Alkalinity–silicon ratio as an assessment factor for the efficiency of silicate slags in wetland rice

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Silicate slags are one of the most widely used silicon (Si) source in agriculture. Even though the agronomic significance of slags has been demonstrated in several crops, only a few attempts were made to evaluate these Si sources based on their chemical composition. The main objective of this study was to characterize different silicate slags based on their chemical properties and to explore the effect of these chemical properties on the yield, and Si uptake in wetland rice, and dissolution of Si into the soil. Slags were characterised for pH, calcium and magnesium content (alkalinity, A), silicon content, 5 day Na₂CO₃ + NH₄NO₃ extractable Si content, and alkalinity to Si ratio (A/Si). Greenhouse and incubation experiments were also conducted using different silicate slags and wollastonite applied at the rate of 300 kg Si ha⁻¹. Slags with A/Si < 3 were found to be ideal Si sources for the economic production of wetland rice and found consistent in increasing soil Si content and rice Si uptake. We conclude that the A/Si ratio of slags can be used as an important parameter to assess the agronomic efficiency of silicate slags in wetland rice.

Rice is the staple food crop of more than half of the world’s population. It is cultivated in about 160.9 m ha with a production of 719.7 mt under four major ecosystems viz. irrigated (57%), rainfed lowland (31%), rainfed upland (9%) and deep water (3%)¹. Rice is considered as a typical Si accumulator plant and the beneficial effects of Si on stimulating plant growth and yield in rice have received increasing attention²,³. The critical concentration of Si in rice straw was reported to be 2.9–3.4%⁴,⁵ and is capable of removing 470–1000 kg Si ha⁻¹⁶,⁷. Soils of major rice growing regions, the tropics and sub-tropics are typically acidic and depleted of soluble sources of silicon (Si) due to weathering and leaching associated with high rainfall and temperatures, together with intensive cropping⁸–¹². This emphasize the need for field application of Si source/sources, which can improve soil Si status and sustain better rice production.

Agronomic significance of many potential Si sources like calcium silicates, calcium magnesium silicate as metallurgic slags, potassium silicates, bagasse fly ash, diatomaceous earth, thermo-phosphates or fused magnesiu phosphate, volcanic rock dust or crushed basalt, foliar/ liquid formulations, crop residues, biochar, etc. has been demonstrated in several studies¹,¹²–¹⁵. Silicate slags is one of the widely used and a promising source of Si in agriculture¹⁶,⁴,⁻¹⁶. Studies have shown that the total Si content of these sources were not a reliable indicator of how effective they release plant-available Si into soil nor facilitate its uptake by the plants¹⁰,¹⁷. There are only few attempts made to describe the agronomic performance of different Si sources and Si uptake based on their chemical composition¹⁸,¹⁹. Most of the studies were limited to extractants for plant available Si from these sources¹,¹²,²⁰,²¹. In this study, silicate slags were evaluated as Si sources based on their alkalinity and Si composition, extractable Si content, ability to release silicon, acquisition of released Si by plants and their performance on growth and yield of rice.

Results and discussion

Chemical properties of silicate slags used in the study. Silicate slags showed a wide variation in their chemical properties (Table 1). Wollastonite and all the silicate slags had an alkaline reaction with water at 1:100 ratio. CCE of different slags used in this study suggests that it has low to moderate liming ability²²–²⁵. Application of silicate slags were reported to be effective in correcting soil acidity and widely used as soil amendment²⁶,²³,²⁵,²⁶.
Alkalinity (CaO) of slags ranged from 27.35 to 52.43%. Total Si content ranged from 3.51 to 11.45%. A/Si ratio ranged from 1.83 to 6.38. The chemical composition observed in this study was in accordance with previous reporting where, silicate slags were reported to contain SiO₂, CaO and A/Si ranging from 11.3–51.71%, 27.3–63.1% and 0.75–4.48 respectively\textsuperscript{19,27}.

Extractable Si estimated by Na₂CO₃ + NH₄NO₃− 5 day incubation method (ESi) from the slags ranged from 0.02 to 3.57% and accounted only to 0.57 to 49.58% relative extractable Si (RESi) (Table 1). Highest Si content was reported in calcium silicate-1 (11.45%), whereas highest RESi was present in EAF slag (49.58%). Least Si content and RESi was noted in Ladle slag-3. Wollastonite used in this study contain 15.4% of Si, of which 25.83% was RESi (Table 1). Wollastonite and silicate slags were reported to contain 2.2–3.6% ESi and 0.0–19% RESi\textsuperscript{17,20}.

Total Si content of the slags seldom represents the bioavailable fraction of Si in them. A significant correlation was found between total Si content of slags and ESi, but, no correlation was observed between total Si content of slags with RESi (Table 2). RESi is the percent Si extracted by Na₂CO₃ + NH₄NO₃ method in relation to the total Si and this extractable part of Si was considered to be bioavailable to plants and found to correlate well with Si uptake in plants\textsuperscript{17,20,21}.

A balanced ratio and amount of calcium, magnesium and silicon was considered to be one of the important characteristic of an ideal Si source, apart from other properties such as high soluble Si content and ready availability of this Si for plants\textsuperscript{5,28}. However, such studies are limited and little attention has been made to study the effect of Si and Ca balance or A/Si content of Si sources on bioavailability of Si. In the present study, ESI and RESi was found to have a strong significant negative correlation with A/Si of slags (p < 0.01) (Table 2). That means, those slag materials with high alkalinity compared to total Si have less extractable or bioavailable Si. The potential of A/Si as an efficiency assessment factor for silicate slags were explored further by greenhouse and incubation experiments.

Greenhouse experiment
Effect of slags on yield, Si content and Si uptake of wetland rice. There was a significant effect on straw and grain yield of rice with the application of Wollastonite and silicate slags (Table 3). Highest straw yield was recorded with the application of Caster slag-1(11.91 g/pot) which was on par with Wollastonite, Calcium silicate-1, Furnace slag, Caster slag-2, EAF slag, steel mill slag-2, BOF LD slag-1 and BOF LD slag-2. Plants

### Table 1. Chemical properties of silicate slags used in the study.

| Sl. no | Si sources         | pH (1:100) | CaO (%) | Total Si (%) | ESi (%) | RESi (%) | A/Si ratio |
|-------|--------------------|------------|---------|--------------|---------|---------|------------|
| 1     | Wollastonite       | 9.32       | 78.51   | 55.75        | 15.41   | 3.98    | 25.83      | 1.69       |
| 2     | Calcium silicate-1 | 9.87       | 75.61   | 43.29        | 11.45   | 2.38    | 20.79      | 1.77       |
| 3     | Calcium silicate-2 | 8.89       | 74.89   | 43.35        | 10.82   | 1.64    | 15.16      | 1.87       |
| 4     | Furnace slag       | 11.65      | 33.57   | 45.23        | 7.75    | 1.35    | 17.42      | 2.76       |
| 5     | Caster slag-1      | 11.74      | 60.35   | 37.23        | 6.80    | 2.04    | 30.00      | 2.55       |
| 6     | Caster slag-2      | 11.14      | 54.25   | 36.15        | 8.67    | 3.10    | 35.76      | 1.91       |
| 7     | EAF slag           | 10.02      | 25.88   | 27.35        | 7.20    | 3.57    | 49.58      | 1.78       |
| 8     | Steel mill slag-1  | 9.53       | 23.56   | 47.98        | 7.08    | 0.16    | 2.26       | 3.15       |
| 9     | Steel mill slag-2  | 9.68       | 9.30    | 27.51        | 7.06    | 2.47    | 34.99      | 1.83       |
| 10    | BOF LD slag-1      | 9.01       | 68.92   | 35.91        | 5.78    | 1.53    | 26.47      | 2.87       |
| 11    | BOF LD slag-2      | 8.98       | 70.48   | 35.24        | 5.49    | 0.78    | 14.21      | 2.96       |
| 12    | Desulfurization slag | 8.59     | 4.37    | 27.35        | 3.76    | 0.67    | 17.82      | 3.38       |
| 13    | Ladle slag-1       | 8.24       | 71.25   | 40.80        | 3.84    | 0.21    | 5.47       | 4.90       |
| 14    | Ladle slag-2       | 10.44      | 77.48   | 52.43        | 4.06    | 0.49    | 12.07      | 6.03       |
| 15    | Ladle slag-3       | 9.64       | 82.12   | 48.57        | 3.51    | 0.02    | 0.57       | 6.38       |

### Table 2. Correlation between different chemical properties of slags [*significant at p < 0.05, **signficant at p < 0.01 (each data represents an average of three replication)].

| Properties of Si sources | pH (1:100) | CaO (%) | Total Si (%) | ESi (%) | RESi (%) | A/Si ratio |
|--------------------------|------------|---------|--------------|---------|---------|------------|
| pH (1:100)               | 1          | ns      | ns           | ns      | ns      | ns         |
| CaO (%)                  | 0.099      | 1       | ns           | ns      | ns      | ns         |
| Total Si (%)             | 0.119      | 0.334   | 1            | ns      | ns      | ns         |
| ESi (%)                  | 0.294      | −0.175  | 0.741        | 1       | **      | **         |
| RESi (%)                 | 0.349      | −0.576  | 0.328        | 0.854   | 1       | **         |
| A/Si ratio               | −0.142     | 0.366   | −0.716       | −0.773  | −0.686  | 1          |
treated with furnace slag produced the highest grain yield and was significantly higher than Wollastonite and on par with other slags like Caster slags, EAF slag, BOF LD slags and calcium silicates. Slags such as caster slag and furnace slag could recorded relative yield higher than 70% which was significantly higher than that of Wollastonite (55.43%). Silicate slags are one of the widely used Si source and its beneficial effect to improve rice yield was reported from many countries like America5,12,29, Japan30, China2,31, Brazil22,32, South East Asian countries33 like South Korea, Thailand, the Philippine, Vietnam, Malaysia as well as in India4,14,28,34–36.

In many studies, Wollastonite was used for comparison to the other materials since a linear relationship was noticed between its rate of application and Si uptake by crops17,22. However, studies in which several slags performing better or on par with wollastonite is also not uncommon22. Significantly high straw and grain Si content was obtained with the application of different slags compared to control. Total Si uptake was significantly high in all slag treatments compared to control except ladle slag-3. Caster slags recorded the highest Si uptake (1.12–1.14 g/pot) which was on par with EAF slag and was significantly higher than that of Wollastonite (0.96 g/pot). Grain yield produced by desulfurization slag and ladle slags were on par with control. The relative yield produced by all the Ladle slags were significantly less than that of Wollastonite (Table 3).

Correlation between yield and Si uptake of rice and A/Si of slags. Linear correlations between yield and Si uptake of rice and different chemical properties of slags is shown in Table 4. ESI and RESi showed significant relationship with straw Si content and total Si uptake of rice (p < 0.01). This is in accordance with previous findings17,20. A/Si of silicate slags also showed significantly higher correlation with straw yield, straw Si content, grain Si content and total Si uptake. Significant correlations between Si uptake of rice with RESi and A/Si ratio of slags proves that the extractable fraction of Si from slag is bioavailable and is influenced by the A/Si

| Treatments            | Yield (g/pot) | Relative yield (%) | Si content (%) | Total Si uptake (g/pot) |
|-----------------------|--------------|--------------------|----------------|-------------------------|
| Control               | 6.52         | 3.97               | –              | 3.76                    |
| Wollastonite          | 11.23        | 5.06               | 55.43          | 6.60                    |
| Calcium silicate-1    | 10.40        | 5.44               | 50.94          | 7.06                    |
| Calcium silicate-2    | 9.94         | 5.36               | 45.76          | 6.59                    |
| Furnace slag          | 11.16        | 7.22               | 75.35          | 6.48                    |
| Caster slag-1         | 11.91        | 6.90               | 79.58          | 7.02                    |
| Caster slag-2         | 11.38        | 6.93               | 74.43          | 7.56                    |
| EAF slag              | 10.48        | 6.93               | 65.97          | 7.52                    |
| Steel mill slag-1     | 9.70         | 5.35               | 43.21          | 5.90                    |
| Steel mill slag-2     | 10.39        | 5.14               | 48.07          | 7.08                    |
| BOF LD slag-1         | 11.33        | 6.12               | 66.34          | 6.31                    |
| BOF LD slag-2         | 10.44        | 5.87               | 55.48          | 6.31                    |
| Desulfurization slag  | 10.02        | 4.53               | 38.41          | 5.30                    |
| Ladle slag-1          | 8.73         | 3.12               | 12.97          | 6.05                    |
| Ladle slag-2          | 6.68         | 4.59               | 7.38           | 6.33                    |
| Ladle slag-3          | 6.43         | 4.32               | 2.46           | 5.21                    |
| LSD (p < 0.05)        | 1.8          | 1.83               | 17.26          | 0.64                    |

| Properties of Si sources | pH (1:100) | CaO (%) | Total Si (%) | ESI (%) | RESi (%) | A/Si ratio |
|--------------------------|------------|---------|--------------|---------|----------|------------|
| Straw yield              | 0.264      | –0.386  | 0.518        | 0.633*  | 0.626*   | –0.878**   |
| Grain yield              | 0.712**    | –0.263  | 0.285        | 0.519   | 0.632*   | –0.598*    |
| Straw Si content         | 0.495      | –0.267  | 0.505        | 0.802** | 0.812**  | –0.692**   |
| Grain Si content         | 0.153      | 0.037   | 0.765**      | 0.638*  | 0.433    | –0.768**   |
| Total Si uptake          | 0.513      | –0.350  | 0.549*       | 0.773** | 0.787**  | –0.869**   |
| Relative yield           | 0.492      | –0.362  | 0.457        | 0.637*  | 0.684**  | –0.826**   |

Table 3. Effect of slags on yield, Si content and Si uptake of wetland rice.

Table 4. Correlation between different properties of slags, yield and Si content of wetland rice [*significant at p < 0.05, **significant at p < 0.01 (each data represents an average of three replication)].
ratio of slags. Further, RESi and A/Si ratio of slags were also found to have strong correlation with relative yield ($p < 0.01$).

Several regression analysis were made between different chemical properties of slag (Table 1) and plant parameters (Table 3) and a significant polynomial relationship was identified between A/Si of slags and relative yield of rice ($r^2 = 0.878$, $p < 0.01$). Addition of an agronomic management practice to be economical for the production of rice, rule of thumb is that, it should contribute to a 45% increase in yield39. It was observed that those slag sources with A/Si < 3 could produce relative yield more than 45% (Fig. 1).

Soil incubation study
An incubation experiment was conducted to study the effect of A/Si of slags on the dissolution of Si from these sources in the soil. Figure 2 depicts the trend in pH, EC and CaCl$_2$ extractable Si (CaCl$_2$-Si) in the soil at different intervals of incubation with wollastonite, slags with A/Si < 3 (Caster slag, Furnace slag and EAF) and slags with A/Si > 3 (Ladle slag-2, ladle slag-3 and Desulfurization slag). The selection of silicate slags with A/Si < 3 and > 3 for this experiment was done based on the chemical characterization (Table 1) and greenhouse experimental results (Table 3).

Effect of slags on soil pH. A/Si > 3 slag treatments tend to increase the soil pH compared to other treatments, but there was no significant effect on soil pH with the application of Si sources over control. Irrespective of treatments, pH of the soil attained near neutral after 30 days of incubation (Fig. 2a). This could be due to three reasons: (1) submerged soil condition in which study was conducted: soil reaction was reported to attain fairly stable value of 6.7–7.2 a few weeks after submergence60, (2) CCE of the silicate slags used: A/Si < 3 slags have low CCE [EAF slag (25.83), Furnace slag (33.57) and Castor slag-2 (54.25)] and A/Si > 3 slags have moderate CCE [ladle slags (71.25 to 82.12)], and (3) Low rate of slag application: Here, silicate slags were used as Si source and rate of application was calculated to provide 300 kg Si ha$^{-1}$. Accordingly, the lowest rate of application was for EAF slag (equivalent to 9 Mg of slag ha$^{-1}$) and highest for ladle slag-3 (equivalent to 18.5 Mg slag ha$^{-1}$). The liming requirement for the soil used in the study was calculated to be 25 Mg ha$^{-1}$ of lime with 100% relative neutralizing value61.

Effect of slags on soil EC. EC of the soil was significantly increased with the addition of wollastonite and slags (Fig. 2b). There was no significant difference in EC with the application of slags with A/Si < 3 and A/Si > 3. This can be due to the higher soluble salt content of these materials especially that of CaO and MgO, which react with water to form Ca(OH)$_2$ and Mg(OH)$_2$ and possess water solubility concentration of 1.20 g L$^{-1}$ and 0.009 g L$^{-1}$, respectively.

Effect of slags on CaCl$_2$ extractable Si in soil. Wollastonite, followed by slags with A/Si < 3 recorded significantly higher CaCl$_2$–Si compared to control up to 90 DAI (Fig. 2c). However, in the present study, slags with A/Si > 3 were found to decrease CaCl$_2$–Si in soil, which is contradictory to the earlier reports of Kato and Owa19 where slags with high A/Si ratio were reported to be ideal as Si source based on the release of Si in to soil. This decrease in CaCl$_2$–Si with the application of slags with higher A/Si ratio can presumably due to the release of large amount of Ca and increase in soil pH, which were found to depress the continuous dissolution of the slags and enhance the specific adsorption of silicic acid by the soil18.

Correlation coefficient calculated between the CaCl$_2$–Si released at different incubation interval and total Si uptake by rice were 0.5986, 0.9097**, 0.4381, and 0.5102 at 30, 60, 90 and 120 DAI respectively. The increase in silicon concentration at 60 DAI was found to be strongly correlated to Si uptake ($r = 0.9097**$, $p < 0.01$). An
increase in soil Si concentration due to dissolution of silicates at the early growth stages of paddy and increased uptake of Si with the application of slags was reported previously also. In general, slags with A/Si < 3 showed to release significantly higher amount of CaCl₂–Si compared to control and slags with A/Si > 3 (Fig. 2). Even though, the CaCl₂–Si released in soil by slags with A/Si < 3 (Caster slag, Furnace slag and EAF) were lesser than that of wollastonite, they found to be more bioavailable as evident with significant increase in Si content and Si uptake in plants treated with these slags (Table 3). Plant available Si estimated by Na₂CO₃ + NH₄NO₃–5 day incubation method and relative extractability of Si from slags with A/Si < 3 were also found to be high. Slags with A/Si > 3 were found to decrease CaCl₂–Si in soil, plant Si content, Si uptake and yield of rice. Hence, it is summarized that slags with A/Si < 3 such as caster slag, furnace slag, EAF slag, slag based calcium silicate, steel mill slag and BOF LD slag can be used as ideal Si source for the economic production of wetland rice.

Conclusions
In this study, different silicate slags were characterized based on their chemical properties, their effect on yield, Si uptake of wetland rice, and dissolution of Si into the soil. This study could bring out the importance of having balanced ratios and amounts of calcium (Ca), magnesium (Mg), and silicon in an ideal Si source and found that A/Si of slags can influence the agronomic potential of silicate slags. Slags with A/Si < 3 like caster slag, furnace slag, EAF slag, slag based calcium silicate, steel mill slag and BOF LD slag were found to have higher Na₂CO₃ + NH₄NO₃ extractable Si content, could increase plant-available Si in soil, Si uptake, and can increase rice production. Slags with less A/Si < 3 can be used as potential Si sources in wetland rice.

Materials and methods
Chemical characterization of Si sources. The Si sources used in this experiment were Wollastonite (Sigma Aldrich, Merck) which was used as a standard Si source, two slag based calcium silicates (Harsco Pvt. Ltd.) and twelve metallurgic slags (from various steel mills across India). Slags were dried till constant weight in a hot air oven, pulverised with a hardened steel pounder and sieved through 100 mesh screen (0.149 mm sieve opening) and further used for characterization, greenhouse and incubation study. Aqua regia extractable (EPA

Figure 2. Change in pH (a), EC (b) and concentration of extractable Si (c) at different days after incubation in soil with the addition of different silicate sources. (each data represents an average of three replication; A/Si < 3-average of treatment with caster slag, furnace slag and EAF slag; A/Si > 3-average of treatment with ladle slag-2, ladle slag-3 and desulfurization slag replicated thrice).
method 3050 B) nutrient content in the Si sources used ranged from 0–0.2% P, 0–2.6% Fe, 0–1.1% Mg and <0.5% Zn, Cu and B.

CaO content (Alkaliinity, A). The sum of calcium and magnesium contents in the slags was extracted by boiling with 0.5 M HCl for 5 min and expressed as CaO (%)35.

Calcium carbonate equivalent (CCE). CCE was analysed using AOAC methodology36. In this study, the slag was ground to pass a 100 mesh sieve before application, thus the relative neutralizing value (RNV) was considered as 100%34.

Total Si content. Silicon content in digested samples were estimated colorimetrically. Microwave digestion technique was adopted for digesting slag samples. 25 mg source material was pre-digested in a mixture of 7 ml of HNO₃ (70%), 2 ml of H₂O₂ (30 per cent) and 1 ml of HF (40%) for 15 min in Teflon vessels, digestion was done using microwave digestion system (Milestone-start D) in SK-10 T high pressure segmented rotor with following programme: 1000 watts for 25 min temperature set at 200 °C; venting for 10 min. Volume of the digested matrix was made up to 50 ml with 4% boric acid immediately. Extracted Si was estimated as described below35. An aliquot of 0.25 ml digested extract was taken into a plastic centrifuge tube and in to it 10.5 ml of distilled water, 0.25 ml of 1:1 hydrochloric acid, and 0.5 ml of 10 per cent ammonium molybdate solution were added. After allowing for 5 min, 0.5 ml of 20 per cent tartaric acid solution was added. After allowing for additional two minutes, 0.5 ml of 1:1 hydrochloric acid and 0.5 ml of 10 per cent ammonium molybdate solution were added. After allowing for 5 min, 0.5 ml of 20 per cent tartaric acid solution was added. After allowing for additional two minutes, 0.5 ml reducing agent (1-amino-2-napthol-4-sulfonic acid-ANSA) was added. After 5 min, but not later than 30 min following addition of the reducing agent, absorbance was measured at 630 nm using UV–visible spectrophotometer (SHIMADZU Pharmaspec, UV-1700 series). Si standards (0, 0.2, 0.4, 0.8, 1.2, 1.6, 1.8 and 2 mg L⁻¹) prepared in the same matrix were also measured to set the standard curve.

Alkalinity- silicon ratio (A/Si). It is the ratio of alkalinity (A) to total Si content of slag39.

5-Day Na₂CO₃ + NH₄NO₃ extractable Si (ESi). Extractable Si was estimated by Na₂CO₃ + NH₄NO₃ extraction17,20. This 5-Day Na₂CO₃ + NH₄NO₃ soluble Si extraction method has been accepted as the official method in the United States for determining plant-available Si from non-liquid fertilizers50.

Relative percentage of extractable Si (RESi). Relative percentage of extractable Si is calculated by comparing percentage Si extracted by the extractant to total Si extracted by microwave digestion. The relative percentage of Si17,20 extracted was calculated using the following formula:

\[
\text{Relative extractable Si (\%)} = \left(\frac{\text{Si extracted by extractant}}{\text{Si extracted by microwave digestion}} \times 100\right)
\]

Greenhouse experiment. Pot culture experiment was conducted at the greenhouse of Department of Soil Science and Agricultural Chemistry, University of Agriculture sciences, Bangalore, India. Bulk soil sample for the experiment were collected at a depth of 10 to 20 cm from Hassan representing southern dry zone of Karnataka, South India with characteristic properties of Rhodic Paleustalfs with acidic pH of 4.78. The soil was air dried and sieved through a 2 mm screen and then its initial chemical and physical properties were determined44 (Table 5). Plant available Si in soil was estimated by 0.01 M CaCl₂ extraction36,45.

Rice plants were grown in 5 kg soil taken in closed plastic pots (20 cm upper diameter × 17 cm height) maintained under submergence. Fifteen Si sources were applied at the rate of 300 kg Si ha⁻¹ and a control without any Si application. The experiment was set up in completely randomized block design with three replications. One seedling of 21 day old rice (var. BR 2655) was transplanted to each pot. Fertilizers were mixed with soil at the recommended dose of 100:50:50 kg ha⁻¹ N:P:O₃:K₂O as urea, single super phosphate and potassium chloride, respectively. The straw and grain samples were collected at harvest, oven dried at 60 °C and recorded the dry weight. Later, the samples were powdered in a Retsch miller mill MM400 with Tungsten balls and analysed for Si content43. Total Si uptake (straw plus grain Si uptake) and relative yield for each treatment was calculated using following formulae.

\[
\text{Total Si uptake (g/pot)} = (\text{Straw yield} \times \text{straw Si content}/100) + (\text{grain yield} \times \text{grain Si content}/100)
\]

Relative yield (%) = [(\text{Yield in treatment} – \text{Yield in control}) \times 100]/\text{yield in control}

Incubation experiment. An incubation study was also conducted with selected six slags viz. caster slag, furnace slag, EAF slag, ladle slag-2, ladle slag-3 and desulfurization slag in addition to wollastonite, to investigate the dissolution and release of silicon from these sources. 200 g soil was mixed with calculated amount of sources to provide 300 kg Si ha⁻¹ and kept under submergence in closed plastic pots (10 cm upper diameter × 8.5 cm height). Twelve replications of each treatment and control (soil with no added Si sources) were kept and sampling was done at four intervals: 30, 60, 90 and 120 DA1 (days after incubation). At each interval,
Table 5. Initial properties of soil used in this experiment.

| Soil parameters | Location |
|-----------------|----------|
| Particle size distribution | Hassan, Karnataka |
| Sand (%) | 51.47 |
| Silt (%) | 20.37 |
| Clay (%) | 26.17 |
| Soil texture | Sandy clay loam |
| pH (1:2.5 soil: water ratio) | 4.78 |
| EC (dS m⁻¹) | 0.16 |
| OC (g kg⁻¹) | 8.3 |
| Available N (kg ha⁻¹) | 466.46 |
| Available P₂O₅ (kg ha⁻¹) | 163.69 |
| Available K₂O (kg ha⁻¹) | 495.14 |
| Available S (mg kg⁻¹) | 13.1 |
| Exchangeable Ca (cmol (p⁺) kg⁻¹) | 6.01 |
| Exchangeable Mg (cmol (p⁺) kg⁻¹) | 3.2 |
| Exchangeable Na (cmol (p⁺) kg⁻¹) | 0.18 |
| CaCl₂ – Si (mg kg⁻¹) | 56.42 |

Destructive sampling of three replications were done. Soil pH, EC and 0.01 M CaCl₂ extractable Si were recorded at each interval.

Statistical analysis. Data generated were statistically analysed using one-way ANOVA by using Fisher's test at \( p \leq 0.05 \) and correlation–regression analysis were done using XLSTAT software.

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Author contributions
T.S.S and N.B.P conceived and designed the experiment, T.S.S. performed the sampling, cultivation, lab analyses, carried out the data analysis and wrote the first draft. N.B.P revised and provided comments on the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
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