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Characteristics of silica nanoparticles from Dayang Rindu rice husk to reduce aluminum and iron toxicity in ultisol soil

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ABSTRACT

This study aims to synthesize and characterize silica nanoparticles derived from rice husks of the local variety Dayang Rindu, and to evaluate their potential to reduce the toxicity of aluminum (Al) and iron (Fe) in Ultisol soils. Rice husks were collected from the Dayang Rindu farmer group in Muara Kelingi District, Musi Rawas Regency, South Sumatra. The synthesis process is carried out by calcination at temperatures of 200 °C, 400 °C, and 600 °C, followed by the formation of a gel from a solution of Na_2SiO_3 using 1 M HCl until the pH reaches 7. The gel is dried at 80 °C for 12 hours and calcined at 400°C for 3 hours using a Thermolyne FB 1410M-33 furnace to produce powdered silica nanoparticles. The characterization results showed that increasing the calcination temperature decreased particle size from 209 nm (200 °C) to 122 nm (600 °C), with a polydispersity index (PDI) of 0.021–0.038, indicating a uniform particle size distribution. The potential zeta value reaches 88.0 mV at 600 °C, indicating excellent dispersion stability. SEM and TEM observations revealed spherical particles with smooth, homogeneous surfaces. The best characteristics are obtained at 600 °C with a particle size of 122 nm, high stability, and a large specific surface area. The best results with silica nanoparticles were then used to test the reduction in Al and Fe toxicity in ultisol soil at doses of 10–80 ppm. The results of the incubation test showed that a higher dose of silica nanoparticles significantly reduced Al^{3+} and Fe^{2+}/Fe^{3+} levels in the soil via adsorption and the formation of silanol surface complexes (Si–OH). Overall, silica nanoparticles derived from Dayang Rindu rice husks have the potential to serve as an environmentally friendly ameliorant to reduce heavy metal toxicity in acidic soils and increase the productivity of tropical farmland.

Keywords: silica nanoparticles, Dayang Rindu rice husk, calcination, zeta potential, ultisol soil, aluminum toxicity, iron.

INTRODUCTION

Nanotechnology is currently one of the fields attracting significant attention in the research community due to its vast potential across sectors such as industry, health, livestock, and agriculture (Ibrahim et al., 2025a; Neme et al., 2021; Wibowo et al., 2020). One of the critical applications of this technology is the use of nanoparticles as functional materials to improve process efficiency and product effectiveness, and to reduce environmental impact. In agriculture, nanoparticles have been used as nutrient carriers, heavy-metal-binding agents, and soil-improvement agents, thereby enhancing soil quality and increasing plant growth (Hussain et al., 2023; Nam et al., 2024; Riyanto et al., 2025).

In agriculture, nanoparticles have been used as nutrient carriers, heavy-metal-binding agents, and soil-improvement agents, thereby enhancing soil quality and increasing plant growth (Sunday et al., 2023). Silica nanoparticles have been shown to improve soil health under environmental stress, increase nutrient absorption, and enhance plant tolerance to stress conditions (Rastogi et al., 2019; Wang et al., 2022). As a silica nanoparticle fertilizer, it can efficiently use fertilizers and reduce the risk of leaching and nutrient loss (Awad-Allah, 2023). One potential source of raw materials for the manufacture of silica nanoparticles is rice husks. Each mill of 1 kg of rice yields an average of 0.28 kg of rice husks (Severo et al., 2023). Rice husks contain high amounts of silica. Nzereogu et al. (2023) reported that rice husks contain 87–97% porous, lightweight silica and a large surface area. So it has the potential to serve as an environmentally friendly base material for producing silica nanoparticles with economic added value (Abadia et al., 2025). In addition, the use of rice husk waste can also reduce environmental problems due to the accumulation of agricultural waste (El-nazer et al., 2025).

The rapid growth of the world population, recent climate anomalies, and declining cultivation potential are feared to lead to food insecurity (Boposhev et al., 2025). One of the efforts made to meet this need is the use of suboptimal land of the ultisol order, however, a common problem found in the field, especially on land of the ultisol type of soil, is low soil productivity due to high levels of aluminum (Al) and iron (Fe), Both elements are toxic to plants, especially in acidic soil conditions. The toxicity of Al and Fe disrupts nutrient absorption, inhibits root growth, and leads to a lack of essential nutrients, resulting in low productivity in ultisol soils (Pan et al., 2021; Paramisparam et al., 2021). Therefore, effective soil-improvement technology is needed to reduce levels of these toxic metals without causing environmental harm.

Dayang Rindu rice is one of the superior local varieties widely cultivated across several regions because it has high adaptability to tropical environmental conditions and resistance to biotic and abiotic stresses. Dayang Rindu's rice production generates considerable husk waste that is not utilized optimally. In fact, Dayang Rindu rice husk is known to have a relatively high silica content, which can be a potential source in the synthesis of silica nanoparticles with economic value The use of rice husks from this local variety not only increases the efficiency of the utilization of agricultural by-products, but also supports the concept of sustainable agriculture based on a circular economy (Jose et al., 2025; Kamboj et al., 2024).

Dayang Rindu rice husk has a hard texture and a brownish color, and is rich in inorganic compounds, such as amorphous silica. The high silica content makes this husk very suitable as a raw material for the synthesis of silica nanoparticles via the sol-gel or calcination method (Riyanto et al., 2025). In addition, the natural porosity of rice husks can accelerate fermentation and the formation of stable silica gel. Thus, rice husks of the Dayang Rindu variety have the potential to produce silica nanoparticles of uniform size and large surface area, which are important for heavy-metal adsorption applications in soil. Several previous studies have discussed the advantages of using silica nanoparticles against heavy metals in soil, such as Cd (Muhammad et al., 2025), Pb, Zn, Cu, Ni, dan Cr (Samani et al., 2024), however, not many have discussed how the application of silica nanoparticles to Al and Fe affects the soil of ultisols, especially on ultisol soils. Previous research used many rice varieties as sources of silica, whereas this study used dry-land rice, a local, superior variety in Musi Rawas Regency, South Sumatra Province, Indonesia. Previous research found that the temperature during rice husk evaporation affected the quality of the silica nanoparticles produced (Trinh et al., 2024).

Calcination temperature is an essential factor in the synthesis of silica nanoparticles, as it helps remove organic components and produce high-silica ash, which is then used as a precursor for silanol formation. The selected temperature range of 200–600 °C ensures effective decomposition of organic matter, complete oxidation of residual carbon, and stabilization of amorphous silica without excessive crystallization, as reported (Guerette et al., 2015; Shchedrina et al., 2023) that temperatures above 600 °C affect the reorganization of amorphous silica structures due to temperature treatment. Based on these considerations, this study used calcination temperatures of 200 °C, 400 °C, and 600 °C for 6 hours to evaluate the effect of thermal treatment on the performance of silica nanoparticles in influencing soil chemical properties.

This research is expected to provide an alternative synthesis method that is more environmentally friendly and produces silica nanoparticles with optimal ability to reduce the toxicity of aluminum (Al) and iron (Fe) in ultisol soil, which is the primary focus of the research. Thus, the results of this study are expected to support the application of agricultural waste-based nanotechnology to improve soil quality and the sustainability of farming systems on marginalized land.

MATERIALS AND METHODS

Rice husks are obtained from rice mills owned by a farmer group cultivating the Dayang Rindu rice variety from Muara Kelingi District, Musi Rawas Regency, South Sumatra Province, Indonesia. The Dayang Rindu variety is a leading local rice variety in Musi Rawas Regency, known for its high productivity and adaptability to the tropical environment. The chemicals used in this study include sodium hydroxide (NaOH, Merck, Germany), hydrochloric acid (HCl, Merck, Germany), and distilled water (aquadest, Brataco, Indonesia). All chemicals have a pro-analysis purity (p.a) level. The main equipment used includes a furnace (electric furnace, Thermolyne Type 48000, USA), magnetic stirrer hotplate (IKA C-MAG HS7, Germany), pH meter (Hanna Instruments HI2211, Romania), drying oven (Memmert UN55, Germany), analytical scales (Shimadzu AUW220, Japan), and sieve (sieve shaker, Retsch AS200, Germany).

Preparation of rice husk extract

Dayang Rindu rice husk was collected from the rice mill of the Dayang Rindu local rice cultivation farmer group located in Muara Kelingi District, Musi Rawas Regency, South Sumatra Province, Indonesia. The rice husks are manually cleaned of dirt, small stones, and straw residues, then ground using the Deximill grinder (Deximill DM-150, China) to reduce particle size. The resulting husk powder is then rinsed using distilled water (Aquadest, Brataco, Indonesia) until it is clean of dust and other fine particles. After washing, the husks are dried for approximately 8 hours at room temperature to remove surface moisture. The dry husks are then calcined in an electric furnace (Thermolyne Type 48000, USA) at 200 °C (T0), 400 °C (T1), and 600 °C (T2) for 6 hours to produce rice husk ash. This calcination process aims to convert the silica in the husk to a more reactive amorphous form for subsequent soil interaction studies, rather than for extensive surface characterization.

The husk ash obtained is then stored in a tightly sealed container to prevent contamination by air and moisture. Next, husk ash is added to a solution of sodium hydroxide (NaOH, Merck, Germany) at a 1:10 (b/v) ratio, i.e., 10 g of husk ash is dissolved in 100 mL of 1 M NaOH. The mixture is stirred magnetically using a magnetic stirrer hotplate (DLAB MS 7-H550-S, Indonesia) at 80 °C and 600 rpm for 120 minutes, until a whitish-gray, homogeneous solution forms. After the dissolution process is complete, the solution is left at room temperature for 60 minutes to ensure the reaction proceeds smoothly and the solid particles settle. The reaction solution is then filtered in stages using a nylon sieve (nylon mesh 200) to separate the coarse residues, followed by filtration using Whatman No. 1 filter paper to obtain a clear Na_2SiO_3 filtrate. This filtrate is then used as a base material in the next stage of the process, in which silica gel is formed by adding acid and marinating until the desired silica nanoparticles are obtained.

Synthesis of silica nanoparticles

The process of synthesis of silica nanoparticles from Dayang Rindu rice husks begins with the manufacture of sodium silicate solution (Na_2SiO_3) obtained from the results of dissolving husk ash in sodium hydroxide solution (NaOH). The resulting sodium silicate filtrate is prepared as the base material for the silica gel formation process. A total of 100 mL of Na_2SiO_3 solution was placed in a heat-resistant glass beaker (Pyrex, Iwaki, Japan) and gently stirred using a magnetic stirrer hotplate (DLAB MS 7-H550-S, Indonesia) at room temperature. Next, a solution of hydrochloric acid (HCl, 1 M, Merck, Germany) is added dropwise to the Na_2SiO_3 solution while stirring slowly until the pH reaches 7.0 ± 0.2, as measured with a digital pH meter (Hanna Instruments HI2211, Romania). Acid is added carefully to avoid uneven gel formation. Once the pH is reached, the solution is left at room temperature (±28 °C) until a homogeneous white silica gel is formed. The formed gel is then aged for 8 hours without interruption to allow the polycondensation of silanol to form a stable silica tissue. After the softening process, the silica gel formed is filtered through Whatman No. 1 filter paper and then rinsed repeatedly with deionized water (Brataco, Indonesia) until the pH is neutral. This rinsing stage aims to remove residual impurity ions, especially sulfate and chloride anions, that may remain in the gel structure. The cleaned gel is then dried in a drying oven (Memmert E07086, USA) at 80 °C for 12 hours until all the moisture is lost and dry xerogel silica is obtained. The dried xerogel silica is then calcined in an electric furnace (Thermolyne FB 1410M-33, Finland) at 400 °C for 3 hours.

The calcination process aims to remove residual organic matter, strengthen the silica structure, and control particle size to achieve nanoscale particles. After the calcination process is complete, the sample is slowly cooled in the furnace to room temperature to prevent cracking from sudden temperature changes. The calcined silica powder is then ground in a mortar and pestle (Porcelain, IKA, Germany) until a fine, homogeneous silica nanoparticle powder is obtained. The resulting powder is stored in a hermetically sealed glass container (Schott Duran, Germany) to prevent air and moisture contamination prior to characterization using advanced instruments such as PSA, XRD, SEM, and EDX.

Characteristics of nanoparticles

A total of 0.1 g of Dayang Rindu silica nanoparticles was dissolved in 5 mL of aquadest (Brataco, Indonesia) and homogenized for nanocharacterization, including particle size, zeta potential, and polydispersity index (PDI). Particle size, stability, and potential zeta distribution analysis were performed using a particle size analyzer (Malvern Zetasizer Nano Series, Malvern Instruments, Malvern, UK). Furthermore, crystallinity and phase analysis of the structure were performed using an X-ray diffractometer (XRD; D8 Advance Eco, Bruker, Germany) with a nanoparticle sample of 1 g, measured in three readings to ensure consistency of results. Analysis of surface morphology and element composition is carried out using scanning electron microscopy (SEM; Thermo Scientific Phenom XL G2 Desktop SEM, Finland) equipped with an energy-dispersive X-ray detector (EDX) to determine the elemental composition of the nanoparticles.

Aluminum and iron toxicity reduction test on ultisol soil

The best characteristics of Dayang Rindu silica nanoparticles are obtained from the results of the first-stage synthesis, with a calcination temperature of 600 °C, resulting in an average particle size of 120 nm and good zeta potential stability. The silica nanoparticles were used to test the adsorption abilities of Al and Fe in an ultisol-type soil using the incubation method. The ultisol soil used was collected from the top layer (0–20 cm) of the research land in Lubuklinggau City, South Sumatra, Indonesia. The soil was wind-dried, filtered through a 2 mm sieve, and analyzed for its initial chemical properties, including pH, exchangeable Al levels, and available Fe, before treatment. Soil samples that have been homogenized are placed in sealed plastic containers containing 1000 g of dry soil each for each experimental unit. Dayang Rindu silica nanoparticle solution is added to the soil according to treatment doses of 10, 20, 30, 40, 50, 60, 70, and 80 ppm. Each treatment is repeated three times. The soil-nanoparticle solution is stirred evenly with *a glass rod* to ensure a homogeneous distribution. Incubation is carried out in a sealed container lined with plastic to retain moisture, then stored at room temperature (±28 °C) for 30 days. Soil moisture is maintained at about 60% of the field's capacity by spraying distilled water every two days. After the incubation period ends, the soil sample is taken and dried, then extracted with 1 M KCl for analysis of the content of exchanged Al (Al^{3+}) and available Fe (Fe^{2+}/Fe^{3+}). Metal concentration measurements were carried out using Atomic Absorption Spectrophotometer (AAS; Shimadzu AA-7000, Japan) at the wavelength of each element. The toxicity reduction efficiency value was calculated based on the comparison of Al and Fe levels before and after treatment with the formula (1):

$$\text{Drop Efficiency (\%)} = \frac{C_0 - C_t}{C_0} \times 100 \tag{1}$$

where: C_0 is the initial concentration of metals in the soil (mg/kg), and C_t is the concentration of metals after treatment (mg/kg) (El-khateeb, 2024; Jain et al., 2020)

Statistical analysis

The characteristics of silica nanoparticles were assessed qualitatively. The silica nanoparticle dose-response test was conducted using a complete random design, with nine treatment levels (0.10 ppm, 20 ppm, 30 ppm, 40 ppm, 50 ppm, 60 ppm, 70 ppm, and 80 ppm), each with three replicates. The data obtained were analyzed using SPSS 25 and Microsoft Excel 2011.

RESULTS AND DISCUSSION

Characteristics of silica nanoparticles Dayang Rindu rice husk

Silica nanoparticles synthesized from rice husks of the Dayang Rindu variety exhibit

Table 1. Size, zeta, and polydispersity index, and morphology of silica nanoparticles

Calcination temperature treatment (°C)	Size (nm)	Zeta	Pdi	Morphology
200 °C (T0)	209	78.0	0.0210	Sperical
400 °C (T1)	150	83.0	0.0330	Sperical
600 °C (T2)	122	88.0	0.0380	Sperical

superior physicochemical characteristics across various calcination temperatures. Test results (Table 1 and Figure 1) of silica nanoparticles treatment T0 (209 nm), T1 (150 nm), T2 (122 nm), These results show that an increase in calcination temperature from 200 °C to 600 °C results in a decrease in particle size from 209 nm to 122 nm. The higher the temperature, the smaller the particle size (Trinh et al. 2024; Uysal and Tepehan 2019). The higher the temperature, the more the particle size will decrease (Trinh et al. 2024; Uysal and Tepehan 2019; Xu et al., 2024), so that the silica structure becomes denser and smaller in size. Smaller particle sizes at 600 °C indicate an increase in specific surface area, which is particularly advantageous for heavy-metal adsorption applications, such as Al and Fe in acidic soils.

The polydispersity index (PDI) for the three treatments was 0.0210, 0.0333, and 0.0338, indicating that the resulting nanoparticles have a very narrow, uniform size distribution (monodisperse). Low PDI illustrates good suspension stability and synthesis quality, as the particles have a relatively homogeneous size and do not form large agglomerates (Ibrahim et al., 2025b; Milyani et al., 2023). The morphology observed through the scanning electron microscope (SEM) shows spherical particle shapes throughout the temperature treatment, indicating a well-controlled particle formation process (Laskowska et al., 2023; Ibrahim et al., 2025b). This spherical shape also provides advantages in terms of dispersion and surface interaction, as the contact area between particles becomes more regular and easily distributed in liquid or solid media, suitable for use in a wide range of applications (Laskowska et al., 2023).

The zeta potential of Dayang Rindu silica nanoparticles (Table 1) was very high, namely 78.0 mV at 200 °C, increasing to 83.0 mV at 400 °C, and reaching 88.0 mV at 600 °C. Potential zeta values above 60 mV indicate excellent electrostatic stability, indicating that the particles can repel each other and avoid clumping or sedimentation. This stability also suggests that the

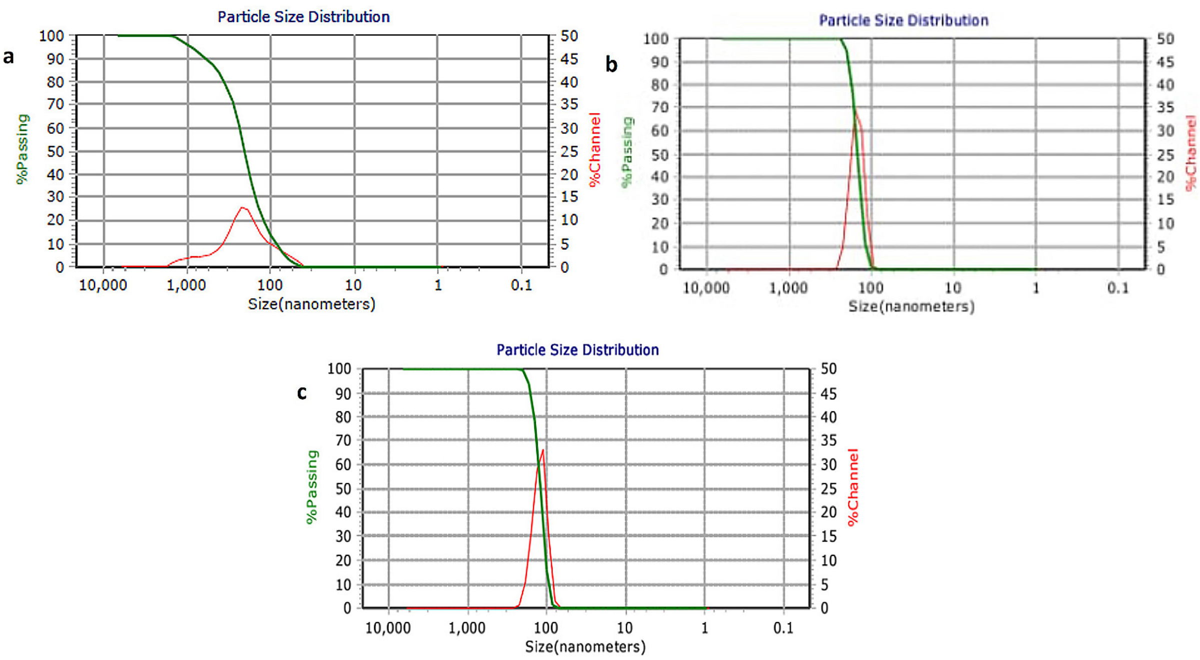

Figure 1. Nanoparticle size distribution of Dayang Rindu rice husk silica – (a) Calcination temperature 200 °C (T1), (b) Calcination temperature 400 °C (T2), (c) Calcination temperature 600 °C (T3)

nanoparticle surface carries a significant charge due to exposure to the silanol group (Si–OH) during calcination. The solution's conductivity of 0.0650 mS/cm indicates a low ionic strength, so the electrostatic force on the particle surface remains effective in maintaining the suspension's stability (Schockman and Byrne, 2022). Thus, the silica nanoparticles produced from Dayang Rindu rice husks are highly stable in liquid media and ready for use in advanced applications.

Overall, the combination of small particle size (122 nm), low PDI, high surface charge, and spherical shape suggests that calcined silica nanoparticles at 600 °C (T2) have the best characteristics. These conditions have great potential for application in acidic soil remediation because their high surface area enables increased interactions with toxic metal ions, such as Al^{3+} and Fe^{2+}/Fe^{3+}. The strong surface charge also supports the formation of surface complexes and selective adsorption of metal ions, thereby decreasing the availability of Al and Fe in soil (Taleb et al., 2024). With these characteristics, silica nanoparticles derived from Dayang Rindu rice husks have great potential as natural, environmentally friendly ameliorant materials to improve the fertility of ultisol soils, which are generally high in Al and Fe saturation.

Xray diffraction analysis of nanoparticle silica Dayang Rindu

The results of the XRD analysis (Figure 2) show that the treatments T0 (22.25°), T1 (22.27°), and T2 (22.32°) exhibited increased intensity and sharpness of the diffraction peak as the calcination temperature increased from 200 °C to 600 °C.

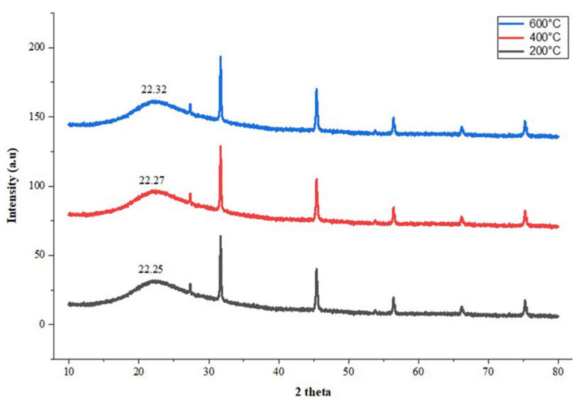

Figure 2. Xray diffraction analysis of the – (a) Calcination temperature 200 °C (T1), (b) Calcination temperature 400 °C (T2), (c) Calcination temperature 600 °C (T3)

In line with the statement by Ülker and Güden (2022), an increase in temperature increases crystallinity, as evidenced by a shift in the 2θ value to higher values.

The increase in the angular value of 2θ indicates the formation of a more regular crystal phase. In general, calcination at higher temperatures accelerates the reorganization of atomic structures, increasing crystallinity, making particles more homogeneous, and decreasing the tendency for agglomeration. This mechanism corresponds to the thermal principle, in which greater heat energy facilitates crystal growth and lattice defect recovery, resulting in sharper, more intense diffraction peaks (Sigalas et al., 2023; W. Wang et al., 2012). The findings of this study are in line with reports (Nazopatul P. Har et al., 2019) that obtained a diffraction angle of 22.18°, as well as a study (Agi et al., 2020) that reported a 2θ angle range of 15° to 35°. These consistencies show that the range and peak shifts observed in this study are common characteristics of the crystallization process of silica-based materials under various calcination conditions. Thus, increasing the calcination temperature has been shown to significantly contribute to the formation of a more stable, well-defined silica crystal structure (Motuzas et al., 2019; Shamim et al., 2022). In addition to the increase in crystallinity, the observed 2θ angular change also indicates a growth in crystal size as the calcination temperature increases. At low temperatures, silica structures tend to retain organic groups from precursor residues and exhibit broader diffraction patterns due to small crystal sizes and high degrees of irregularity.

However, at higher temperatures, the volatile group is completely decomposed, leading to lattice compaction and purification. This phenomenon contributes to the migration of ions in the lattice and to a more complete rearrangement of SiO_2 atoms, ultimately resulting in narrower, more intense diffraction peaks. In addition, increased temperature can accelerate nucleation and crystal growth, making the particles more uniform and improving the stability of the silica phase.

Chemical composition of Dayang Rindu silica nanoparticles

Analysis of the chemical composition of Dayang Rindu silica nanoparticles (Figure 3) showed an increase in the concentration of silicon oxide (SiO_2) along with an increase in the treatment temperature from 200 °C to 600 °C. The percentage of silica in T0 treatment was 31.31%, increasing to 35.13% in T1 and reaching 35.75% in T2. This increase in silica levels indicates that the heating process plays a significant role in improving the purity of the produced silica (Islam et al., 2025). At low temperatures, the material generally still contains organic compounds, bound water, and other volatile components that have not been fully degraded (Zhang et al., 2011).

However, as the temperature increases, especially near 600 °C, the components undergo dehydration and thermal decomposition, resulting in a more silica-rich structure (Uysal and Tepehan, 2019). This phenomenon is consistent with the thermal mechanism in amorphous silica, where high temperatures accelerate the dissociation of the hydroxyl group (–OH) and eliminate residual organic impurities (Chun and Lee, 2020). Furthermore, an increase in the percentage of SiO_2 also indicates the occurrence of a process of compaction and stabilization of the silica structure during calcination. In the temperature range of 400–600 °C, the silanol group condenses into a siloxane bond (Si–O–Si), thereby improving chemical stability and material homogeneity (Potapov and Zhuravlev, 2005).

This transformation encourages the formation of stronger, more defined silica tissues, so that its chemical composition becomes increasingly dominated by SiO_2 (Kannengießer et al., 2024). In addition, the process of removing impurities at high temperatures increases the Si-to-other-component ratio, reflected in a higher final percentage. These findings are in line with the literature on silica nanoparticle synthesis, where calcination is a crucial stage to obtain high-quality silica structures with purer compositions and more optimal functional properties. Overall, increasing the calcination temperature has been shown to significantly improve the purity, stability, and chemical quality of Dayang Rindu silica nanoparticles.

Morphology of silica husk nanoparticles of rice husk

The morphology of the silica nanoparticles from Dayang Rindu rice husks (Figure 4) shows that the resulting particles have a spherical or near-spherical shape, with a size distribution spanning the electron beam's scattering range of 1–50 µm. This spherical, hollow shape has the potential to adsorb heavy metals (Samani et al., 2024).

This morphological pattern indicates that the synthesis process produces a relatively uniform particle structure and does not suffer from shape damage during calcination. A low acceleration voltage of 10 kV was used in SEM imaging to maintain surface resolution, minimize damage to particle structure from electron bombardment, and improve topographic contrast. This spherical morphology is also often reported as a result of a controlled sol–gel or biomass combustion process,

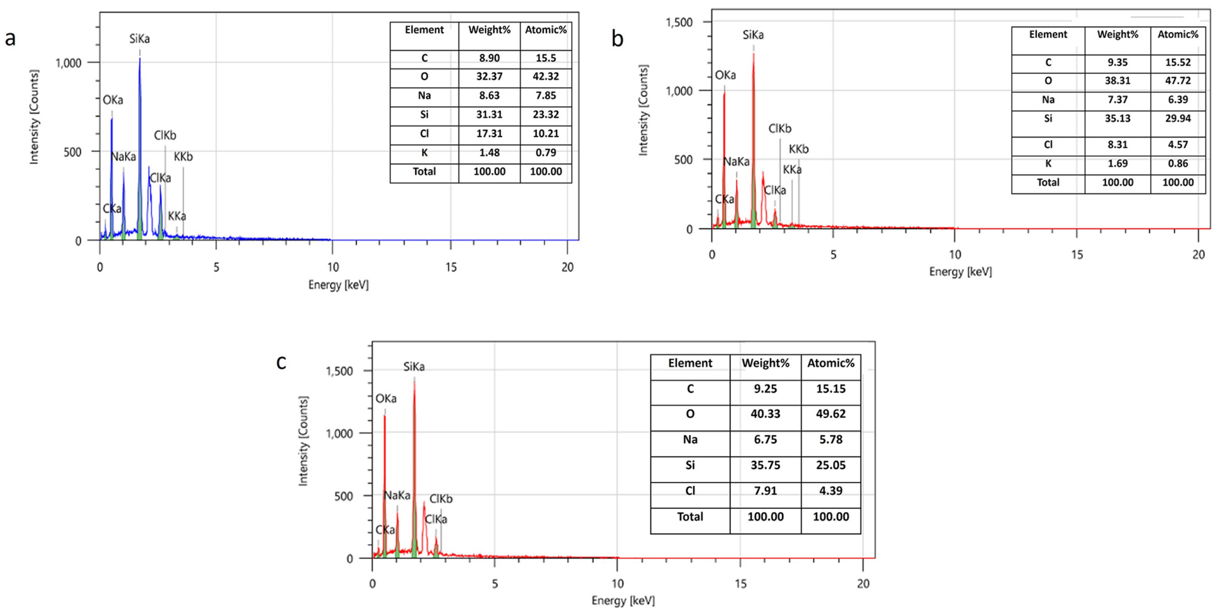

Figure 3. EDX Images of the (a) Calcination temperature 200 °C (T1), (b) Calcination temperature 400 °C (T2), (c) Calcination temperature 600 °C (T3)

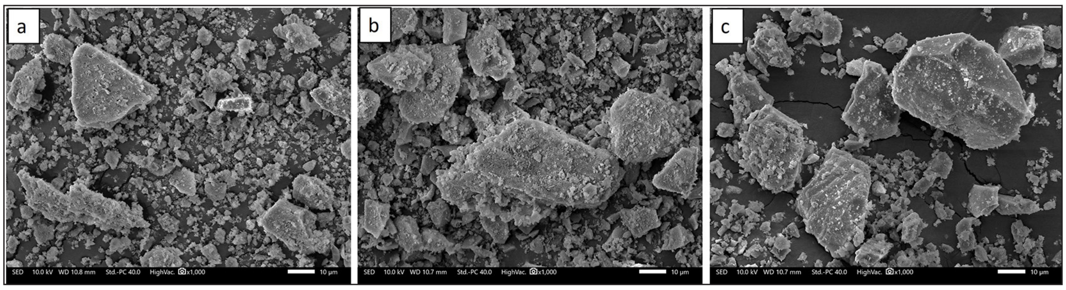

Figure 4. SEM images of the – (a) Calcination temperature 200 °C (T1), (b) Calcination temperature 400 °C (T2), (c) Calcination temperature 600 °C (T3)

in which silica nuclei form gradually, allowing particles to grow to a more regular shape (Wang et al., 2012). The spherical shape of silica nanoparticles is generally associated with greater thermodynamic stability and facilitates controlled agglomeration during particle formation, resulting in a relatively smooth surface (Sigalas et al., 2023).

In addition, the electron-scattering range of 1–50 µm in SEM imagery suggests that, although the nanoparticles are at the nanometer scale, they tend to form agglomerates at the micrometer scale due to van der Waals forces and the hygroscopic properties of silica. This phenomenon was also reported in a study (Agi et al., 2020) which stated that silica particles from biomass combustion often aggregate into larger clusters in SEM, without altering the properties of nanoparticles in their basic structure. Thus, the morphological character obtained in this study indicates that Dayang Rindu rice husk silica has a structure suitable for functional material applications, especially as an adsorbent, a supporting catalyst, or a composite reinforcer.

Silica nanoparticles of Dayang Rindu rice husk in reducing the concentration of aluminum in ultisol soil

The data in (Figure 5) show that the application of silica nanoparticles from Dayang Rindu rice husk consistently reduced the concentration of aluminum (Al) available in ultisol soil compared to the control without treatment (S0 = 3.09 cmol(+)/kg). All nanoparticle treatments (S1–S8) resulted in lower available Al values (2.52–2.76 cmol(+)/kg), indicating that this material has the potential to suppress Al toxicity in acidic soils. The largest decrease was observed in the S1, S3, S7, and S8 treatments, each of which showed a higher Al^{3+} adsorption efficiency than the other doses. This decrease in available Al corroborates that rice husk silica nanoparticles work through an Al^{3+} ion binding mechanism on the active surface of silanol (Si–OH), which then forms a relatively insoluble Al–silicate complex. Silanol is able to absorb metal compounds and ions (Jadhav et al., 2019; Yadav et al., 2022). This mechanism is in line with previous reports that amorphous silica can absorb Al cations through complexation and precipitative binding reactions, thereby lowering the activity of monomeric Al, which is toxic in acidic soils. Thus, the presence of silica nanoparticles has the potential to improve the chemical quality of ultisol soil by reducing Al saturation and increasing mineral stability. Interestingly, the pattern of Al decrease did not show a linear relationship with increasing nanoparticle dose. Some low doses actually have the same or greater reducing effect than high doses. The value of Al reduction effectiveness is still below 50%, based on the results of the research on the dose of silica nanoparticles of rice husk Dayang Rindu 10 ppm (S1) showing the highest Al reduction effectiveness value of 18.53% and the lowest at 40 ppm (S4) dose of 10.75% when compared to the Al concentration value in the control treatment (S0).

This can be explained by the possibility of particle agglomeration at high concentrations, which reduces the specific surface area and decreases the ability of effective adsorption. This phenomenon is common in nanomaterials that are not fully dispersed, so the adsorptive capacity does not increase in proportion to the amount of material given. The adsorptive capacity of heavy metals is also affected by the soil's cation exchange capacity, thereby reducing the silanol group's ability to select and bind heavy metals (Singh et al., 2021; Youssef et al., 2023). Overall, these results indicate that the silica nanoparticles derived from Dayang Rindu rice husk have strong potential as an ameliorant for ultisol soil through the available Al reduction mechanism. Its effectiveness even appears to be stable at some

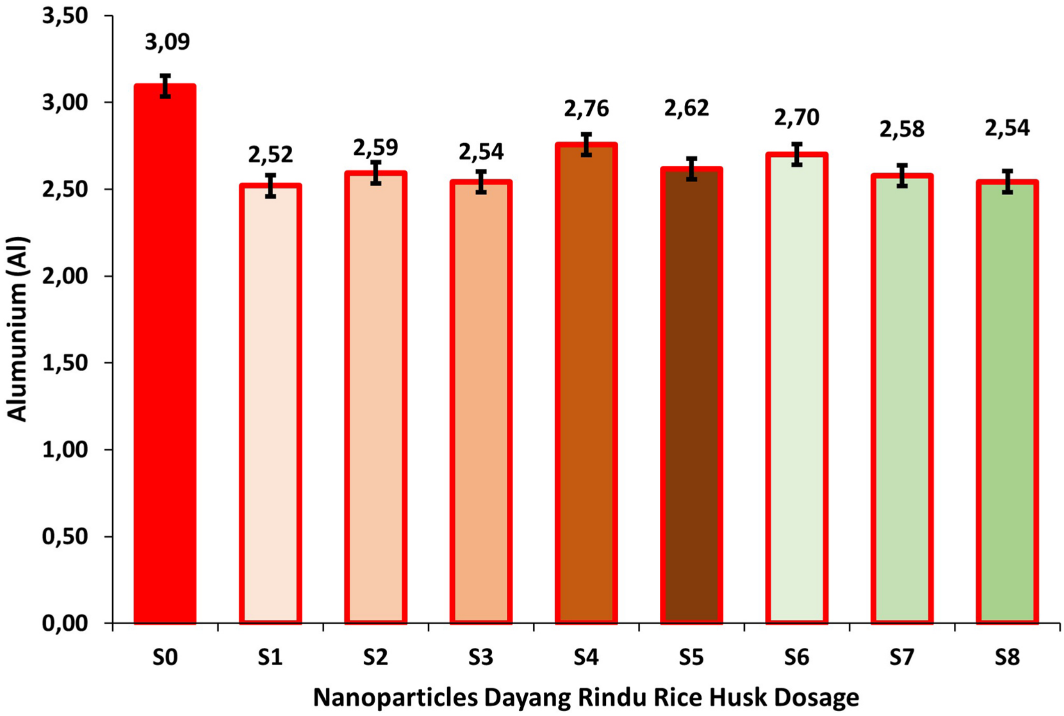

Figure 5. Silica nanoparticles dosage to Al - Control (S0), 10 ppm (S1), 20 ppm (S2), 30 ppm (S3), 40 ppm (S4), 50 ppm (S5), 60 ppm (S6), 70 ppm (S7), 80 ppm (S8)

concentrations, thus opening up opportunities for economical dose optimization in field applications. These findings confirm that using local biomass as a source of silica nanoparticles can be an environmentally friendly technological strategy to increase the productivity of acidic soils.

Silica nanoparticles of Dayang Rindu rice husk in reducing the concentration of iron in ultisol soil

Based on the results of the study, the application of Dayang Rindu rice husk silica nanoparticles

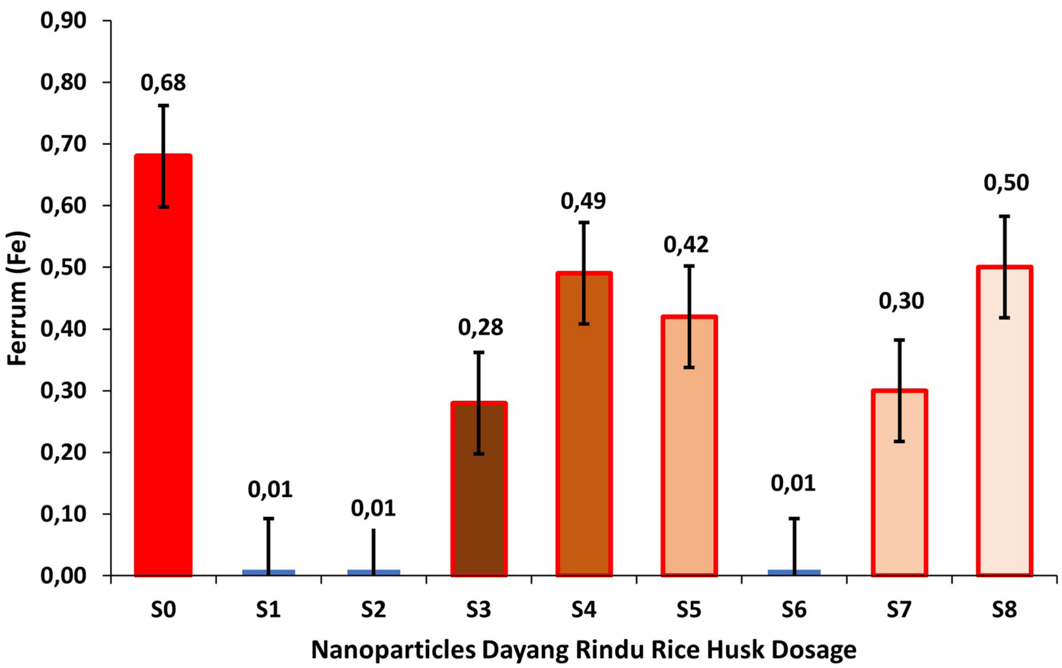

Figure 6. Silica nanoparticles dosage to Fe – Control (S0), 10 ppm (S1), 20 ppm (S2), 30 ppm (S3), 40 ppm (S4), 50 ppm (S5), 60 ppm (S6), 70 ppm (S7), 80 ppm (S8)

showed a clear ability to reduce the available iron concentration in ultisol soil compared to the control without treatment (S0 = 0.68 cmol(+)/kg). All nanoparticle treatments (S1–S8) resulted in lower Fe values of 0.01–0.50 cmol(+)/kg, indicating that this material effectively reduces soluble Fe abundance in acidic soils. The effectiveness of Fe reduction varied widely across treatments, with the highest percentages reaching 98% in S1, S2, and S6. Meanwhile, the lowest effectiveness value (26%) was found in the S8 treatment. These variations in responses indicate differences in the level of interaction between nanoparticles with Fe^{2+} or Fe^{3+} in soil, which may be related to changes in adsorption ability due to nanoparticle concentration, dispersion conditions, and agglomeration potential at specific doses (Qader, 2025; Silica and Enable, 2020). High concentrations do not always guarantee greater adsorption efficiency, especially if particles form clusters, reducing the active surface area (Alkhaldi et al., 2024). This decrease in available Fe is very important, as the high solubility of Fe in ultisol soils can disturb root growth, cause ionic competition with other microelements, and affect soil redox dynamics. Silica from rice husks acts through surface adsorption and the formation of silica–Fe complex bonds, decreasing Fe mobility and stabilizing it in a form less biologically available. This interaction is in line with the principle that the surface of silanol (Si–OH) in amorphous silica has a high affinity for metal cations, including Fe^{2+} and Fe^{3+}, thereby decreasing the ionic activity of Fe in soil solutions.

Overall, these results confirm that Dayang Rindu rice husk silica nanoparticles have strong potential as an ameliorant to reduce Fe availability in ultisol soils. Its consistent effectiveness at various doses suggests that this agricultural waste-based biomaterial can be an environmentally friendly and economical alternative to overcome the chemical constraints of acidic soils, supported by research on the use of silica nanoparticles as soil improvers is a relevant step in supporting sustainable agriculture (Juturu et al., 2024; Kalyan et al., 2025) (Figure 6).

CONCLUSIONS

Dayang Rindu's rice husk silica nanoparticles, with fine particle size, spherical morphology, and a high specific surface area, are effective in reducing the concentrations of available Al and Fe in ultisol soil. The concentration of Al decreased from 3.09 to 2.52–2.76 cmol(+)/kg, while Fe decreased from 0.68 to 0.01–0.50 cmol(+)/kg. This decrease occurs through the adsorption of metal cations by the silanol groups and the formation of a less-soluble silicate complex. Although the response between doses differs, the nanoparticles as a whole show strong potential as an environmentally friendly ameliorant to reduce metal toxicity in acidic soils. Nanoscale characteristics resulting from calcination temperatures ranging from 200 °C to 600 °C decrease particle size from 209 nm to 122 nm, indicating that temperature affects particle size and morphology. Polydispersivity index (PDI) 0.021–0.038, indicating a uniform particle size distribution. Electrostatic stability values with zeta values above 60 mV between 70 – 88 mV, spherical morphological shape, so that it is suitable for use in agricultural applications. Although the particle size is in the range of 209 to 122 nm, the manufacturing process uses minimal chemicals, and the temperature is not too high; this result is considered different from previous research in the range above 600–1000 °C.

This research deserves to be considered more economically because it reduces energy use associated with high temperatures and is environmentally friendly. The results of applying silica nanoparticles derived from rice husks show good effectiveness in overcoming cultivation obstacles in ultisol soils, especially Al and Fe problems.

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