscript.

Author contributions

Elaboration and execution, Development of methodology, Conception and design; Editing of articles and supervision of the study have involved all authors.

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