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# Spatial distribution of status silicon availability for plant and its effect to rice yield

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**ABSTRACT**

Silicon (Si) is a beneficial element for rice plants. However, evaluating the Si availability status of paddy soil is rarely done. This study aimed to investigate the Si availability for plant ($Si_{AP}$), spatial distribution, $Si_{AP}$ correlations with some soil properties and the effect of $Si_{AP}$ status on the rice yield. This study used a survey method to collect paddy soil and water sample. The pot experiment method was used to evaluate paddy plant response to $Si_{AP}$ level. Based on K-means, cluster analysis showed that soil $Si_{AP}$ was categorized low (< 147 mg $SiO_2$ $kg^{-1}$), moderate (147 – 224 mg $SiO_2$ $kg^{-1}$) and high (> 224 mg $SiO_2$ $kg^{-1}$). The $Si_{AP}$ status of the paddy soil area of 26,395 hectares (25%), 61,744 hectares (59%) and 15,952 hectares (15%) was categorized as low, moderate and high, respectively. This present study revealed that the upland area paddy soil has higher $Si_{AP}$ than the lowland area. Total silicon dioxide ($SiO_2$) and clay percentage were negatively correlated with the SiAP in soils. Silicon addition to the paddy soil with $Si_{AP}$ status showed low to high increase in rice yield by 0.2%, 3.9% and 2.7%.

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## 1. INTRODUCTION

The total population of the Republic of Indonesia, based on (United Nations, 2022), is the 4th largest in the world. According to the (BPS, 2020), the population in Indonesia in 2020 was 270.2 million. The increase in population is directly proportional to the increase in food demand. Indonesia and other countries in the Asian region consume rice as a staple food (Song et al., 2014). Efforts to increase rice production face challenges of land conversion and climate change (Panuju et al., 2013). Conversion of paddy fields occurs on both low and high fertile soil, decreasing harvested area and production (Harjanti & Hara, 2020).

Paddy plants grown in a field face more biotic-abiotic stresses than those grown in a controlled environment such as a greenhouse (Etesami & Jeong, 2018). The biotic-abiotic stresses in paddy plants include pests and diseases, nutrient imbalances, droughts, extreme temperatures, high salinity and high-heavy metal contents (Debona et al., 2017). Imtiaz et al. (2016) states that the silicon element (Si) plays an essential role for plants facing biotic-abiotic stress. Therefore, to increase the resistance of rice plants to various stress conditions, the availability of Si nutrients in paddy fields needs to be maintained.

Paddy is a Si accumulator plant, so the Si requirement must be fulfilled for optimum yield (Ma & Yamaji, 2015). Si nutrient deficiency results in small rice grains and plants susceptible to disease (Coskun et al., 2016). The total Si content ($SiO_2$) on the earth's surface is relatively high equivalent to 28.7% Si (Tubana et al., 2016). However, the problem is that paddy plants absorb Si in the form of mono silicic acid ($H_4SiO_4$), whose availability varies depending on parent material, soil pH, soil temperature and redox potential (Liang et al., 2015).

The plant-available Si ($Si_{AP}$) of paddy soils on Java island, according to Darmawan et al. (2006), decreased by 11-20% over a period of 33 years (1970-2003). The low $Si_{AP}$ content of paddy soil indicates that the Si element is absorbed by paddy plants but it is not properly returned to the paddy soil in the form of Si fertilization and paddy plant residues (straw and husks) (Husnain et al., 2012). The decrease in $Si_{AP}$ content in paddy soil in the tropics is accelerated by the desilication process, namely, removing Si from the soil matrix (Tubana et al., 2016). According to Husnain et al. (2012) and Qurrohman et al. (2022), $Si_{AP}$ content in paddy soil in West Java Province, Indonesia, is dominated by low (< 300 mg $kg^{-1}$) to moderate (300-600 mg $kg^{-1}$) $Si_{AP}$ content.

Silicon addition for paddy plants should consider the level of $Si_{AP}$ and Si concentration in irrigated water. The average irrigated water in Java island contains $SiO_2$ ranging from 10.81-17.37 mg $L^{-1}$ or 5.08-8.16 mg Si $L^{-1}$, equivalent to 25.4-40.8 kg Si $ha^{-1}$ (water level 5 cm) (Darmawan et al., 2006). The water requirement of paddy plants is varied depending on the type of variety and the age of the plant. For example, one rice variety in India that is maintained conventionally requires 19,686 $m^3$ $ha^{-1}$ of water, equivalent to 100-161 kg Si per season (Yaligar et al., 2017). Based on data on the Si content of irrigated water (Darmawan et al., 2006) and data on the loss of soil $Si_{AP}$ at each harvest, we can simulate that irrigated water application contributes to control of Si loss by 21 - 34% per harvest.

Implementation of Si addition to meet the needs of $Si_{AP}$ in paddy plants requires the support of a spatial database in the form of a $Si_{AP}$ level map of paddy soil. The Si distribution map was used to determine the Si fertilization dose and the priority area for Si fertilization. The $Si_{AP}$ level maps previously developed by other researchers include the $Si_{AP}$ level map for paddy soil on the island of Java (Darmawan et al., 2006), the $Si_{AP}$ potential map for West Java Province (Qurrohman et al., 2022) and the $Si_{AP}$ map for the Citarum (West Java) and Kaligarang (Central Java) watersheds (Husnain et al., 2008). The $Si_{AP}$ level maps were still limited and needed to be developed to increase their accuracy and make them easy to read by various groups, especially paddy farmers.

This study aimed to investigate the Si availability for plant ($Si_{AP}$), $Si_{AP}$ correlations with some soil properties, spatial distribution and the effect of $Si_{AP}$ status on the rice yield.

## 2. MATERIAL AND METHODS

The research was carried out from September 2021 to June 2022. The survey and sampling of paddy soil and irrigated water were in the administrative area of Subang Regency (107° 31' - 107° 54 E; 6° 11' - 6° 49' S), West Java Province, Indonesia. The experiment assessing paddy plant yield response was conducted in Neglasari-Majalaya (7° 4' 26.23" S; 107° 43' 52.10" E), Bandung Regency, West Java Province, Indonesia.

This study used a survey method to collect paddy soil and water samples. Paddy soil samples collected at each survey location were used as planting media. Pot experiments were carried out to study the effect of the $Si_{AP}$ level on crop yield. Surveys and samplings of soil and irrigated water were conducted to assess $Si_{AP}$ in paddy soil, distribution of $Si_{AP}$ levels and Si content of irrigated water in Subang Regency. Survey and sampling activities began by making a unit map of paddy fields. The land map unit (LMU) was obtained by overlaying the land use map over a soil classification map. The land map unit was used to determine the number of soil samples in each LMU using the stratified random sampling method based on the area of each LMU (Fig. 1).

The soil samples (20 kg) and 300 ml of irrigated water samples were taken at each survey location. Soil samples were collected from the topsoil (0-15 cm) to analyze the soil texture and chemical properties. The soils were analyzed in the laboratory to assess total organic carbon (TOC), total nitrogen (N), soil pH, total $SiO_2$ and available Si ($Si_{AP}$). Water samples were taken from irrigated canals or irrigated water in paddy fields. The samples were analyzed to assess Si concentration, pH, and electrical conductivity (EC).

Soil textures were measured by the pipette method. Organic carbon content (TOC) was measured using the 1 N Potassium Dichromate ($K_2Cr_2O_7$). Total nitrogen content was measured using the Kjeldahl method. Soil pH measurement used a pH meter with a 1 M KCl and $H_2O$ extractor. The comparison between soil samples and reagents was 1:5. The measurement of total Si ($SiO_2$) used the wet washing method and the measurement of available Si used the acetic acid method (Husnain et al., 2008). The atomic absorption spectrometer method measured Si content in water (Husnain et al., 2008). The glass electrode method used a pH meter to measure irrigated water pH (Lutron PH201, Taiwan) and water conductivity was measured using an EC meter (TDS & EC, China).

The rest of the soil samples from the survey site were used as media for paddy plants to study the effect between $Si_{AP}$ level and crop yield. The experimental design used was a completely randomized design (CRD) consisting of six treatments with unequal replication. The treatments consisted: of low Si with Si addition, moderate Si with Si addition, high Si with Si addition, low Si without Si addition, moderate Si without Si addition and high Si without Si addition. The Si addition was derived from rice husk as a source of silicon which was applied as 20 mL $L^{-1}$ (Frasetya et al., 2019).

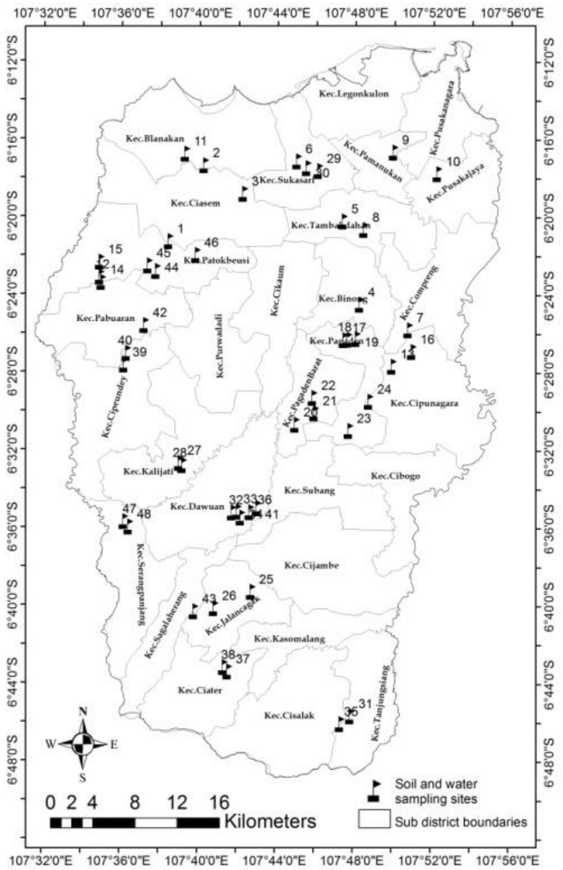



**Figure 1**. Survey location, soil and irrigated water sampling point of paddy soils

The Ciherang cultivar seeds showed first and, after 21 days, they were ready to transplant. The paddy was transplanted into the pot (two plants per pot). Fertilization in each pot was given based on the recommendation from Husnain et al. (2020) 1.8 g of urea, 0.5 g of Super Phosphate (SP-36) and 0.3 g of KCl. Phosphorus and K fertilizers were applied as a basal application at day-9 after planting (DAP) and N fertilizer was split into three portions and applied at 9, 24 and 40 DAP. In this study, Foliar Si addition was split into six portions and applied at 10, 20, 30, 40, 50, and 60 DAP. The crop yield parameter observed was the un-milled grain weight.

The K-means cluster analysis grouped the $Si_{AP}$ of paddy soil from 48 survey sites (Fig. 1). The $Si_{AP}$ class resulting from the K-means cluster analysis was presented in a map of $Si_{AP}$ spatial distribution (Arc GIS 10.1). Regression analysis was carried out to determine the relationship between the soil properties (texture, organic carbon, total N, pH and $SiO_2$) and the irrigated water properties (pH, EC, and Si) to the $Si_{AP}$ concentration of paddy soil. Multiple regression analysis was carried out to determine the significant parameter ($p < 0.05$) affecting the $Si_{AP}$. One way analysis of variance ($p < 0.05$) and Duncan's multiple range test were used to compare the crop yield, both with and without adding Si at $Si_{AP}$ level status. The statistical analysis in this study used SPSS version 19.

## 3. RESULTS

### 3.1. Plant-available silicon ($Si_{AP}$) in paddy soil

The results of the laboratory analysis of paddy soils (Fig. 2) from 48 sample locations showed that the $Si_{AP}$ content in Subang Regency ranged from 70 - 378 mg $kg^{-1}$, with an average $Si_{AP}$ of 172 mg $kg^{-1}$. The soil sample containing $Si_{AP}$ below the critical point of 300 mg $kg^{-1}$ was 45 samples and the rest had $Si_{AP}$ content of more than 300 mg $kg^{-1}$. Six paddy field soil samples contained $Si_{AP}$ content lower than 105 mg $kg^{-1}$. Overall, 81% of paddy soil samples in Subang Regency were between 105 mg $kg^{-1}$ < $Si_{AP}$ < 300 mg $kg^{-1}$.

### 3.2. The relationship between several soil properties and irrigated water on the $Si_{AP}$ of paddy fields

The results of the regression analysis of soil properties namely the concentration of $SiO_2$ (Fig. 3A), total nitrogen (Fig. 3B), pH ($H_2O$) (Fig. 3C), pH (KCl) (Fig. 3D), total organic carbon (Fig. 3E), clay fraction (Fig. 3F), sand (Fig. 3G), and silt (Fig. 3H) on the $Si_{AP}$ content of paddy soil had a coefficient of determination ($R^2$) 0.23; 0.12; 0.14; 0.19; 0.13; 0.17; 0.003 and 0.19, respectively. Based on the F test, the coefficient of determination showed significance ($P < 0.05$), except sand texture that was non-significant ($P > 0.05$). Regression analysis produced another output, namely the correlation coefficient (R). The correlation coefficient exhibited the relationship between each soil characteristic and $Si_{AP}$. The value of the correlation coefficient sequentially was 0.48; 0.35; 0.37; 0.44; 0.36; 0.41; 0.17 and 0.44. The relationship between soil properties and $Si_{AP}$ was categorized as weak to moderate. Total nitrogen, organic carbon, and sand content were categorized as a weak correlation, while the concentration of $SiO_2$, pH ($H_2O$ base), pH (KCl base), clay and silt were categorized as a moderate correlation.

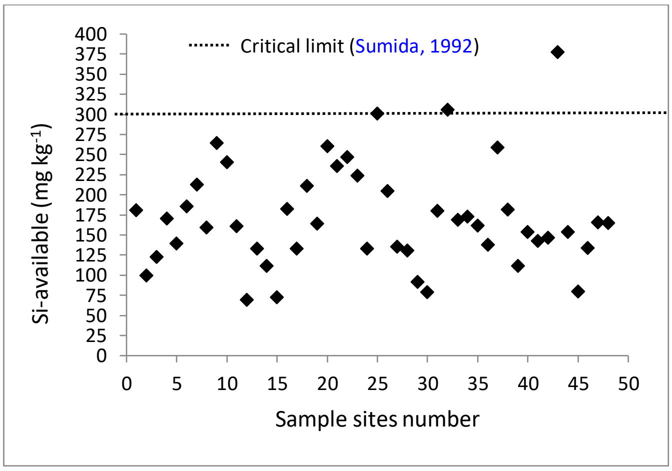



**Figure 2.** $Si_{AP}$ content of paddy soil at each survey point

The results of the regression analysis of the chemical properties of irrigated water showed that the electrical conductivity (EC) (Fig. 4A), pH (Fig. 4B), and $SiO_2$ in irrigated water (Fig. 4C) had a low coefficient of determination ($R^2$). The $SiO_2$ of irrigated water had a low coefficient determination but had a significant effect ($P < 0.05$) on variations in the $Si_{AP}$ of paddy soils.

The results of multiple regression analysis (Table 1) obtained a determination coefficient ($R^2 = 0.78$), and proved that independent variables can explain 78% of the variation in $Si_{AP}$ for paddy soils.

The observed parameters have a low coefficient of determination for each parameter. However, if all parameters were incorporated, the analysis showed a high coefficient of determination of 78%. The results of the multiple regression equation ($p < 0.05$) showed a linear relationship between the $Si_{AP}$ of paddy soil and the independent variables. Based on the analysis results, the P-value for each parameter significantly affected the $Si_{AP}$ of paddy soils, namely soil pH, total $SiO_2$ of soil, $SiO_2$ of irrigated water, and pH of irrigated water. The multiple regression equation can be found in Equation 1.

$$Y(Si_{AP}) = -316{,}456 + 64{,}864\ (\text{Soil pH}) - 3{,}197\ (\text{Total } SiO_2) + 6{,}396\ (SiO_2 \text{ irrigated water}) + 34{,}254\ (\text{irrigated water pH}) \quad [1]$$

### 3.3. Plant available silicon grouping of paddy soil based on cluster analysis

The $Si_{AP}$ level was divided into three levels in this study including low, medium and high, using the K-means cluster method. Members of each $Si_{AP}$ level (Table 2) consisted of 18 samples (low), 21 samples (moderate) and nine samples (high). The $Si_{AP}$ level 70-143 mg $kg^{-1}$ was the low category, with an average of 114 mg $kg^{-1}$. The $Si_{AP}$ status class 147 – 224 mg $kg^{-1}$ was the medium category, with an average of 177 mg $kg^{-1}$. The $Si_{AP}$ status 236 – 378 mg $kg^{-1}$ was the high category, with an average of 277 mg $kg^{-1}$. The results of the $Si_{AP}$ level based on cluster analysis were used as the basis for making the $Si_{AP}$ level map for paddy soils in Subang Regency (Fig. 5).

The $Si_{AP}$ status of paddy soils in Subang Regency based on Figure 5 was 26,395 ha in the low category, 61,744 ha in the medium category and 15,952 ha in the high category. Areas with low to moderate $Si_{AP}$ levels were in the northern part of Subang (lowland area), while in southern Subang (upland area) $Si_{AP}$ levels were moderate to high.

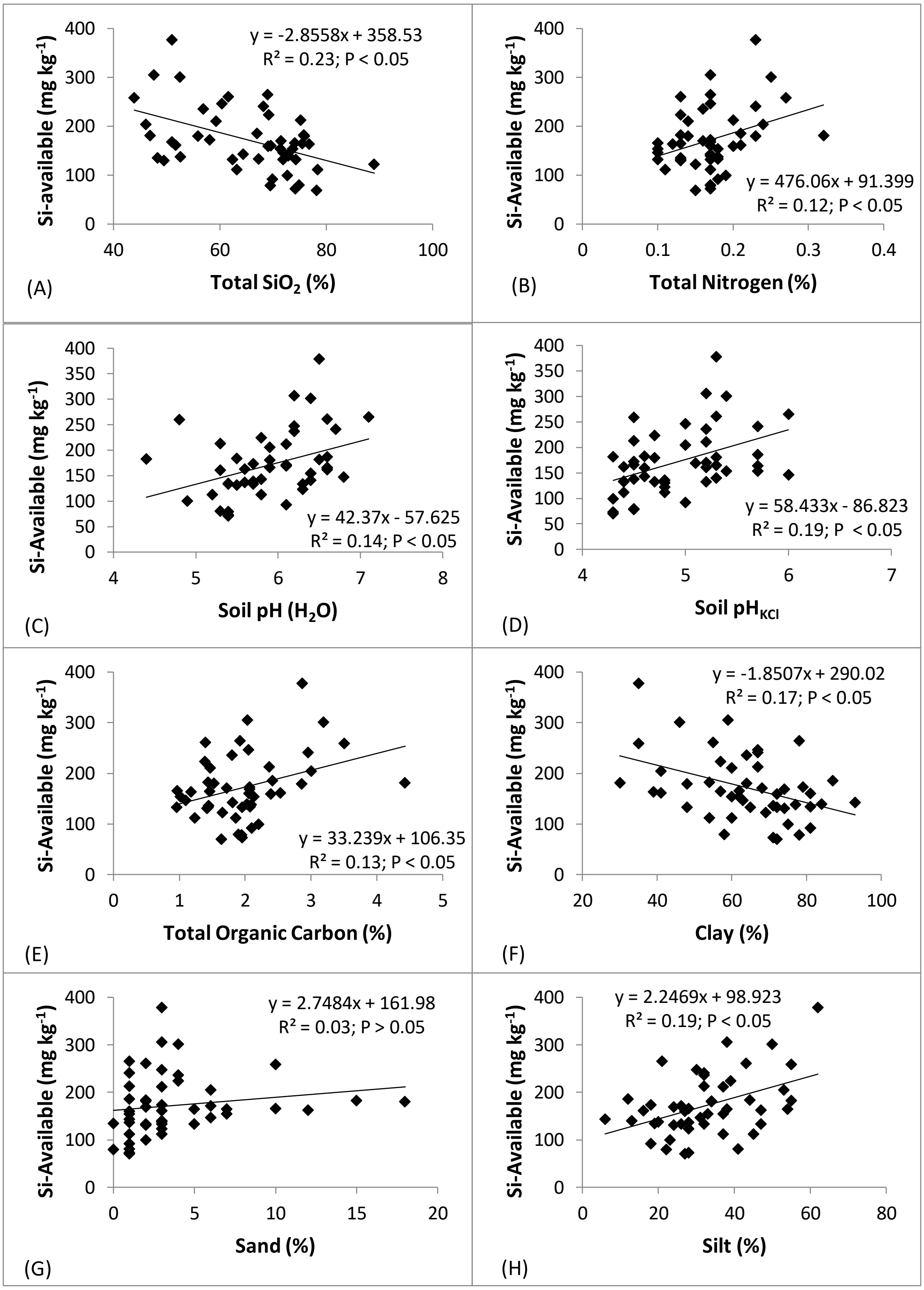



**Figure 3**. Relationship between $Si_{AP}$ and some soils chemical properties. (A) Total $SiO_2$ (B) Total Nitrogen, (C) Soil pH (water base), (D) Soil pH (KCl base), (E) Total Organic Carbon, (F) Clay Fraction, (G) Sand Fraction, (H) Silt Fraction

The silicon addition at $Si_{AP}$ level status did not significantly increase crop yield. The highest average yield was obtained in the Si addition treatment of 105.8 g pot$^{-1}$ at a high $Si_{AP}$ level. In contrast, the lowest yield was obtained in the treatment without Si addition at a low $Si_{AP}$ level. The highest increase in yield was obtained in the Si addition treatment at moderate $Si_{AP}$ status of 4.9%. In the high $Si_{AP}$ category, the increase in yield was 2.6%. At low $Si_{AP}$ conditions, the increase in yield was only 0.2%.

## 4. DISCUSSION

The results of the $Si_{AP}$ cluster analysis of paddy fields in this study were divided into three classes, namely low ($Si_{AP}$ < 147 mg kg$^{-1}$), medium (147 ≤ $Si_{AP}$ ≤ 224 mg kg$^{-1}$) and high ($Si_{AP}$ > 224 mg kg$^{-1}$) (Table 2). The upper limit value for the medium category of $Si_{AP}$ for paddy soils in this study (224 mg kg$^{-1}$) was below the critical $Si_{AP}$ limit set by Sumida (1992) of 300 mg kg$^{-1}$ (Fig. 2).

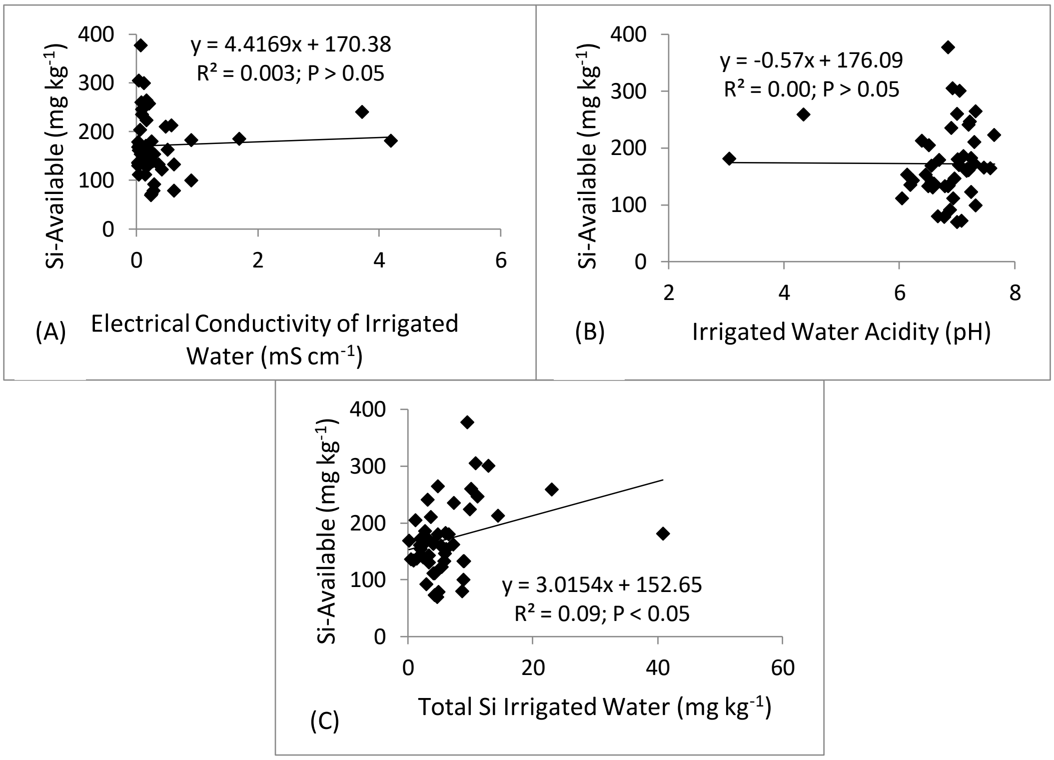



**Figure 4**. The relationship between $Si_{AP}$ and the chemical properties of irrigated water, (A) Electrical Conductivity, (B) Water pH, (C) Total Si

**Table 1.** Multiple regression analysis $Si_{AP}$ with soil properties and irrigated water

| y | x | Unstandardized Coefficients B | Standardized Coefficients Beta | P-value |
|---|---|---|---|---|
| Si-Available for Plant (mg kg$^{-1}$) | Sand (%) | -3.050 | -0.178 | 0.073$^{ns}$ |
| | Silt (%) | 0.902 | 0.175 | 0.088$^{ns}$ |
| | pH ($H_2O$) | 64.864 | 0.581 | 0.034* |
| | pH (KCl) | 1.555 | 0.012 | 0.961$^{ns}$ |
| | Total Organic Carbon (%) | -19.889 | -0.212 | 0.815$^{ns}$ |
| | Total Nitrogen (%) | 525.431 | 0.376 | 0.658$^{ns}$ |
| | Total SiO2 (%) | -3.197 | -0.536 | 0.000* |
| | Total Si Irrigated Water (mg L$^{-1}$) | 6.396 | 0.651 | 0.000* |
| | pH Irrigated water | 34.254 | 0.403 | 0.009* |
| | Electrical Conductivity Irrigated water (mS cm$^{-1}$) | -7.165 | -0.090 | 0.435$^{ns}$ |
| | Constant | -316.456 | | 0.002* |

**Remarks**: $R^2$= 0.78; Adjusted $R^2$= 0.71; F= 12.754; P-value= 0.000*; * = Significant P < 0.05; ns = not significant P > 0.05

Variations in $Si_{AP}$ paddy soils in Subang Regency are influenced by several factors, such as parent material (Liang et al., 2015). This study indicates that the southern part of Subang is dominated by tuff parent material and andesite breccia, while clay deposits dominate the northern part of Subang. The parent material of tuff comes from volcanic rocks, so it has a higher Si content than the parent material derived from non-volcanic rocks (Husnain et al., 2008).

Regression analysis of soils and irrigated water properties (Fig. 3 and Fig. 4) on the $Si_{AP}$ of paddy soil resulted in a coefficient of determination ($R^2$) and correlation (r) of several soil properties, namely total Silicon, total Nitrogen, pH (irrigated water), pH (KCl), organic Carbon, clay, sand and silt on $Si_{AP}$ Sawah soil. The most significant coefficient of determination value was obtained in the regression equation for the total Si content of $Si_{AP}$ ($R^2$ = 0.23) (Fig. 3A). The total Si content influences the variation of $Si_{AP}$ in paddy soil at 23%, while other factors influence the remaining 77%. Plant-available Si ($Si_{AP}$) comes from weathering rocks containing $SiO_2$ to mono-silicate acid (Kowalska et al., 2021). The relationship between $SiO_2$ content and $Si_{AP}$ was moderately correlated (r = -0.48). The negative value of the correlation coefficient indicates an increase in dissolved Si ($Si_{AP}$), resulting in a decrease in total Si in the soil. The negative value of the correlation coefficient between $Si_{AP}$ and the total Si content reveals that Si reserves in the soil for a certain period will decrease if there is no additional source of Si in the soil (Cornelis & Delvaux, 2016). This study found a negative relationship between clay content and available Si.

**Table 2.** The $Si_{AP}$ level based on K-means cluster analysis

| Cluster | Level of $Si_{AP}$ | Cluster membership | Total | Interval of $Si_{AP}$ (mg kg$^{-1}$) |
|---|---|---|---|---|
| 1 | Low | 2, 3, 5, 12, 13, 14, 15, 17, 24, 27, 28, 29, 30, 36, 39, 41, 45, 46 | 18 | < 147 |
| 2 | Moderate | 1, 4, 6, 7, 8, 11, 16, 18, 19, 23, 26, 31, 33, 34, 35, 38, 40, 42, 44, 47, 48 | 21 | 147 – 224 |
| 3 | High | 9, 10, 20, 21, 22, 25, 32, 37, 43 | 9 | > 224 |

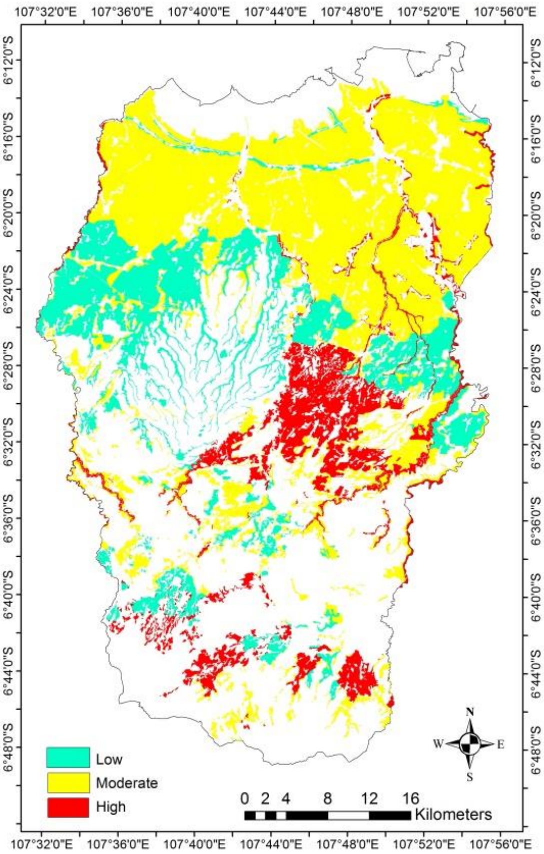



**Figure 5**. The $Si_{AP}$ level map of paddy soil in Subang Regency, West Java Province, Indonesia

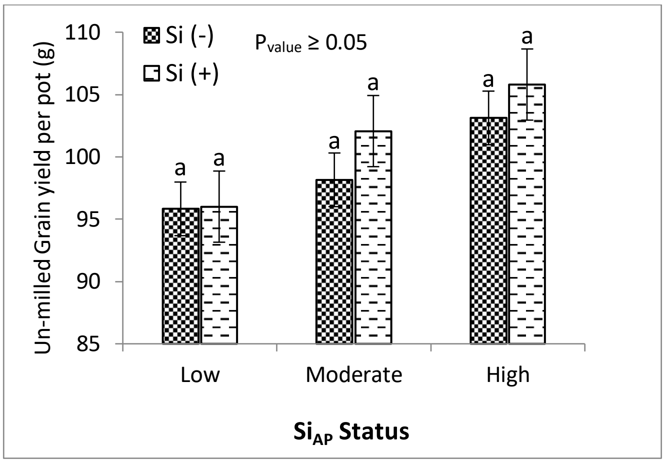
However, Chirkes Johanna et al. (2018) reported the opposite result, that $Si_{AP}$ and clay have a positive relationship. The difference between the correlation results between $Si_{AP}$ and clay in this study with Chirkes Johanna et al. (2018) may occur due to variations in the types of kaolinite and montmorillonite clay minerals.

Other soil properties, including total nitrogen, pH (water-based), pH (KCl-based), total organic carbon, silt and sand content, have a positive relationship to the increase in $Si_{AP}$ of paddy soils. The relationship between $Si_{AP}$ and nitrogen in this study was positive, while Chirkes Johanna et al. (2018) reported that the relationship between $Si_{AP}$ and total nitrogen was negative. The positive correlation between $Si_{AP}$ and total nitrogen occurs because the $Si_{AP}$ can increase the activity of microorganisms involved in the N and P cycle in paddy soils (Liang et al., 2021). The relationship between $Si_{AP}$ and soil pH is positive, meaning that an increase in soil pH will increase the $Si_{AP}$ concentration. The solubility of Si will increase in alkaline conditions (Landré et al., 2018). In this study, the relationship between $Si_{AP}$ and soil pH was consistent with previous studies which reported that soil pH was positively correlated with soil $Si_{AP}$ (Sirisuntornlak et al., 2021). The $Si_{AP}$ of paddy soil has a positive correlation with organic carbon. Adding organic materials such as paddy straw and rice husks will increase the $Si_{AP}$ of paddy soil (Nwite et al., 2019). The sand fraction's percentage positively correlates to the increase in $Si_{AP}$, but has an insignificant effect.

The sand fraction dominated by $SiO_2$ in the crystalline phase is difficult to dissolve resulting in a minor effect on the increase of $Si_{AP}$ concentration (Meunier et al., 2018). The silt fraction with $Si_{AP}$ in this study was positively correlated to the increase in $Si_{AP}$. In line with Chirkes Johanna et al. (2018), the silt fraction positively correlates with the $Si_{AP}$ content. There is a positive correlation between $Si_{AP}$ and the sand and silt fraction. The sand and silt fractions of the constituent materials are dominated by the minerals quartz ($SiO_2$) and feldspar (Sufardi et al., 2021). However, the soil solubility of soil mineral constituent as a source of $Si_{AP}$, is influenced by other factors such as soil pH. The effect of soil texture on the $Si_{AP}$ of paddy soil will vary depending on the type of parent material. The main difference between sand, clay, and silt fractions is their particle size (sand > silt > clay particle size) (Beretta et al., 2014). The size of the silt particles is smaller than the sand particles; therefore, the solubility of Si in the silt particles is higher (Abidin et al., 2017).

The relationship between $Si_{AP}$ paddy fields on electrical conductivity (EC), water pH, and irrigated water shows a positive relationship (Fig. 4). However, only the silicon of irrigated water significantly affected variations in the $Si_{AP}$ of paddy soil. In this study, the Si content of irrigated water ranges from 0.2 to 40.8 mg kg$^{-1}$ with an average of 6.5 mg kg$^{-1}$. Variations in Si contents of irrigated water in paddy fields in Subang Regency are influenced by rocks through which the river flows. Irrigated water flowing through volcanic rocks has a higher Si content (Husnain et al., 2008). In simulation of water requirement for paddy plants (Yaligar et al., 2017) with an average Si content of irrigated water of 3.05 mg L$^{-1}$, the results show that irrigated water that flows to paddy fields in Subang Regency contributes to the addition of Si by 6.25% or equivalent to 30 kg h$^{-1}$ a Si per season. The role of irrigated water in supplying the Si requirement of paddy plants is varied depending on the Si of irrigated water in each region.

The results of multiple regression analysis (Table 1) of $SiO_2$, total nitrogen, pH (water-based), pH (KCl based), organic C, clay texture, sand, silt, $SiO_2$ irrigated water, electrical conductivity (EC) and pH to $Si_{AP}$ paddy soil obtains a coefficient of determination 0.78. This shows that the observed variables influence 78% of the variation in $Si_{AP}$ of paddy soils in the Subang Regency. However, four variables significantly affect the $Si_{AP}$ of paddy soil, namely soil pH, total $SiO_2$, $SiO_2$ irrigated water and irrigated water pH.




**Remark**: values followed by the same letters are not significantly different ($P \geq 0.05$) according to Duncan's multiple range test

**Figure 6**. Effect of Si fertilization on each $Si_{AP}$ status

This study's results align with previous studies, which showed that the solubility of $SiO_2$ in the soil increased with increasing soil Ph (Li et al., 2019). $SiO_2$ reserves in the soil will affect the level of $Si_{AP}$. Soils with high $SiO_2$ reserves will contain more $Si_{AP}$ than soils with low $SiO_2$. However, soils with low $SiO_2$ reserves are helped by the supply of $Si_{AP}$ from watercourses (Darmawan et al., 2006).

The Si addition to the rice plants with $Si_{AP}$ status low, moderate and high increased rice yield by 0.2%, 3.9% and 2.7%, respectively (Fig. 6). The low rice yield at $Si_{AP}$ paddy soil status indicated the increased Si addition. In this study, the rice yield increase was not in line with Siregar et al. (2016) in that adding exogenous Si could increase the growth and yield of paddy plants. This research shows that Si addition in paddy soils has potential to be implemented to increase the Si availability for paddy plants. The silicon addition to the soil inhibits the rate of declining the $Si_{AP}$ of paddy soil and increases rice yield.

In the present study, the $Si_{AP}$ status of the paddy soil area (Fig. 5) of 26,395 hectares (25%), 61,744 hectares (59%), and 15,952 hectares (15%) were categorized as low, moderate, and high, respectively. The spatial distribution of paddy soils with high $Si_{AP}$ was in the southern part of Subang (upland area). In contrast, the low to moderate $Si_{AP}$ category was dominant in the northern part of Subang (lowland area). The chemical properties of soil and irrigated water that contribute to $Si_{AP}$ were pH (soil and irrigated water) and total $SiO_2$ (soil and irrigated water). The silicon addition had potential to increase rice yield.

## 5. CONCLUSION

Silicon availability for plant ($Si_{AP}$) in paddy soil consisted of 70 – 378 mg $kg^{-1}$. Paddy fields with low to moderate $Si_{AP}$ levels were in the northern part of Subang (lowland area), while in the south of Subang (upland area), $Si_{AP}$ levels were moderate to high. The $Si_{AP}$ level status of paddy soil may depend on total $SiO_2$, soil pH, $SiO_2$ of irrigated water, and irrigated water pH. The $Si_{AP}$ level status of low to high in paddy soil has potential to increase rice productivity by 95.8 g $pot^{-1}$, 98.2 g $pot^{-1}$ and 103.1 g $pot^{-1}$, respectively. Silicon addition to the paddy soil with $Si_{AP}$ status low to high increased rice yield by 0.2%, 3.9%, and 2.7%. The limitation of the study is that it cannot collect paddy soil samples on the same paddy plant growth stage because the planting calendar in each site location was different. The recommendation for future research is to increase the dosage of silicon addition to paddy plants at various levels of $Si_{AP}$ paddy soil.

## Declaration of Competing Interest

The authors declare that no competing financial or personal interests that may appear and influence the work reported in this paper.

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