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The Optimization of Biosilica and Humic Acid to Increase Soil Nutrient Availability and Nutrient Uptake in Rice Plant in Sandy Soil

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Abstract

Nutrients in sandy soil are limited due to low absorption capacity and are easily leached or evaporated. Biosilica and humic acid extracted from compost and husk ash can improve the soil structure and absorption capacity to optimize the availability and uptake of nutrients. Therefore, this research aims to examine the optimal application dose of biosilica and humic acid to improve the chemical properties of soil with a sandy texture. The experiment was structured based on a completely randomized design (CRD). Factor 1 consisted of biosilica doses of 0, 0.5, 1.0, and 1.5 tons ha^{-1}, while factor 2 comprised humic acid doses of 0, 20, 40, and 60 kg ha^{-1}. Data analysis was performed using ANOVA, followed by Tukey's Honest Significant Difference (HSD) test, correlation, and determination analysis. The study results indicate that the combination of biosilica and humic acid contributes to the changes in nutrient availability. The impact of the treatment was observed 90 days after application on the parameters of soil pH, organic C, total N, and exchangeable K. The effects of the treatment were also evident in plant nutrient uptake, specifically in total N in the roots and total K in the stems. The optimal combination for improving soil nutrient availability and nutrient uptake in plant tissues was a biosilica dose of 1.0 tons ha^{-1} (S2) and humic acid at 40 kg ha^{-1} (H2).

Keywords: chelate; leaching; nutrient uptake; paddy soil; soil amendment

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INTRODUCTION

Sandy soil is characterized by lower fertility, unstable aggregation, high porosity, and an organic C content of < 1% (Aditya et al., 2020). In this context, plant growth requires soil with stable aggregation characteristics to prevent water loss and nutrient availability (Xiao et al., 2021). Low soil organic matter content is susceptible to loss of available water and nutrients. This condition is caused by the leaching process, which decreases soil fertility (Rodrigues et al., 2023). The low capacity to retain nutrients, such as P, in sandy soils presents a significant challenge. Phosphorus can be lost through leaching or become unavailable due to binding with heavy metals, reducing its accessibility for plants. This depletion of nutrients negatively impacts crop yield and soil productivity, thereby hindering sustainability efforts (Karimah et al., 2024).

Adding calcium silicate ($CaSiO_3$) can induce chemical changes in the soil, such as increased pH

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and enhanced cation exchange capacity (CEC). These improvements improve nutrient retention, including P, and a healthier soil structure, supporting long-term agricultural productivity. Managing the chemical properties of soil through amendments like $CaSiO_3$ thus contributes to more sustainable farming by reducing the need for excessive fertilizers, improving crop yield, and mitigating environmental degradation (Schaller et al., 2020; Amoakwah et al., 2023).

Addressing nutrient management issues in sandy soils through Si applications aligns with sustainable agriculture practices, as it helps maintain soil fertility and reduces harmful leaching into the environment. Soil with a sandy texture often lacks sufficient organic matter and nutrients, adversely affecting its fertility and water retention capacity. Without intervention, sandy soils can remain low in organic carbon and moisture, reducing soil fertility and poor plant growth. This can result in decreased crop yields and diminished soil health over time. Organic amendments such as manure, biochar (Karimah et al., 2024), and humic acid can be applied to improve sandy soil texture and fertility. Manure enhances water availability and soil moisture (Seyedsadr et al., 2022).

Humic acid serves as an effective soil conditioner for sandy soils. It enhances soil fertility by improving soil respiration and reducing ecotoxicity. The carboxyl (-COOH) and phenolic (-OH) groups in humic acid chelate nutrients are prevent to their loss and promote nutrient retention (Mindari et al., 2022). This helps mitigate the slow release of nutrients such as N in the form of ammonium (NH_4^+) and nitrate (NO_3^-) (Ennan et al., 2022). Using compost as a source of humic acid has a lower economic value while maintaining the same effectiveness as leonardite (Piccolo et al., 2018). The optimal dosage for soil remediation by humic acid ranges from 10 to 20 kg ha^{-1}, combined with vetiver plants. Applying humic acid at these doses can reduce the available Cu content in the soil by 47.13 to 76.79% (Vargas et al., 2016). An application dose of 40 mg kg^{-1} at pH 7 increases the content of -COOH and -OH groups and forms adsorption complexes with Fe metals (Boguta et al., 2019). This application dose is equivalent to using 80 kg ha^{-1} of humic acid.

Biosilica acts as a soil conditioner by influencing plant cellular tissue and biochemical interactions extracted from husk ash or other organic materials (Bhat, 2019). It enhances the antioxidant system, reduces photosynthesis inhibition, and facilitates the complexation of heavy metals (Khan et al., 2021). Silica's role in reducing heavy metal availability and improving nutrient uptake is also significant. For instance, previous research has found that applying humic acid (Pambayun et al., 2023) and Si (Sinatrya et al., 2022) improved N availability, plant length, and tiller count (Bakhsh et al., 2022). Additionally, silica's impact on macronutrients like N, P, and K is crucial for overall plant health (Shukla et al., 2014). By implementing these soil management techniques, the fertility and health of sandy soils can be significantly improved, leading to better crop yields and more sustainable soil practices.

The impact of biosilica and humic acid soil amendment treatment was assessed to improve soil chemical properties with indicators of soil nutrient availability and plant nutrient uptake. Therefore, this research aims to examine the optimal application dose of biosilica and humic acid to improve the chemical properties of soil with a sandy texture. Application of 30 kg ha^{-1} humic acid combined with 100% recommended dose of nitrogen (RDN) showed significant results on N availability, available P_2O_5, and several micronutrients such as Fe, Mn, Zn, and Cu. The increase in N availability could be caused by soil microbial activity, which was influenced by adding humic acid to the treatment (Manjeera et al., 2021). The addition of humic acid also aims to control the release of N by fertilizer. This results in higher crop yields and N uptake, efficient use of N, and reduced volatilization into the air, which has the potential to become pollution (Guo et al., 2022). Available nutrients caused by humic acid include ammonium-N, nitrate-N, and P_2O_5, which increase the balance of enzymes that promote microbial activity (Kong et al., 2022). Applying Si nutrients has been shown to improve paddy growth and yield under saline conditions potentially (Nasrudin et al., 2022). The accumulation of Si in the epidermal cell layer enhances the structure of cell walls, helping plants better withstand abiotic stress. By applying Si 150 kg ha^{-1} as $CaSiO_3$ shows positive results on plant growth, physiology, grain production, and soil availability (Mahendran et al., 2022).

Sandy soils exhibit a low capacity to retain nutrient ions due to their limited negative charge, which results in poor nutrient absorption (Rong et al., 2020). Effective management of sandy soils is essential to address various challenges such as water repellency, compaction, crust formation, erosion, salinization, and reduced fertility. Moreover, sandy soils are often susceptible to both inorganic and organic contamination. Strategies to improve their fertility frequently involve the use of organic amendments. For instance, biosilica and humic acid extracts have demonstrated the potential to enhance nutrient retention and improve soil structure, thereby boosting soil fertility. These factors are significant under intensive agricultural activities and climate change. Additionally, the impacts of soil texture are evaluated on soil properties and processes. Applying biosilica and humic acid is expected to increase the negative charge of soil in absorbing and releasing nutrients. The quality and quantity determine the ability to absorb ions in soil. The optimum dose is recommended for improving soil with similar characteristics. The characteristics of other materials used as a basis for extracting humic acid or biosilica must be identical to the samples in this research.

MATERIALS AND METHOD

Study area

The study was conducted at the Greenhouse and Land Resources Laboratory, Faculty of Agriculture, Universitas Pembangunan Nasional Veteran Jawa Timur in East Java. Soil samples, used as plant media, were collected from the Mekikis Village area, Purwoasri Sub-district, Kediri Regency, East Java. Soil was classified as an Entisol order according to the USDA Soil Taxonomy. The coordinates of the region are approximately between 111°47’05” to 112°18’20’ E and 7°18’12” to 8°0’32” S.

Research design

The research employed a completely randomized design (CRD). The first factor was biosilica dosage with 0, 0.5, 1.0, and 1.5 tons ha^{-1} (Nasrudin et al., 2022). The second factor was humic acid dosage at levels 0, 20, 40, and 60 kg ha^{-1} (Manjeera et al., 2021), resulting in 16 treatment combinations, each repeated 3 times. The soil media was obtained from the Mekikis Village at 0 to 20 cm depth, resulting in a sandy soil texture. The raw materials for the soil amendments were sourced from compost produced by the Faculty of Agriculture, Universitas Pembangunan Nasional Veteran Jawa Timur, and rice husk ash collected from post-harvest residues in Gresik Regency.

Soil characteristics

Soil serves as a medium for plant growth and is generally characterized by fertility, but the type dominated by sand fraction is inferior (Sukarman and Gani, 2020). This condition aligns with the soil used in this research (Table 1). The pH value of 5.73 is slightly acidic, while soil organic C content and CEC of 0.79% and 13.89 cmol(+) kg^{-1} are relatively low. Low CEC is caused by reduced soil organic C content of 0.79% and sand fraction content of 55% (Table 1).

Soil nutrient conditions are classified as less fertile, while the total N content and exchangeable K of 0.10% and 0.34 cmol(+) kg^{-1} are low. Only the available P nutrient is classified as very high at 59.60 ppm. The impact of high sand fraction content and low CEC value of soil causes low nutrient retention (Darlita et al., 2017; Hamid et al., 2017). This condition is due to the complex role of soil organic C in holding water, retaining nutrients, and binding soil aggregation (McCauley et al., 2017). The slightly acidic soil pH is attributed to organic matter decomposition and leaching processes, while the high available P content in sandy loam soils results from its well-drained texture, which prevents P from binding too tightly to soil particles.

Table 1. Chemical and physical properties of soil

Parameter	Unit	Value	Criteria
pH	-	5.73	Slightly acid
Organic C	%	0.79	Very low
Total N	%	0.10	Very low
Available P	ppm	59.60	Very high
Exchangeable K	cmol(+) kg^{-1}	0.34	Low
CEC	cmol(+) kg^{-1}	13.89	Low
Sand	%	55	-
Silt	%	32	-
Clay	%	13	-
Soil texture	-	Sandy loam	-

Note: Book-based criteria Technical Instructions for Soil Chemical Analysis of the Indonesian Soil Research Institute (2023)

Extraction of biosilica and humic acid

Biosilica

The husk ash was crushed and sieved through a 200-mesh sieve. In addition, 60 ml of 10% KOH solution was added to 10 g of husk ash, heated to 85 °C, and stirred for 90 minutes. The solution was filtered, and the residue was extracted with the first filtrate as a silicate solution. Solution 1 N HCl was added gradually to the extracted biosilica solution while continuously monitoring the pH until it reached 9 (Anggraini et al., 2022).

Humic acid

Humic acid was extracted using the modified method (Stevenson, 1982). The 10 g of organic material was extracted using 100 ml of KOH 0.5 N solution (1:10). The extraction and refrigeration processes were conducted for 24 and 16 hours. The substance was separated using Whatman 42 filter paper, resulting in a humic substance. The humic substance was added with H_2SO_4 6 N until pH 2. The addition of H_2SO_4 6 N produced two layers of solution. The solution was filtered again using the Whatman 41 filter paper. The residue was then rinsed with CO_2-free distilled water to remove residual humic acid chloride. Subsequently, the supernatant obtained was titrated to pH 7 using KOH 0.1 N (Piccolo et al., 2019).

Characterization of biosilica and humic acid

Humic acid soil amendments and biosilica were characterized based on their chemical and physical properties. The chemical properties of the soil amendments included organic C content measured by the Walkley and Black method, total N using the Kjeldahl digestion method, P using the molybdate blue method, K using the ash method, CEC measured by the $BaCl_2$ extraction method, and pH using the potentiometric method. The C, N, P, K, and CEC were analyzed using Spectroquant Prove 600 and AAS Hitachi ZA3000.

The physical properties of the soil amendments were analyzed through surface morphology and particle shape using a Hitachi SU3500 Scanning Electron Microscope (SEM). The sample solids were ground to a particle size of 100 mesh. A small powder sample was taken with a spatula and sprinkled onto carbon tape. The carbon tape attached to the specimen stub was then placed into the SEM chamber. The conditions during SEM observation were as follows: Accelerating voltage = 5 kV; Magnification = 5,000 to 10,000x; Working distance = 10 mm; Observation mode = High vacuum (SE).

Planting media preparation

Soil taken from the location was crushed and sieved using a 2 mm sieve to make soil particle size homogeneous. Soil media was analyzed for physical and chemical properties using the USDA guidebook. The planting medium weighed 7 kg and was then converted to oven-dry soil.

Preparation and planting of paddy plant

Soil amendments were applied 7 days before planting rice seeds, and the incubation process was evenly distributed. Fertilizer application was carried out at the beginning of planting rice seedlings at a dose of 120 kg N ha^{-1} (260 kg urea ha^{-1}), 22 kg P ha^{-1} (61 kg SP36 ha^{-1}), and 41.5 kg K ha^{-1} (69 kg KCl ha^{-1}) (Bijay-Singh et al., 1991). Meanwhile, each pot was given 1.08 g of urea, 0.25 g of SP36, and 0.29 g of KCl. The application was conducted by sowing in a circle 10 cm from the center of the pot, using the Cibogo rice plant variety.

Soil and plant sampling

Soil sampling was conducted using composite sampling, with samples taken from experimental pots by repeating three sampling points for each pot. The sampling was carried out 7 and 90 days after treatment (DAT) at the same time as rice plant harvesting. Meanwhile, harvesting was performed 90 days after planting according to the age of the rice. The process included separating the plant into three parts: rice grains, straw, and plant roots.

Soil and plant analysis

The observation parameters for soil samples included pH measured by the potentiometric method, organic C using the Walkley and Black method, total N using the Kjeldahl digestion method, available P using the Olsen method, exchangeable K using the 1 N ammonium acetate extraction method at pH 7, and CEC using the same extraction method. The observation parameters for plant tissue nutrient samples were total N uptake measured by the Kjeldahl digestion method and total P and K uptake using the HNO_3:$HClO_4$ extraction method. The analysis methods refer to the Soil, Plant, Water, and Fertilizer Analysis Guidelines from the Soil Research Institute (2009).

Research data analysis

The observational data from the study were analyzed using normality and homogeneity tests. The data testing was followed by the analysis of variance (ANOVA) at a 5% error level to determine the effect of the applied treatments. A Tukey's Honestly Significant Difference (HSD) test was conducted at the 5% error level if significant differences were found among the treatments. Data analysis utilized correlation and determination methods for each observed variable.

RESULTS AND DISCUSSION

Characteristics of biosilica and humic acid

Soil amendment is a material used to improve soil's physical and chemical properties. Soil conditioners have gained considerable attention due to their potential to enhance soil health and fertility. Among these, biosilica and humic acid have become practical materials for improving soil properties. Biosilica, derived from organic sources such as husk ash, rice straw, and corn stalks, plays a crucial role in soil management by contributing to soil structure and nutrient availability (Shim et al., 2014; Bakhat et al., 2018). On the other hand, humic acid, extracted from compost and manure, is known for its beneficial effects on soil fertility and plant growth (Piccolo et al., 2019; Mindari et al., 2022).

These soil conditioners are increasingly recognized for their ability to modify soil texture, enhance water retention, and improve nutrient uptake, making them valuable tools in sustainable agriculture. This study explores the practical applications of biosilica and humic acid, focusing on their impact on soil quality and plant productivity.

Technical requirements for soil improvement are regulated in Minister of Agriculture Regulation Number 261/KPTS/SR.310/M/4/2019 concerning minimum technical requirements. The observation parameters are consistent with the Ministry of Agriculture regulations, but organic C is below the technical specifications. The regulation specifies that soil amendments should aim to increase CEC to a minimum of 60 cmol(+) kg^{-1} (Mindari et al., 2022). Meanwhile, the CEC of humic acid (total acidity) is higher than that of biosilica. The difference in CEC stems from their chemical properties. Humic acid, a complex organic material, has a higher CEC due to its abundance of functional groups, such as carboxyl and phenolic, which attract and hold cations (Mindari et al., 2022).

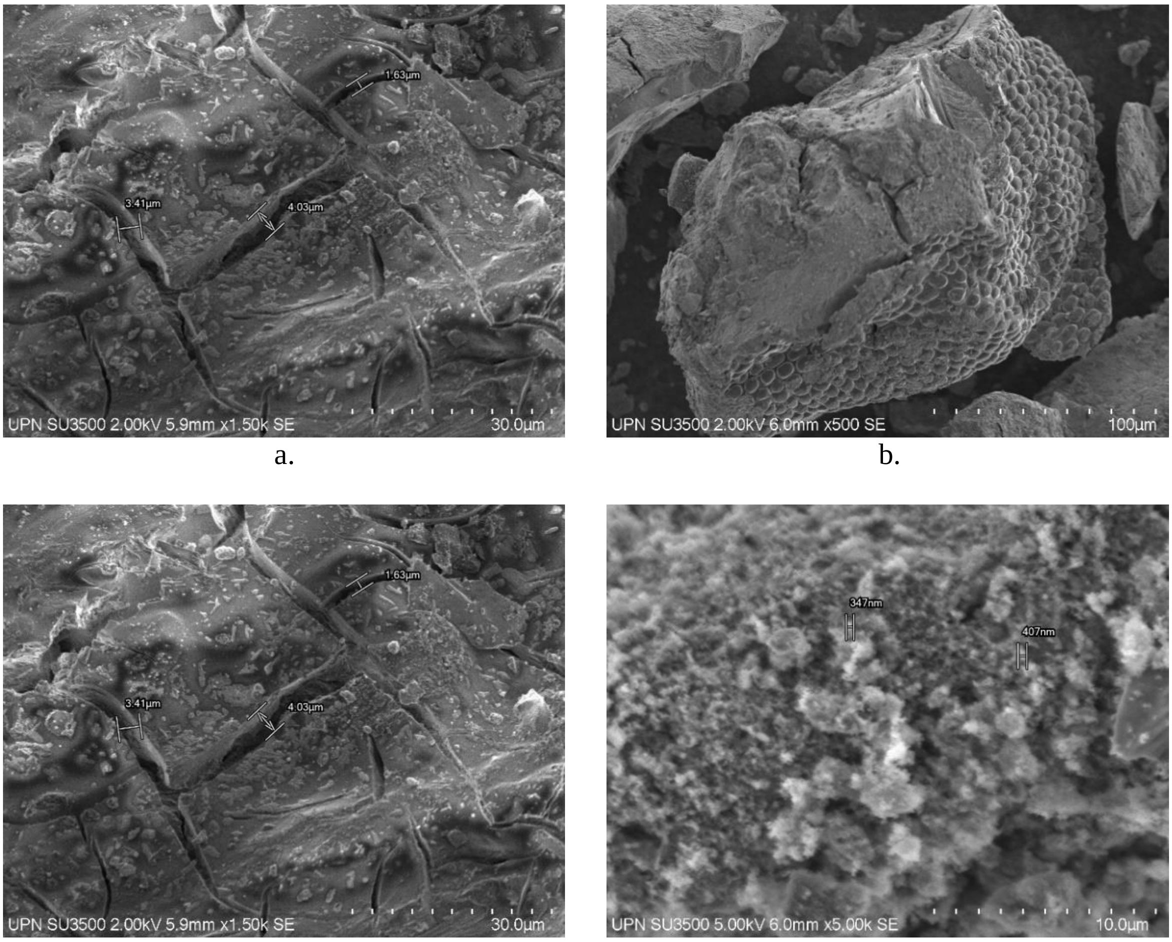
In contrast, biosilica, primarily composed of SiO_2 from sources like husk ash, has a lower CEC because it lacks these functional groups, thus limiting its CEC (Shim et al., 2014). While biosilica improves soil structure and water retention, humic acid is more effective at enhancing soil fertility through better nutrient retention and exchange, with a value of 275 cmol(+) kg^{-1}. The organic C content in humic acid is higher than biosilica, containing 0.01%, as reported in Table 2. Morphological characterization using SEM-EDX was performed to analyze soil amendment materials' structure and surface characteristics. This was intended to determine the aggregate form and the impact on the nutrient chelation system. SEM observations show different forms of micro aggregates from the two types of soil amendments. The structural form of humic acid is shown in Figure 1a and 1b, and the micro aggregates are more evident than biosilica (Figure 1c and 1d).

The surface of humic acid has a layered shape accompanied by cracks. This condition is influenced by a pH of 7 and a thick sheet aggregate structure at the edges (Chen and Schnitzer, 1976). The structure tends to be porous with cracks, a sign of the deformation activity of several aliphatic and aromatic bonds (Fatima et al., 2021). Moreover, humic acid surface pores are formed at x1.50k magnification, as shown in Figure 1a. Since humic macromolecules contain hydrophobic and hydrophilic groups, the sponge-

Table 2. Characteristics of biosilica and humic acid

Parameter	Unit	Humic acid	Biosilica	Requirements
pH	-	7.21	9.65	4–9
Organic C	%	0.32	0.01	Min. 10
Total N	%	0.02	nd	-
Total P	%	0.002	0.001	-
Total K	%	0.34	0.68	-
CEC	cmol(+) kg^{-1}	275.00	255.00	Min. 60

Note: nd = Not detected



a. b.

c. d.

Figure 1. Surface structure of humic acid (a, b) and biosilica (c, d) by SEM analysis

like structure of humic acid shows more polar groups on the surface (Chen et al., 2009).

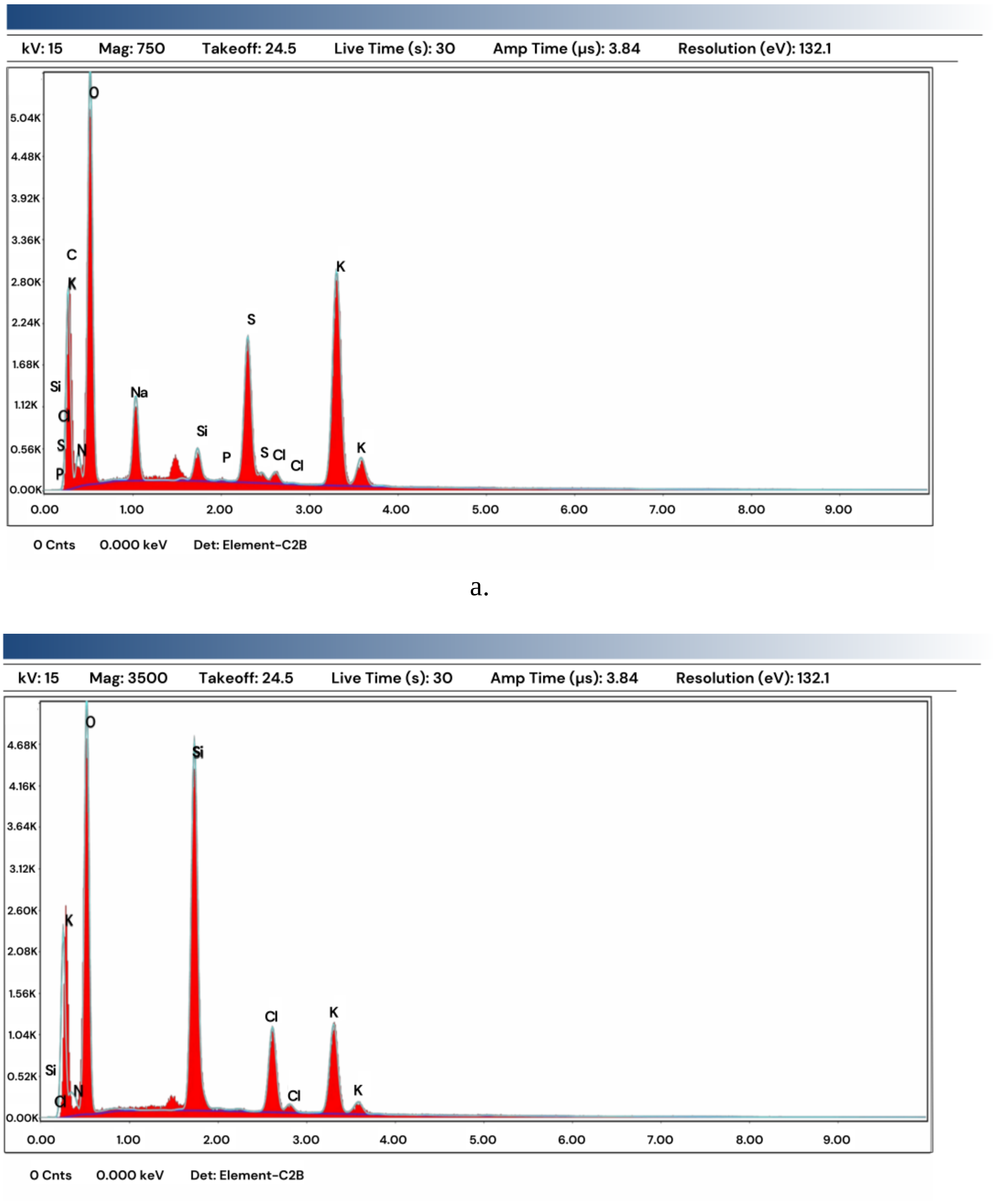
The structure of biosilica is different from the apparent surface shape of humic acid. Biosilica surface tends to be irregular at x5.00K magnification and amorphous (Figure 2a). The structure at x1.50k magnification is an irregular grain, as shown in Figure 2b. After SEM analysis, biosilica from husk ash shows an amorphous particle shape (Sriwuryandari et al., 2020). The characteristics are related to biosilica extracted from husk ash using essential and acid solutions such as HCl. In addition, the shape of the particles is irregular and amorphous (Sapei et al., 2018). The amorphous form of biosilica, characterized by its non-crystalline structure, has a limited impact on nutrient retention compared to more structured materials; however, it can still influence soil processes by improving soil aeration and water retention.

The content of biosilica and humic acid resulting from EDX analysis shows differences between the nutrients, as reported in Figure 2. Humic acid contains atoms of C, O, N, P, K, S, and several other nutrients, with the highest being C and O at 28.25% and 46.54%, respectively. Meanwhile, biosilica contains Si, O, K, N, and Cl, and the content tends to be less than humic acid. The highest nutrients are Si and O at 12.26% and 60.35%, with several other constituents. Humic acid with high C and O contains increased aliphatic and aromatic groups.

The high Si and O content indicates the increased level of SiO_2 in biosilica. The average Si from SEM-EDX analysis results is 23 to 35% (Ali and A-Ali Drea, 2021), and the robust acid solution affects the purity. HCl is a strong acid that produces purer silica than other extractors, such as H_2SO_4 (Sapei et al., 2018).

Soil chemical properties after biosilica and humic acid treatment

Soil media observations were carried out at 7 and 90 DAT with the observation parameters including pH, organic C, total N, available P, exchangeable K, and CEC. The observation data showed no significant differences in the parameters, as confirmed by the HSD test with



a.

b.

Figure 2. Content of humic acid (a) and biosilica (b) using SEM-EDX analysis

an error of 5%. The exchangeable K parameter exhibited different results in the treatment combination. The treatment did not significantly impact soil changes after 7 days of soil amendment.

The combination treatment did not show significantly different results on several parameters. However, the single-factor (individual) application of biosilica and humic acid has various impacts on the observed parameters. The pH parameter provided considerably different results (Table 3) among treatments S0, S1, S2, and S3 with slightly acidic pH criteria (Indonesian Soil and Fertilizer Instrument Standard Testing Center, 2023). The CEC of soil showed different results, with a maximum value in treatment S1 at 17.35 cmol(+) kg^{-1}.

The pH 7 DAT observation showed significantly different results in the HSD test, with an error of 0.05. However, the result did not show a significant difference in treatments S1, S2 and S3. Using biosilica at a dose of 0.5 tons ha^{-1} 7 DAT obtained optimal results for pH parameters. The application provided significantly different results in the HSD test at an error of 0.05, and the pH characteristics of soil amendment influenced the outcome.

Table 3. Soil chemical properties after 7 days of biosilica and humic acid soil amendment treatment

Treatment	pH	Organic C (%)	Total N (%)	Available P (ppm)	Exchangeable K (cmol(+) kg^{-1})	CEC (cmol(+) kg^{-1})
S0H0	6.21	0.54	0.03	53.18	0.24^{a}	12.26
S0H1	6.20	0.56	0.03	56.97	0.36^{ab}	12.34
S0H2	6.20	0.54	0.02	52.86	0.37^{b}	15.33
S0H3	6.19	0.54	0.02	59.65	0.35^{ab}	13.57
S1H0	6.13	0.54	0.03	56.62	0.29^{ab}	15.73
S1H1	6.26	0.53	0.03	56.87	0.33^{ab}	17.95
S1H2	6.26	0.46	0.03	59.73	0.32^{ab}	17.69
S1H3	6.13	0.48	0.02	66.40	0.30^{ab}	18.02
S2H0	6.04	0.56	0.02	52.81	0.31^{ab}	17.04
S2H1	5.99	0.46	0.03	58.07	0.30^{ab}	15.20
S2H2	6.05	0.48	0.03	59.19	0.33^{ab}	16.40
S2H3	6.07	0.51	0.03	57.12	0.30^{ab}	17.71
S3H0	6.23	0.54	0.02	54.01	0.32^{ab}	17.30
S3H1	6.31	0.48	0.02	56.90	0.30^{ab}	13.34
S3H2	6.19	0.58	0.02	56.37	0.36^{ab}	17.22
S3H3	6.17	0.47	0.03	54.94	0.36^{ab}	16.17
Tukey's HSD 0.05	ns	ns	ns	ns	0.11	ns

Note: Numbers followed by the same letter show that the results are not significantly different in Tukey's HSD at an error of 0.05, ns = Not significant. S0 = 0; S1 = 0.5; S2 = 1.0; S3 = 1.5 tons ha^{-1}; H0 = 0; H1 = 20; H2 = 40; H3 = 60 kg ha^{-1}

Despite the initial pH values of humic acid (7.21) and biosilica (9.65), the soil pH converged to similar values after 7 days due to the soil's buffering capacity, neutralizing the effects of both acidic and alkaline amendments, resulting in pH stabilization (Piccolo et al., 2019).

Soil amendment with biosilica resulted in an alkaline pH compared to humic acid (Table 2). However, the treatment increased the pH value from 4.0 to 6.2. Biosilica's ability to neutralize acidic pH is attributed to the binding of H^+ ions to form mono-silicic acid compounds (H_4SiO_4) (Siregar et al., 2020). Meanwhile, the observations of the availability of P in soil showed significantly different results. The effect of soil amendment showed different results compared to the control. The optimal biosilica and humic acid doses were 0.5 tons ha^{-1} (S1) and 20 kg ha^{-1} (H1). The high content of available P nutrient was influenced by applying 20 kg ha^{-1} of humic acid. This finding is supported by previous research showing that humic acid can increase the P nutrient in Alfisols and Vertisols (Li, 2020).

Biosilica and humic acid have a positive impact on increasing available P. In this context, biosilica, through the binding ability to heavy metals, causes P to be fixed by metals through changes in soil pH (Schaller et al., 2020). Research shows that the treatment with Si straw extract could increase soil N, P, and K (Birnadi et al., 2019). Humic acid with a heavy metal binding mechanism releases P nutrient bonds with the ability of complex chelate groups (Akimbekov et al., 2021). Phosphorus release occurs despite negative charges because humic acid influences soil pH and microbial activity, which can enhance phosphate availability through indirect mechanisms rather than direct binding (Schubert et al., 2020).

At 7 DAT, the CEC showed changes compared to the value before ameliorant treatment. Biosilica and humic acid treatments impacted increasing CEC, but only biosilica gave a significantly different response to Tukey's HSD test at an error of 0.05. The combination did not show any interaction between soil amendments. Hence, the influence of the single factor appeared at 7 DAT. Biosilica treatment produced the highest CEC value at a dose of 0.5 tons ha^{-1}. Meanwhile, Si treatment obtained from corn plant extract at a dose of 5% (w/w) increased the CEC of the initial soil from 94 to 100.3 cmol(+) kg^{-1} (Shim et al., 2014).

Soil media observations were carried out at 90 DAT, where the parameters showed significantly different results from Tukey's HSD test of 0.05. The combination of biosilica and humic acid treatment provides different impacts. The results showed significant pH, organic C, total N, and exchangeable K values. The parameters of P availability and CEC were not significant in the treatment combination, but the single factor with Tukey's HSD test, at an error of 0.05, showed different results. The interaction between biosilica and humic acid treatment did not occur for all parameters.

Biosilica and humic acid treatments at doses of 0.5 tons ha^{-1} (S1) and 20 kg ha^{-1} (H1) gave optimal results in changing pH values 6.42 and 6.61, as reported in Table 4. This condition is based on the HSD test, which showed an error of 0.05 between all treatments. There were significant changes at 90 DAT (Table 4) since the maximum results were demonstrated by a combination of 1.5 tons biosilica ha^{-1} (S3) and 60 kg humic acid ha^{-1} (H3), yielding 1.15% soil organic C. The optimum dose used was 1.0 tons biosilica ha^{-1} (S2) and 60 kg humic acid ha^{-1} (H3), which resulted in a soil organic C value of 1.05%.

Biosilica and humic acid can bind nutrients through cations and anions. For example, N in soil is in the form of NH_4^+ and NO_3^-. Humic acid supplies N because the organic compound contains amino acids. In addition, N associated with humic compounds cannot be explained in the compound. This nutrient occurs as (1) free amino groups (-NH_2), (2) open chain (-N-, =N-), (3) part of heterocyclic rings, such as -NH- of indole and pyrrole or -N= pyridine, (4) bridging constituents connecting quinone rings, and (5) attached to aromatic rings (Kelley and Stevenson, 1995).

Availability of P also increased 90 DAT of biosilica soil amendment and humic acid. Single-factor treatment (Table 4) has a significantly different impact on the value of P. Therefore, the application of biosilica and humic acid to increase P availability can be achieved in combination or individually. In this context, combination treatment increases the availability of other factors. Humic acid binds P to increase availability in soil due to the chelating ability (Purwanto et al., 2021). This condition helps protect P from loss because of leaching when the sandy soil is very porous and allows water to pass through easily. The presence of humic acid also increases the solubility of P in soil and absorption by plants. Biosilica can also replace the position of bound PO_4^- and bind to metal to release P through Si ability (Schaller et al., 2020).

Increasing the CEC value and soil pH impacts nutrient availability such as K. The total content in soil amendments also supports the soil's relatively high exchangeable K value. Table 2 shows that the total K content of biosilica and humic acid is 0.34% and 0.68%, respectively. An increase in CEC by adding biosilica and humic acid indicates a chain link between organic

Table 4. Soil chemical properties after 90 days of biosilica and humic acid soil amendment treatment

Treatment	pH	Organic C (%)	Total N (%)	Available P (ppm)	Exchangeable K (cmol(+) kg^{-1})	CEC (cmol(+) kg^{-1})
S0H0	6.36^{a}	0.72^{a}	0.02^{a}	44.13	0.86^{a}	18.45
S0H1	6.47^{ab}	0.78^{ab}	0.03^{ab}	47.25	0.94^{a}	19.63
S0H2	6.43^{ab}	0.80^{ab}	0.03^{ab}	47.07	0.91^{a}	23.17
S0H3	6.37^{a}	0.82^{ab}	0.03^{ab}	50.44	0.96^{ab}	21.14
S1H0	6.38^{a}	0.86^{abc}	0.03^{ab}	52.38	0.95^{a}	20.46
S1H1	6.42^{ab}	0.88^{abc}	0.03^{ab}	51.70	0.91^{a}	20.79
S1H2	6.61^{abc}	0.88^{abc}	0.03^{ab}	52.20	1.26^{abc}	21.29
S1H3	6.81^{abc}	0.93^{bcd}	0.03^{ab}	54.26	2.05^{c}	20.81
S2H0	7.07^{c}	0.85^{abc}	0.03^{ab}	49.32	2.16^{c}	23.85
S2H1	7.04^{c}	0.81^{ab}	0.03^{ab}	53.51	2.15^{c}	20.92
S2H2	7.13^{c}	0.93^{bcd}	0.03^{ab}	54.95	2.11^{c}	29.43
S2H3	6.90^{abc}	0.92^{abcd}	0.03^{ab}	55.70	1.93^{abc}	24.29
S3H0	6.87^{abc}	1.05^{cde}	0.05^{c}	50.63	2.18^{c}	22.26
S3H1	6.96^{b}	1.05^{cde}	0.04^{bc}	53.32	2.07^{c}	24.90
S3H2	6.69^{abc}	1.10^{de}	0.03^{ab}	54.07	1.68^{abc}	26.54
S3H3	6.60^{abc}	1.15^{e}	0.02^{a}	54.01	1.25^{abc}	25.10
Tukey's HSD 0.05	0.56	0.21	0.01	ns	0.97	ns

Note: Numbers followed by the same letter show that the results are not significantly different in Tukey's HSD at an error of 0.05, ns = Not significant. S0 = 0; S1 = 0.5; S2 = 1.0; S3 = 1.5 tons ha^{-1}; H0 = 0; H1 = 20; H2 = 40; H3 = 60 kg ha^{-1}

compounds and soil nutrients. Applying Si in the form of K_2SiO_3 was proven to significantly change the CEC value of soil from 48.63 to 63.65 me 100 g^{-1}. Therefore, the application in several forms, such as biosilica with the compound K_2SiO_4, increases CEC value where the single factor treatment shows significant results in the HSD test at an error of 0.05.

Changes in organic C values impact soil CEC values in forming carboxyl groups and adsorption complexes (Bakri et al., 2016). This condition is supported by the regression graph that produces $R^2 = 0.7008$ and organic C of 69.94% (Figure 3). In addition, the content correlates with the availability of soil nutrients, such as available P, with a value of r = 0.7247 (Adrees et al., 2015; McCauley et al., 2017).

The pH of soil media impacts nutrient availability, such as P and K (Figure 4 and 5). The effect of pH is shown by the available P value

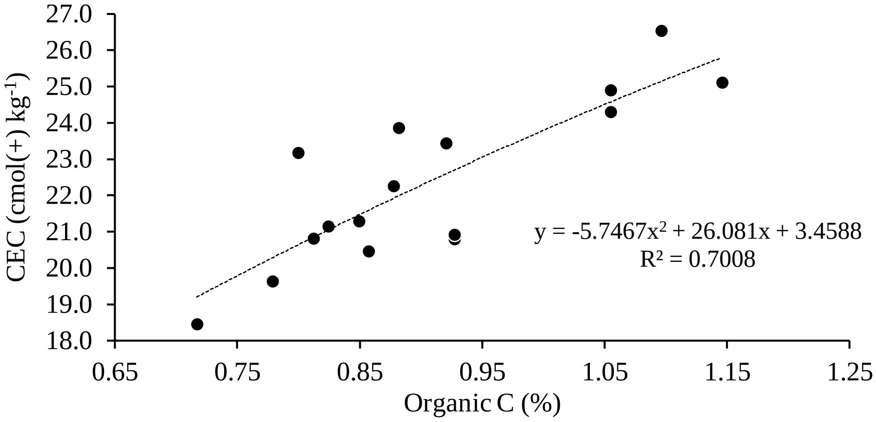


Figure 3. Impact of organic C on soil CEC value

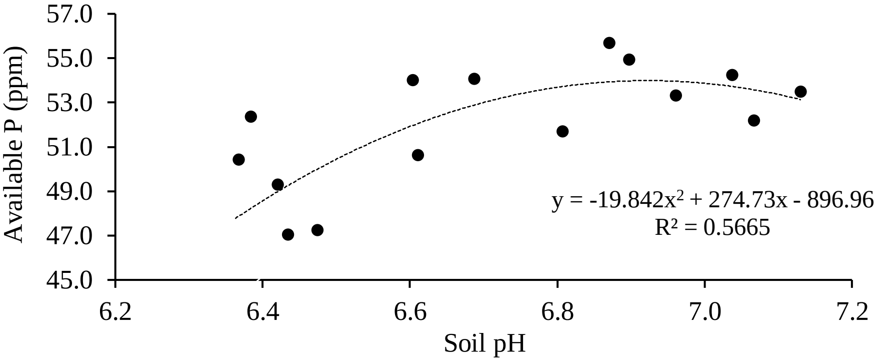


Figure 4. Effect of soil pH on soil available P

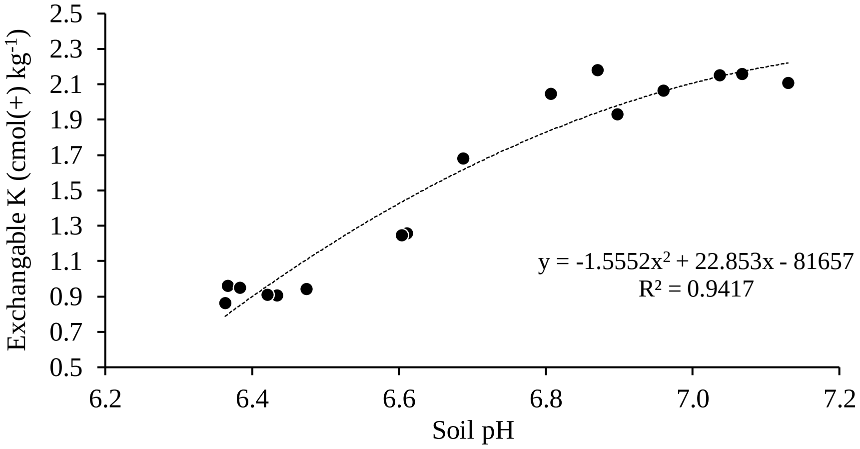


Figure 5. The impact of soil pH conditions on soil exchangeable K

R^2 = 0.5665 and exchangeable K value R^2 = 0.9416. The conditions greatly influence nutrient availability, such as K, which is relatively high in soil with an alkaline pH (Darlita et al., 2017). Changes in soil pH are caused by applying biosilica and humic acid (Mindari et al., 2022). Biosilica increases the pH value of soil through the ability to bind H^+ ions (Siregar et al., 2020). In addition, humic acid can bind ions, decreasing soil pH (Li, 2020).

Nutrient level in rice plant

Soil amendment treatment increases the availability of nutrients for plants. High nutrient content may not necessarily be absorbed by plants optimally. The role of biosilica and humic acid as soil conditioners increases the amount of nutrient uptake in plant tissue. Moreover, N, P, and K are macronutrients needed by plants for growth and development (Birnadi et al., 2019).

Observation of nutrient uptake in plant tissue is divided into three parts of the plant, namely roots, leaf stems, and rice grains. Based on the observations, only total N showed significantly different results from the HSD test, with an error of 0.05 for each plant part. Uptake of P and K reported significant differences in plant leaf stems using the HSD test at an error of 0.05.

N nutrient uptake showed significantly different results in the roots, leaf stems, and rice grains. Biosilica and humic acid showed significant results on N uptake in each part of the plant. In addition, plant root parts with an optimal dose of 1.0 tons ha^{-1} and 60 kg ha^{-1} biosilica and humic acid reported uptake of 0.28% and 0.29% N, respectively. The leaf stem part was not influenced by soil amendment, and each control treatment gave maximum results compared to the application. Uptake of P and K in each part of the plant showed significantly different results. The leaf stem section, which had a single influence of humic acid, demonstrated significant differences in P nutrient uptake using the HSD test, with an error level of 0.05. The optimal P nutrient uptake was shown by humic acid at a dose of 20 kg ha^{-1} (H1), resulting in 0.057%.

The biosilica and humic acid provided significant results on the total N-uptake value of roots, leaf stems, and rice grains. This condition is caused by the total N-value of soil, which has increased due to biosilica treatment and humic acid, as reported in Table 5. Silica treatment causes the accumulation of N in rice grains, straw, and plant biomass (Cuong et al., 2017). The function helps reduce nutrient loss in the soil through leaching and evaporation. Silica can withstand nutrient loss in soil, such as N bound in the form of NH_4^+ and K^+, which are exchangeable (Malav et al., 2017).

Table 5. Nutrient level in the roots, stems, and grains of rice

Treatment	Root			Shoot			Grain		
	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)
S0H0	0.19^{a}	0.10	0.62	0.06	0.04	0.56^{a}	0.24^{a}	0.21	0.40
S0H1	0.21^{a}	0.10	0.57	0.06	0.07	0.56^{a}	0.32^{bc}	0.20	0.40
S0H2	0.24^{ab}	0.07	0.60	0.07	0.05	0.53^{a}	0.36^{c}	0.24	0.57
S0H3	0.35^{c}	0.09	0.71	0.06	0.05	0.98^{a}	0.25^{ab}	0.25	0.40
S1H0	0.24^{ab}	0.09	0.71	0.05	0.04	1.19^{b}	0.25^{ab}	0.23	0.41
S1H1	0.28^{abc}	0.08	0.60	0.05	0.05	1.15^{b}	0.29^{abc}	0.20	0.40
S1H2	0.29^{abc}	0.08	0.90	0.05	0.05	1.15^{b}	0.25^{ab}	0.23	0.39
S1H3	0.24^{ab}	0.10	0.69	0.04	0.06	1.16^{b}	0.27^{ab}	0.21	0.43
S2H0	0.27^{abc}	0.09	0.71	0.05	0.04	1.11^{b}	0.30^{abc}	0.20	0.38
S2H1	0.25^{ab}	0.08	0.54	0.05	0.06	1.13^{b}	0.26^{ab}	0.20	0.41
S2H2	0.25^{ab}	0.11	0.64	0.05	0.06	1.14^{b}	0.29^{abc}	0.23	0.41
S2H3	0.31^{bc}	0.07	0.85	0.06	0.05	1.19^{b}	0.29^{abc}	0.20	0.38
S3H0	0.28^{abc}	0.05	0.73	0.05	0.05	1.15^{b}	0.27^{ab}	0.25	0.42
S3H1	0.24^{ab}	0.08	0.76	0.04	0.05	1.11^{b}	0.24^{a}	0.23	0.45
S3H2	0.25^{ab}	0.08	0.82	0.04	0.05	1.18^{b}	0.25^{ab}	0.22	0.35
S3H3	0.29^{abc}	0.08	0.76	0.05	0.06	1.17^{b}	0.22^{a}	0.22	0.35
Tukey's HSD 0.05	0.09	ns	ns	ns	ns	0.30	0.07	ns	ns

Note: Numbers followed by the same letter show that the results are not significantly different in Tukey's HSD at an error of 0.05, ns = Not significant. S0 = 0; S1 = 0.5; S2 = 1.0; S3 = 1.5 tons ha^{-1}; H0 = 0; H1 = 20; H2 = 40; H3 = 60 kg ha^{-1}

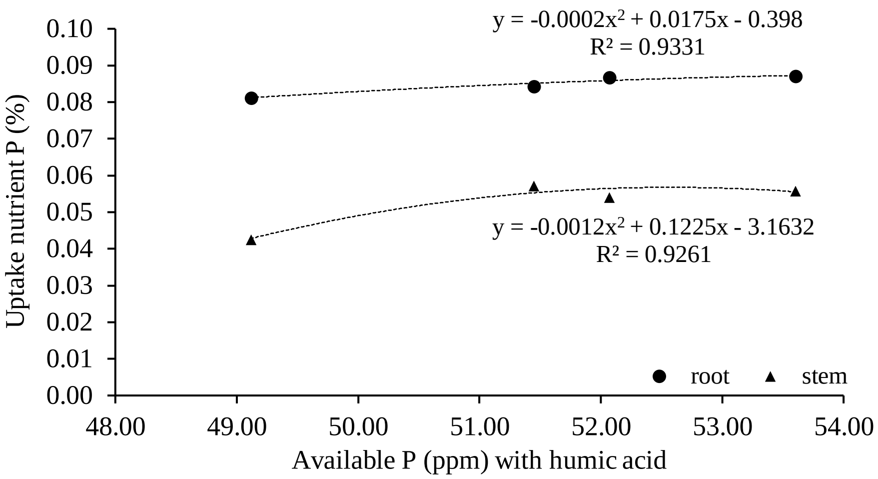


Figure 6. Effect of available P (humic acid) on P uptake in roots and stems

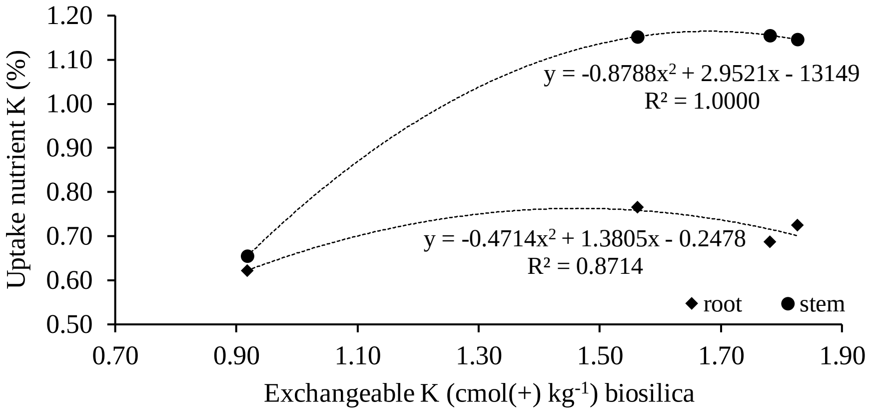


Figure 7. Effect of exchangeable K (biosilica) on K uptake in roots and stems

Humic acid directly impacts plants through physiological and metabolic processes. This organic molecule increases the availability of nutrients for plant tissue (Akimbekov et al., 2021). For example, increasing P available in soil due to the application of humic acid also impacts uptake (Figure 6). Additionally, biosilica can exchange anions with Si when P experiences low availability.

Biosilica significantly influences nutrient availability, and combining with humic acid increases soil exchangeable K (Table 4 and Figure 7). K-silicate compound supplies K to the soil as a source of plant nutrients. Since plants absorb K to form K^+ ions, the nutrient does not change into organic bonds such as C, N, and P (Malav et al., 2017; Rashad and Hussien, 2020).

CONCLUSIONS

The study shows combining biosilica and humic acid can improve soil quality and plant nutrition. After 90 DAT, this combination increased organic C (0.92 to 1.05%), total N (0.05%), exchangeable K (1.93 cmol(+) kg^{-1}), and soil pH (6.90). The best results came from using 1.0 tons ha^{-1} of biosilica and 40 kg ha^{-1} of humic acid. This combination also improved plant nutrient uptake. Nitrogen in roots reached 0.31% with 1.0 tons ha^{-1} biosilica and 60 kg ha^{-1} humic acid, while N in grains was 0.36% with no biosilica and 60 kg ha^{-1} humic acid. Potassium in stems was highest at 1.19% with 1.0 tons ha^{-1} biosilica and 60 kg ha^{-1} humic acid. As a recommendation, combining biosilica and humic acid enhances soil structure by increasing water retention and nutrient-holding capacity, promoting better root growth and microbial activity. This synergistic effect improves plant nutrition by providing essential minerals and boosting overall plant health, leading to higher yields and more resilient crops. However, additional research is required to optimize and evaluate the practical feasibility of using biosilica and humic acid for large-scale sustainable agriculture applications.

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REFERENCES

Aditya, H. F., Gandaseca, S., Rayes, M. L., Karam, D. S., Prayogo, C., & Nugroho, G. A. (2020). Characterization, changes in soil properties and vegetation distribution as affected by topography in Ayer Hitam Forest Reserve, Selangor, Peninsular Malaysia. *AGRIVITA Journal of Agricultural Science, 42*(3), 548–562. https://doi.org/10.17503/agrivita.v42i3.2617

Adrees, M., Ali, S., Rizwan, M., Zia-ur-rehman, M., Ibrahim, M., Abbas, F., … & Kashif, M. (2015). Ecotoxicology and environmental safety mechanisms of silicon-mediated alleviation of heavy metal toxicity in plants : A review. *Ecotoxicology and Environmental Safety*, *119*, 186–197. https://doi.org/10.1016/j.ecoenv.2015.05.011

Akimbekov, N. S., Digel, I., Tastambek, K. T., Sherelkhan, D. K., Jussupova, D. B., & Altynbay, N. P. (2021). Low-rank coal as a source of humic substances for soil amendment and fertility management. *Agriculture*, *11*(12), 1261. https://doi.org/10.3390/agriculture11121261

Ali, M., & A-Ali Drea, A. (2021). Green synthesis and characterization of antibiotic amorphous nano silicon oxide powder extracted from rice husk ash. *International Journal of Current Research and Review*, *13*(24), 94–99. https://doi.org/10.31782/ijcrr.2021.132406

Amoakwah, E., Shim, J., Kim, S., Lee, Y., Kwon, S., Sangho, J., & Park, S. (2023). Impact of silicate and lime application on soil fertility and temporal changes in soil properties and carbon stocks in a temperate ecosystem. *Geoderma*, *433*, 116431. https://doi.org/10.1016/j.geoderma.2023.116431

Anggraini, L., Hendriawan, R. A., Anggraina, P. L., & Hakiki, R. (2022). Homogenization of green SiO_2 from rice husk burn through potassium hydroxide solid-liquid extraction. *Journal of Physics: Conference Series*, *2312*(1), 012034. https://doi.org/10.1088/1742-6596/2312/1/012034

Bakri, I., Thaha, A. R., & Isrun, I. (2016). Status beberapa sifat kimia tanah pada berbagai penggunaan lahan di DAS Poboya Kecamatan Palu Selatan. *AGROTEKBIS: JURNAL ILMU PERTANIAN (e-journal)*, *4*(5), 512–520. Retrieved from http://jurnal.faperta.untad.ac.id/index.php/agrotekbis/article/view/53

Bakhat, H. F., Bibi, N., Zia, Z., Abbas, S., Hammad, H. M., Fahad, S., … & Saeed, S. (2018). Silicon mitigates biotic stresses in crop plants: A review. *Crop Protection*, *104*, 21–34. https://doi.org/10.1016/j.cropro.2017.10.008

Bakhsh, E. M., Khan, S. B., Akhtar, K., Danish, E. Y., Fagieh, T. M., Qiu, C., Sun, Y., Romanovski, V., & Su, X. (2022). Simultaneous preparation of humic acid and mesoporous silica from municipal sludge and their adsorption properties for U (VI). *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *647*, 129060. https://doi.org/10.1016/j.colsurfa.2022.129060

Bhat, M. M. U. R. (2019). Processed flyash geopolymer concrete and effects of MIRHA (microwave incinerated rice husk ash) on processed flyash geopolymer concrete and its comparison with different geopolymer concrete & cement concrete. *International Research Journal of Engineering and Technology (IRJET)*, *6*(3), 333–348. Retrieved from https://www.irjet.net/archives/V6/i3/IRJET-V6I363.pdf

Bijay-Singh, Yadvinder-Singh, Khind, C. S., & Meelu, O. P. (1991). Leaching losses of urea-N applied to permeable soils under lowland rice. *Fertilizer Research*, *28*(2), 179–184. https://doi.org/10.1007/BF01049748

Birnadi, S., Frasetya, B., & Sundawa, E. P. (2019). Pengaruh dosis bokashi jerami padi sebagai sumber silika (Si) terhadap pertumbuhan dan hasil tiga varietas padi sawah (*Oryza sativa* L.). *Jurnal Agro*, *6*(2), 123–133. https://doi.org/10.15575/4817

Boguta, P., D'Orazio, V., Senesi, N., Sokołowska, Z., & Szewczuk-Karpisz, K. (2019). Insight into the interaction mechanism of iron ions with soil humic acids. The effect of the pH and chemical properties of humic acids. *Journal of Environmental Management*, *245*, 367–374.

https://doi.org/10.1016/j.jenvman.2019.05.098

Chen, H., Berndtsson, R., Ma, M., & Zhu, K. (2009). Characterization of insolubilized humic acid and its sorption behaviors. *Environmental Geology*, *57*(8), 1847–1853. https://doi.org/10.1007/s00254-008-1472-0

Chen, Y., & Schnitzer, M. (1976). Scanning electron microscopy of a humic acid and of a fulvic acid and its metal and clay complexes. *Soil Science Society of America Journal*, *40*(5), 682–686. https://doi.org/10.2136/sssaj1976.03615995004000050024x

Cuong, T. X., Ullah, H., Datta, A., & Hanh, T. C. (2017). Effects of silicon-based fertilizer on growth, yield and nutrient uptake of rice in tropical zone of Vietnam. *Rice Science*, *24*(5), 283–290. https://doi.org/10.1016/j.rsci.2017.06.002

Darlita, R. D., Joy, B., & Sudirja, R. (2017). Analisis beberapa sifat kimia tanah terhadap peningkatan produksi kelapa sawit pada tanah pasir di Perkebunan Kelapa Sawit Selangkun. *Agrikultura*, *28*(1), 15–20. https://doi.org/10.24198/agrikultura.v28i1.12294

Ennan, Z., Zhu, Y., Hu, J., & Xu, T. (2022). Effects of humic acid organic fertilizer on soil environment in black soil for paddy field under water saving irrigation. *Nature Environment and Pollution Technology*, *21*(3), 1243–1249. https://doi.org/10.46488/NEPT.2022.v21i03.030

Fatima, N., Jamal, A., Huang, Z., Liaquat, R., Ahamad, B., Haider, R., … & Sillanpää, M. (2021). Extraction and chemical characterization of humic acid from nitric acid treated lignite and bituminous coal samples. *Sustainability*, *13*(16), 8969. https://doi.org/10.3390/su13168969

Guo, Y., Ma, Z., Ren, B., Zhao, B., Liu, P., & Zhang, J. (2022). Effects of humic acid added to controlled-release fertilizer on summer maize yield, nitrogen use efficiency and greenhouse gas emission. *Agriculture (Switzerland)*, *12*(4), 448. https://doi.org/10.3390/agriculture12040448

Hamid, I., Priatna, S., & Hermawan, A. (2017). Karakteristik beberapa sifat fisika dan kimia tanah pada lahan bekas tambang timah. *Jurnal Penelitian Sains*, *19*(1), 23–31. https://doi.org/10.56064/jps.v19i1.8

Indonesian Soil and Fertilizer Instrument Standard Testing Center. (2023). Analisis kimia tanah, tanaman, air, dan pupuk. *Petunjuk Teknis*. Retrieved from https://tanahpupuk.bsip.pertanian.go.id

Indonesian Soil Research Institute. (2023). *Technical instructions for chemical analysis edition 3: reference procedures for soil, plant, water and fertilizer analysis. I*ndonesian Soil and Fertilizer Instrument Standard Testing Center (BPSIP). Retrieved from https://bit.ly/JUKNISTANAHEDISIBARU

Karimah, A., Wistara, N. J., Fatriasari, W., Watanabe, T., & Hussin, M. H. (2024). Green preparations of nanolignin from acid-saccharification-treated sugarcane trash. *Process Biochemistry*, *144*, 266–277. https://doi.org/10.1016/j.procbio.2024.06.009

Kelley, K. R., & Stevenson, F. J. (1995). Forms and nature of organic N in soil. *Fertilizer Research*, *42*, 1–11. https://doi.org/10.1007/BF00750495

Khan, I., Awan, S. A., Rizwan, M., Ali, S., Hassan, M. J., Brestic, M., … & Huang, L. (2021). Effects of silicon on heavy metal uptake at the soil-plant interphase: A review. *Ecotoxicology and Environmental Safety*, *222*, 112510. https://doi.org/10.1016/j.ecoenv.2021.112510

Kong, B., Wu, Q., Li, Y., Zhu, T., Ming, Y., Li, C., … & Dong, Z. (2022). The application of humic acid urea improves nitrogen use efficiency and crop yield by reducing the nitrogen loss compared with urea. *Agriculture*, *12*(12), 1996. https://doi.org/10.3390/agriculture12121996

Li, Y. (2020). Research progress of humic acid fertilizer on the soil. *Journal of Physics: Conference Series*, *1549*(2), 022004. https://doi.org/10.1088/1742-6596/1549/2/022004

Mahendran, P. P., Gowthamraj, K., Balasubramaniam, P., Chandramani, P., & Yuvaraj, M. (2022). Status and distribution of plant available silicon in relation to some soil properties and response of rice (*Oryza sativa* L.) to silicon nutrition in the intensively rice growing soils of Kanyakumari District, Tamil Nadu, India. *Silicon*, *14*(4), 1519–1529. https://doi.org/10.1007/s12633-021-00947-2

Malav, J. K., Ramani, V. P., Sajid, M., & Kadam, G. L. (2017). Influence of nitrogen and silicon fertilization on yield and nitrogen and silicon uptake by rice (*Oryza sativa* L.) under lowland conditions. *Research Journal of Chemistry and Environment*, *21*(8), 45–49. Retrieved from https://scholar.google.co.id/scholar?cluster=18176707464421280906&hl=id&as_sdt=2005&sciodt=0,5

Manjeera, K. S., Subbaiah, P. V., Prasad, P. R. K., & Rekha, M. S. (2021). Available nutrient status of soil as influenced by combined application of humic acid and inorganic nitrogen. *International Journal of Plant & Soil Science*, *33*(22), 209–217. https://doi.org/10.9734/ijpss/2021/v33i2230697

McCauley, A., Jones, C., & Jacobsen, J. (2009). Soil pH and organic matter. *Nutrient Management Module*, *8*(2), 1–12. Montana: Montana State University. Retrieved from https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=ef8466de3a8c3353ed88470ca3de21883d10012c

Mindari, W., Sassongko, P. E., & Syekhfani. (2022). *Asam humat sebagai amelioran dan pupuk* (3rd ed.). Surabaya: UPN “Veteran” Jawa Timur. Retrieved from http://repository.upnjatim.ac.id/id/eprint/4125

Nasrudin, Rosmala, A., & Wijoyo, R. B. (2022). Application of silica nutrients improves plant growth and biomass production of paddy under saline conditions. *Caraka Tani: Journal of Sustainable Agriculture*, *37*(1), 111–122. https://doi.org/10.20961/carakatani.v37i1.43425

Pambayun, L. P. S., Purwanto, B. H., & Utami, S. N. H. (2023). Carbon stock, carbon fraction and nitrogen fraction of soil under bamboo (*Dendrocalamus asper* Back.) and non-bamboo vegetation. *Caraka Tani: Journal of Sustainable Agriculture*, *38*(2), 404–420. https://doi.org/10.20961/carakatani.v38i2.75881

Piccolo, A., Spaccini, R., Drosos, M., Vinci, G., & Cozzolino, V. (2017). The molecular composition of humus carbon: Recalcitrance and reactivity in soils. *The Future of Soil Carbon*, 87–124. https://doi.org/10.1016/B978-0-12-811687-6.00004-3

Piccolo, A., Spaccini, R., Martino, A. De, & Scognamiglio, F. (2019). Chemosphere soil washing with solutions of humic substances from manure compost removes heavy metal contaminants as a function of humic molecular composition. *Chemosphere*, *225*, 150–156. https://doi.org/10.1016/j.chemosphere.2019.03.019

Purwanto, B. H., Wulandari, P., Sulistyaningsih, E., H. Utami, S. N., & Handayani, S. (2020). Improved corn yields when humic acid extracted from composted manure is applied to acid soils with phosphorus fertilizer. *Applied and Environmental Soil Science*, *2021*(1), 8838420. https://doi.org/10.1155/2021/8838420

Rashad, R. T., & Hussien, R. A. (2020). Agronomic efficiency of feldspar, quartz silica, and zeolite as silicon (Si) fertilizers in sandy soil. *Communications in Soil Science and Plant Analysis*, *51*(8), 1078–1088. https://doi.org/10.1080/00103624.2020.1751184

Rodrigues, C. I. D., Brito, L. M., & Nunes, L. J. (2023). Soil carbon sequestration in the context of climate change mitigation: A review. *Soil Systems*, *7*(3), 64. https://doi.org/10.3390/soilsystems7030064

Rong, Q., Zhong, K., Huang, H., Li, C., Zhang, C., & Nong, X. (2020). Humic acid reduces the available cadmium, copper, lead, and zinc in soil and their uptake by tobacco. *Applied Sciences*, *10*(3), 1077. https://doi.org/10.3390/app10031077

Sapei, L., Suseno, N., Riadi, L., Padmawijaya, K. S., Thia, S. G. W., Dewi, V., & others. (2018). Biosilica recovery from pulped rice husk by acid precipitation. *Chemeca 2018: Chemical Engineering in Autralasia*, 179. Retrieved from http://repository.ubaya.ac.id/id/eprint/34069

Schaller, J., Frei, S., Rohn, L., & Gilfedder, B. S. (2020). Amorphous silica controls water storage capacity and phosphorus mobility in soils. *Frontiers in Environmental Science*, *8*, 546942. https://doi.org/10.3389/fenvs.2020.00094

Schubert, S., Steffens, D., & Ashraf, I. (2020). Is occluded phosphate plant-available?. *Journal of Plant Nutrition and Soil Science*, *183*(3), 338–344. https://doi.org/10.1002/jpln.201900402

Seyedsadr, S., Šípek, V., Jačka, L., Sněhota, M., Beesley, L., Pohořelý, M., Kovář, M.,

& Trakal, L. (2022). Biochar considerably increases the easily available water and nutrient content in low-organic soils amended with compost and manure. *Chemosphere*, *293*, 133586. https://doi.org/10.1016/j.chemosphere.2022.133586

Shim, J., Shea, P. J., & Oh, B. T. (2014). Stabilization of heavy metals in mining site soil with silica extracted from corn cob. *Water, Air, and Soil Pollution*, *225*(10), 2152. https://doi.org/10.1007/s11270-014-2152-1

Shukla, A., Mehrotra, R. C., Spicer, R. A., Spicer, T. E., & Kumar, M. (2014). Cool equatorial terrestrial temperatures and the South Asian monsoon in the Early Eocene: Evidence from the Gurha Mine, Rajasthan, India. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *412*, 187–198. https://doi.org/10.1016/j.palaeo.2014.08.004

Sinatrya, A. N., Soeparjono, S., & Setiawati, T. C. (2022). Soil drenching with silicon improves the adaptive response of tobacco cultivation under excess water condition. *Caraka Tani: Journal of Sustainable Agriculture*, *37*(2), 344–356. https://doi.org/10.20961/carakatani.v37i2.60756

Siregar, A. F., Kartawisastra, S., & Survey, S. (2020). Ameliorasi berbasis unsur hara silika di lahan rawa. *Jurnal Sumberdaya Lahan*, *14*(1), 37–47. Retrieved from https://epublikasi.pertanian.go.id/berkala/jsl/article/view/3337

Sriwuryandari, L., Priantoro, E. A., Janetasari, S. A., Butar Butar, E. S., & Sembiring, T. (2020). Utilization of rice husk (*Oryza sativa*) for amorphous biosilica (SiO_2) production as a bacterial attachment. *IOP Conference Series: Earth and Environmental Science*, *483*(1), 012023. https://doi.org/10.1088/1755-1315/483/1/012023

Stevenson, F. (1982). *Humus chemistry: Genesis, composition, reactions*. New York, USA: A Willey & Sons, Inc. Retrieved from https://www.wiley.com/en-ca/Humus+Chemistry%3A+Genesis%2C+Composition%2C+Reactions%2C+2nd+Edition-p-9780471594741

Sukarman, N., & Gani, R. A. (2020). Lahan bekas tambang timah di Pulau Bangka dan Belitung, Indonesia dan kesesuaiannya untuk komoditas pertanian. *Jurnal Tanah dan Iklim*, *41*(2), 101–114. https://doi.org/10.21082/jti.v41n2.2017.101-114

Vargas, C., Pérez-Esteban, J., Escolástico, C., Masaguer, A., & Moliner, A. (2016). Phytoremediation of Cu and Zn by vetiver grass in mine soils amended with humic acids. *Environmental Science and Pollution Research*, *23*(13), 13521–13530. https://doi.org/10.1007/s11356-016-6430-x

Xiao, C., Li, M., Fan, J., Zhang, F., Li, Y., Cheng, H., Li, Y., Hou, X., & Chen, J. (2021). Salt leaching with brackish water during growing season improves cotton growth and productivity, water use efficiency and soil sustainability in southern Xinjiang. *Water*, *13*(18), 2602. https://doi.org/10.3390/w13182602