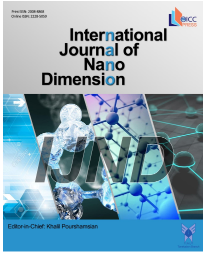

Int. J. Nano Dimens. 2026; 17(2) : 186-204

International Journal of Nano Dimension (IJND)

https://doi.org/10.57647/ijnd-2026-1702-05

Original Research

Synthesis of Potassium-Silica Nanofluid Fertilizer from Banana Peel and Rice Husk Waste for the Growth of Sweet Corn Plants

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Article History

Received:
23 April 2025
Revised:
4 June 2025
Accepted:
30 August 2025
Published online:
12 October 2025
Published in Issue:
10 April 2026

Abstract:
The increasing market demand for sweet corn has made it a widely cultivated crop among local farmers. One method of enhancing sweet corn productivity is combining potassium sulfate nanofertilizers from banana peel waste and nanosilica from rice husk waste. Nanosilica was synthesized using the sol–gel method; nanopotassium sulfate was synthesized by precipitating potassium using ammonium sulfate. Characterization results from FTIR (Fourier Transform Infrared Spectroscopy), XRD (X-Ray Diffraction), FESEM-EDX (Field Emission Scanning Electron Microscopy with Energy Dispersive X-ray), and TEM (Transmission Electron Microscopy) showed that the potassium–silica nanofluid fertilizer had a particle size of 8.6 nm. A single application of nanosilica enhanced the vegetative growth of sweet corn. Applying nanopotassium sulfate significantly increased plant height, especially in the S3W1 treatment 28 DAS (days after sowing). The combination of application time and concentration of potassium–silica nanofluid fertilizer had a significant effect on plant height. Best results were obtained with a concentration of 5 mL applied 35 DAS.

Keywords: Banana peel; Nanofertilizer; Nanosilica; Nano-potassium sulfate; Potassium-silica nanofluid; Rice husk; Sweet corn plants

Cite this article: Rosanti AD, Fitriyah N, Rahmatika W, Hidayat F, Helilusiatiningsih N, Kusumawati Y, Ni'mah YL, Oktavia D. Synthesis of Potassium-Silica Nanofluid Fertilizer from Banana Peel and Rice Husk Waste for the Growth of Sweet Corn Plants. Int. J. Nano Dimens. 2026;17(2): 186-204. https://doi.org/10.57647/ijnd-2026-1702-05

1. Introduction

The production of sweet corn (Zea mays L. saccharata Sturt) is considered more profitable than regular corn production. The planting season for sweet corn is shorter, and the planting index is greater, which helps reduce production costs and increases farmers' income. The consumer demand for sweet corn is increasing annually, often resulting in limited availability [1]. Soil nutrient availability significantly affects plant growth and productivity, and conventional fertilization practices frequently fail to meet the specific demands of high-value crops, such as sweet corn, while simultaneously posing environmental risks [1].

Agricultural systems are under increasing pressure to meet global food demand while minimizing environmental degradation. The excessive use of conventional fertilizers contributes to serious problems, including soil acidification, groundwater pollution, and nutrient leaching, which significantly reduce nutrient use efficiency. Consequently, interest in developing innovative fertilizer sources to increase use efficiency is increasing. To address these challenges, nanotechnology-based fertilizers have emerged as creative and sustainable solutions. With particle sizes ranging from 1 to 100 nm, nanofertilizers offer controlled nutrient release, enhanced uptake efficiency, and reduced environmental impact [2, 3]. Owing to their size (10^{-9} m), these fertilizers penetrate plant tissues more efficiently.

Potassium is an essential macronutrient for sweet corn productivity. The potassium requirements of corn plants vary based on the processes involving it, such as photosynthesis, CO_2 fixation, photosynthate transfer to various plant parts, and water balance regulation [4, 5]. In addition to nitrogen and phosphorus fertilizers, balanced potassium fertilization can promote better growth, increase resistance to lodging, pests, and diseases, and improve crop quality [6]. Banana peels, commonly discarded agricultural waste, are an abundant source of potassium [7].

Banana peels contain a high concentration of potassium and can be used to produce potassium-rich salts, which contain approximately 15% more potassium and 2% more phosphorus than that from fruit pulp. They also contain magnesium, sulfur, and sodium [8]. Research by Franck et al., (2020) shows that banana peels contain 86% potassium, and that a 200 kg dose provides results comparable to conventional NPK (10-20-10) fertilizers [7]. Aside from macronutrients, micronutrients like silica also play an essential role in plant growth and productivity.

The addition of silica is a strategy to optimize dry land for agriculture in Indonesia. Indonesia has approximately 144.47 million hectares of dry land, much of which could be developed for agrarian purposes [9]. Silica enhances plant resistance to drought stress by balancing water content in tissues, increasing photosynthetic activity, and strengthening cell walls to reduce water loss [10]. Silica also neutralizes acidic soils by exchanging OH- anions with silicate ions, resulting in increased soil pH [11]. Rice husks, which contain $87 - 97\%$ silica, are one of the most abundant sources of this micronutrient [12].

The prolonged intensive use of traditional fertilizers has caused severe environmental problems globally, including groundwater pollution, eutrophication (excessive algal growth in water bodies, inhibition of the oxygen supply to aquatic life), soil degradation, and air pollution [13]. In this context, nanopotassium and nanosilica fertilizers are examples of innovative fertilizers developed using nanotechnology. Among nanotechnology methods, the sol-gel method is frequently employed for producing nanosilica. Kusumawati et al. successfully synthesized nanomaterials using sol–gel, impregnation, and solvothermal methods [14, 15, 16, 17, 18]. Azari et al., (2023) successfully synthesized SiO_2 from Equisetnm arvense plants and composited SiO_2 with zeolite imidazolate framework-8. On the basis of these studies, SiO_2 was obtained with an amorphous structure [19]. Ni'mah et al., (2023) synthesized nanosilica from sugarcane bagasse using the sol–gel process. XRD and FTIR analyses confirmed that the resulting silica had an amorphous phase, siloxane and silanol functional groups, and an average particle size of 53 nm [20].

Hussein et al., (2019) synthesized a nanopotassium fertilizer from banana peels and applied it to tomato and fenugreek plants. Their findings indicated that increasing dosages of banana peel extract significantly improved germination rates of both plants. After 7 days of sowing, the germination rate of the tomato plants rose from 14% (control without nanofertilizer) to 97%. Similarly, the germination rate of the fenugreek plants rose from 25% (control without nanofertilizer) to 93.14% [21].

Hoang et al., (2022) reported that nanosilica particles produced from silica sand using the sol–gel process had particle sizes ranging from 16 to 37 nm and a purity level of 99.9% (SiO_2). The application of nanosilica fertilizer to corn plants resulted in increased yield and improved quality [22]. Similarly, Hayati, Rosanti, and Utomo (2020) synthesized a nanosilica fertilizer from rice husks using the sol-gel method. The synthesized fertilizer contained 32% silica and enhanced the sweetness of sweet corn [23].

Subagio et al., (2015) developed a nanochip colloidal fertilizer consisting of nanochitosan and nanosilica colloids with a particle size of $10 - 20$ nm [24]. This study introduces a novel integrated approach that employs a modified sol–gel synthesis method to simultaneously extract and process potassium from banana peels and silica from rice husk waste into a stable nanofluid fertilizer. A key innovation in this study is the use of an ultrasonic sonicator to assist in the formation of nanoscale structures. Sonication enhances particle dispersion and significantly reduces particle size by promoting cavitation and energy transfer, resulting in a more homogeneous and efficient nanofertilizer formulation. This combination of sol–gel processing and sonication has not been widely applied in previous studies, particularly for dual-nutrient fertilizers derived from organic waste.

Therefore, this study aimed to fill this gap by synthesizing a potassium–silica nanofluid fertilizer using banana peel and rice husk waste and evaluating its effects on the vegetative and generative growth stages of sweet corn. Specifically, this study synthesized and characterized a nanofluid fertilizer containing potassium and silica derived from natural waste sources. The impacts of different concentrations and application timings on sweet corn growth parameters, including plant height, leaf number, and stem diameter, were investigated. Additionally, the optimal formulation and application strategy to maximize plant productivity were identified. To the best of our knowledge, this is the first study to evaluate the combined effects of banana peel- and rice husk-derived potassium–silica nanofluid fertilizers on sweet corn under field conditions. The findings of this research are expected to provide novel insights that contribute to sustainable crop management practices.

https://doi.org/10.57647/ijnd-2026-1702-05

2. Material and methods

2.1 Material

Rice Husk, Kepok Banana Peel, Aqua DM (Bratachem), Ammonium Sulfate p.a (Merck), Asam Perchlorate 72% (Merck), Hydrochloric acid 37% p.a (Merck), Sodium Hydroxide p.a (Merck), Sodium Lauryl Sulfate (SDS) p.a (MERCK), Sweet corn seeds with exotic varieties produced by PT. Agri Makmur Pertiwi.

2.2 Synthesis of nanosilica fertilizer from rice husks

Rice husks were cleaned of dirt and dried under the sun. After drying, the rice husks were heated at 700 °C for 4 hours until ash formed. The rice husk ash was then crushed and sieved to 200 mesh.

Two grams of rice husk ash were added to 20 mL of 1 M HCl, stirred, and heated at 100 °C for 1 hour. The resulting solution was separated and washed with warm Aqua DM. The residue was mixed with 12 mL of 2.5 N NaOH, stirred, and heated at 100 °C for 1 hour. The solution was cooled and filtered through a vacuum filter. The filtrate was diluted with 100 mL of Aqua DM and adjusted to pH 7 using HCl. The mixture was left for 18 hours to form a gel, which was subsequently dried in an oven at 105 °C. The dried gel was then crushed and sieved to 200 mesh. The resulting nanosilica powder was weighed (1 gram) and mixed with 100 mL of Aqua DM. The mixture was stirred for 15 minutes, 3 grams of SDS was added, and then stirred for 30 minutes. The mixture was then sonicated for approximately 30 minutes.

2.3 Synthesis of nanopotassium sulfate fertilizer from banana peels

Banana peels were washed and dried in an oven at 105 °C until completely dry and then blended into a fine powder. The powder was calcined in a furnace at 500 °C for 4 hours. Approximately 20 grams of banana peel ash was added to 200 mL of Aqua DM and soaked for 30 minutes. The solution was then filtered through a vacuum filter. The banana peel extract was mixed with 10% ammonium sulfate, evaporated until a thick precipitate formed, and sonicated for 30 minutes. The residue was oven-dried for 8 hours at 105 °C and crushed into a fine powder, which was sieved using a 60-mesh sieve.

2.4 Synthesis of potassium-silica Nanofluid fertilizer

The resulting nanosilica powder (1 gram) was mixed with 100 mL of Aqua DM, stirred for 15 minutes, followed by the addition of 3 grams of SDS, and stirred for 30 minutes. The mixture was then combined with the synthesized potassium sulfate and sonicated for approximately 30 minutes.

2.5 Application of nanofluid silica fertilizer to sweet corn plants

The application of nanofluid silica fertilizers to sweet corn plants was carried out using a factorial randomized block design (RBD) with two factors and four repetitions. The first factor was nanosilica: S1: nanofluid silica and S2: silica. The second factor was application time, which consisted of 3 levels: W1 = early vegetative stage (7 DAS (days after sowing)); W2 = late vegetative stage (21 DAS); W3 = early generative stage (35 DAS). The combinations obtained were S1W1: application of silica nanofluid at the beginning of the vegetative stage (7 DAS); S1W2: application of silica nanofluid at the end of the vegetative stage (21 DAS); and S1W3: application of silica nanofluid at the early generative stage (35 DAS). S2W1: application of silica at the early vegetative stage (7 DAS); S2W2: silica application at the end of the vegetative stage (21 DAS), S2W3: application of silica at the early generative stage (35 DAS). Observations of plant growth were carried out at 14 DAS, 28 DAS, and 42 DAS. The total number of plants per treatment combination was 10, with 5 plants per treatment and four replications. Nanosilica application was carried out on sandy loam soil containing 0.03% N, 1.99% organic C, 0.76% P, and 34.6% Si.

2.6 Application of nanopotassium sulfate fertilizer from banana peels on sweet corn plants

The application of nanopotassium fertilizer to sweet corn plants combined the treatment of nanopotassium addition with the timing of application. This study employed a factorial randomized block design (RBD) with two factors and four replications. The first factor was the type of potassium fertilizer, which included S3 (nanopotassium sulfate) and S4 (potassium sulfate). The second factor was the application timing, which comprised three levels: W1 (early vegetative stage, 7 DAS), W2 (late vegetative stage, 21 DAS), and W3 (early generative stage, 35 DAS). The combinations obtained were S3W1 (application of nanopotassium sulfate at the early vegetative stage, 7 DAS), S3W2 (application of nanopotassium sulfate at the late vegetative stage, 21 DAS), S3W3 (application of nanopotassium sulfate at the early generative stage, 35 DAS), S4W1 (application of potassium sulfate at the early vegetative stage, 7 DAS), S4W2 (application of potassium sulfate at the late vegetative stage, 21 DAS), and S4W3 (application of potassium sulfate at the early generative stage, 35 DAS), where the total number of plants per treatment combination was 10, with 5 plants for each treatment and four replications. Nanosilica application was carried out on sandy loam soil containing 0.03% N, 1.99% organic C, 0.76% P, and 34.6% Si. Observations of plant growth were carried out at 14 DAS, 28 DAS, and 42 DAS.

2.7 Application of potassium-silica nanofluid fertilizer to sweet corn plants

The application of potassium–silica nanofluid fertilizer to sweet corn plants followed a factorial randomized block design (RBD). The type of experimental treatment had two factors, namely, the first factor was the concentration of the nanopotassium silica treatment. There were four levels, namely, K0, K1, K2, and K3, while the second treatment factor was the time of administration of the nanopotassium silica fertilizer. There were three levels, namely, W1, W2, and W3, resulting in 12 treatment combinations that were carried out three times in the experiment, totaling 36 treatment combinations. In one plot, there were 10 plants, so the total number of experimental plants was 360.

Factor 1 was the timing of fertilizer application and consisted of four treatments: W0 (no fertilizer application), W1 (early vegetative stage, 7 DAS), W2 (late vegetative stage, 21 DAS), and W3 (early generative stage, 35 DAS). Factor 2 was the concentration of potassium–silica nanofluid fertilizer, which consisted of three treatments: K0 (no fertilizer), K1 (1 mL/L water), K2 (3 mL/L water), and K3 (5 mL/L water). This resulted in 12 treatment combinations: W1K0 (0 mL + 7 DAS), K1W1 (1 mL + 7 DAS), K2W1 (3 mL + 7 DAS), K3W1 (5 mL + 7 DAS), K0W2 (0 mL + 21 DAS), K1W2 (1 mL + 21 DAS), K2W2 (3 mL + 21 DAS), K3W2 (5 mL + 21 DAS), K0W3 (0 mL + 35 DAS), K1W3 (1 mL + 35 DAS), K2W3 (3 mL + 35 DAS), and K3W3 (5 mL + 35 DAS). Observations of plant growth were conducted at 14 DAS, 28 DAS, and 42 DAS.

2.8 Analisa data statistic

The statistical analysis of the data utilized the Shrestha and Williams methodology, organizing the data into tables and performing analysis of variance (ANOVA) for the least significant difference (LSD) multiple-range test. The LSD refers to the threshold defined at a specific level of statistical significance ($P \leq 0.01$ indicates 99% confidence, whereas $P \leq 0.05$ indicates 95% confidence). When the difference between two varietal means for a given characteristic exceeds this value, the two varieties are considered distinct for that characteristic at that level of probability or lower. Typically, the LSD is computed for $p \leq 0.01$ and $p \leq 0.05$. In this study, the p value used was $p \leq 0.05$. The equation for calculating the least significant difference is [25, 26]:

$$\mathrm{LSD}_{A,B} = t_{0.05/2,\mathrm{DFW}}\sqrt{\mathrm{MSW}\left(\frac{1}{n_A}+\frac{1}{n_B}\right)} \quad (1)$$

where t is the critical value from the t-distribution table and MSW is the mean square within, which was obtained from the ANOVA results test. n is the number of scores used to calculate the means.

3. Results and discussion

3.1 Characterization of nanosilica powder

Nanosilica fertilizer can be synthesized using the sol–gel method from rice husk material. Calcination of rice husk at 700 °C removes water and organic compounds such as cellulose, hemicellulose, and lignin, producing ash with a high silica content and an amorphous silica structure. At higher temperatures, such as 800 °C and 900 °C, calcination produces crystalline silica. The calcined rice husk is washed with hydrochloric acid (HCl) and extracted with sodium hydroxide (NaOH). Washing with HCl reduces the mineral content in the ash; NaOH extraction converts silica into sodium silicate [12].

Gradual addition of HCl until the pH reaches 7 causes silicic acid [$Si(OH)_4$] to form. This gradual addition allows silicic acid monomers to polymerize and form siloxane bonds. Free silicic acid easily polymerizes to form dimers, trimers, and eventually larger polymer particles. According to Sholika et al., (2010) silanol groups from primary silica particles undergo condensation, releasing water molecules to form secondary particles larger than the primary particles [27]. This polymerization continues until the solution thickens to a soft gel, which is left to age for 18 hours. A process known as syneresis occurs during aging, forming a firmer gel while causing shrinkage. Syneresis results from liquid evaporation from the gel's pores. After aging, the gel is broken apart and washed with distilled water to remove salts, which are by-products of the silicic acid polymerization reaction. The sol–gel synthesis of nanosilica involves the following reactions:

$$\text{C, H dan Si} + \text{O} \rightarrow CO_2(g) + H_2O(g) + SiO_2(s)$$
$$SiO_2(s) + 2NaOH(l) \rightarrow Na_2SiO_3(aq) + H_2O$$
$$Na_2SiO_3(aq) + H_2O(l) + 2HCl(aq) \rightarrow Si(OH)_4(aq) + 2NaCl(s)$$

Infrared spectroscopy showed the characteristic absorption bands of silica at specific wavenumbers. The FTIR spectra (Fig. 1) showed no significant shift in peak positions for either rice husk ash or nanosilica powder. The broad absorption band in the 3670 – 3000 cm^{-1} region was attributed to the stretching vibrations of hydroxyl (O-H) groups. The bending vibrations of adsorbed water molecules were observed around 1640–1625 cm^{-1}. Strong absorption bands in the 1200 – 1050 cm^{-1} region, with prominent peaks at 1092.21 cm^{-1} and 798.68 cm^{-1} for nanosilica powder and 1097.07 cm^{-1} and 800.67 cm^{-1} for rice husk ash, confirmed the asymmetric and symmetric stretching vibrations of the Si–O–Si bonds in siloxane, respectively. The bending vibration of the Si–O–Si bond was also detected at 467.09 cm^{-1}. These findings align with previous research associating absorption in these wavenumber ranges with the presence of specific functional groups in silica structures [12, 28, 29, 30].

The differences in peak intensities and narrowing of bands in the nanosilica sample reflect a higher degree of purity and ordering compared with those of raw rice husk ash. These results align with the XRF data, which revealed a significant increase in SiO_2 content from 91.9% in rice husk ash to 97.9% in nanosilica powder, indicating a successful reduction in mineral impurities.

Moreover, these FTIR findings support the XRD results, which indicate a broad peak at $2\theta = 15 - 30°$, which is consistent with an amorphous silica phase. This amorphous character is typical for silica synthesized via sol–gel methods, especially when followed by low-temperature drying, which avoids crystallization. The reduction in the –OH group intensity also suggests enhanced condensation of silanol groups into siloxane bonds, which is consistent with the aging and drying behavior of the gel.

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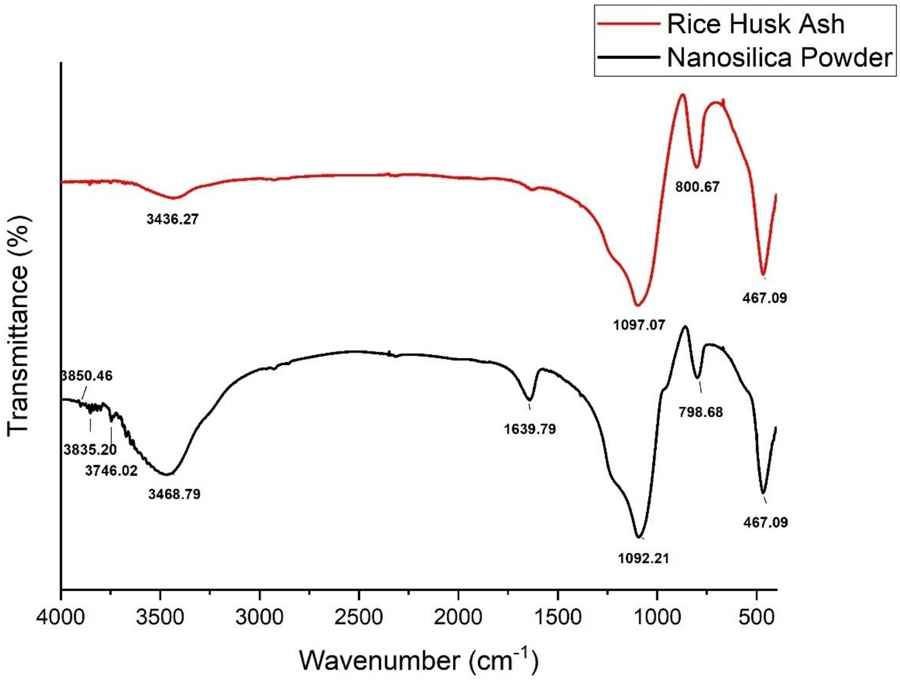

Figure 1. FTIR spectra of Rice Husk Ash and nanosilica powder.

Rice husk ash and nanosilica powder were analyzed using XRD to determine the crystal structure of silica. Rice husk ash, the starting material for nanosilica, was also analyzed to determine the crystal structure of silica prior to nanosilica synthesis using the sol–gel method. The material to be tested was placed in a 3D zone with uniform spacing. Unlike conventional materials, amorphous materials exhibit randomly distributed atoms in 3D zones. X-ray scattering by these atoms can reveal their structural arrangement. An ordered arrangement of atoms exposed to X-rays produces high-intensity peaks in specific directions, indicating a crystalline structure. Conversely, X-rays scattered in multiple directions create broad, hill-like peaks in the range of $2\theta = 15 - 30°$, indicating amorphous structures and irregular atomic arrangements. Figure 2 displays a prominent peak at 2θ between 22.25° and 22.55°, indicating the absence of a crystalline structure [31]. Crystalline silica is undesirable in the manufacture of silicon-based products as it renders them inert. Based on this analysis, rice husk ash could serve as a viable silica source for nanosilica production.

The broader peaks observed in the nanosilica sample compared with rice husk ash indicate a less ordered atomic structure, further supporting its amorphous phase. XRD analysis of the synthesized nanosilica powder (Fig. 2) also confirmed the amorphous phase of silica. Ni'mah et al., (2023) reported that SiO_2 crystals exhibit a characteristic peak at 2θ around 22.6° [20]. Based on

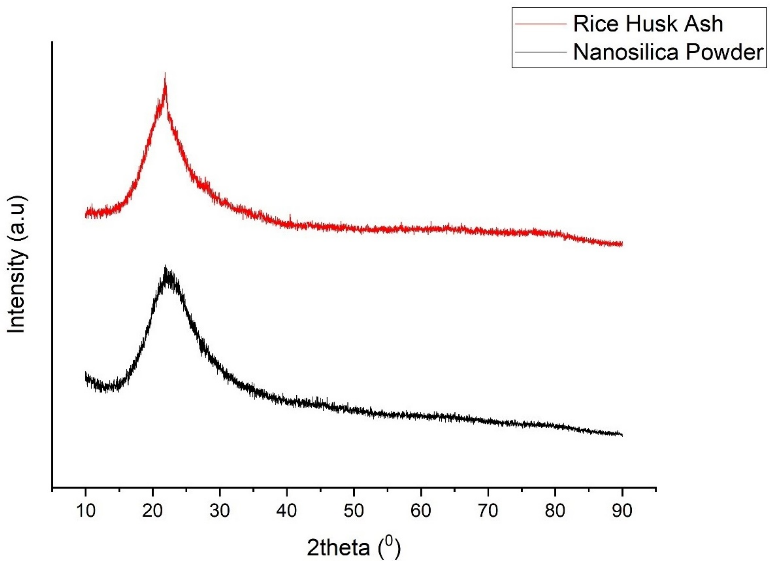

Figure 2. XRD pattern of Rice Husk Ash and nanosilica powder.

https://doi.org/10.57647/ijnd-2026-1702-05

the peaks observed (Fig. 2), it is evident that nanosilica powder exhibits broader peaks than rice husk ash, indicating the amorphous phase of silica.

The peak results are supported by the crystallinity index measurement of the nanosilica, which was 20.9%. This result indicates that the crystal structure of nanosilica tends to be amorphous, with only approximately 20.9% of the material exhibiting a regular crystal structure, whereas the majority (79.1%) is amorphous. In contrast, rice husk ash has a more crystalline structure, with a crystallinity index of 81.5%, meaning that rice husk ash has an 18.5% amorphous content, indicating that rice husk ash has a more crystalline structure than the synthesized nanosilica.

FESEM analysis was conducted to evaluate the morphology and homogeneity of the synthesized material. Figure 3 (a, b, c, d), shows morphological images and energy dispersive X-ray (EDX) spectra for rice husk ash and nanosilica. At $50,000\times$ magnification, the surface morphology of rice husk ash revealed a hollow and inhomogeneous structure. In contrast, the nanosilica surface appeared smooth and homogeneous, with no visible cavities. Additionally, the particle size of nanosilica was smaller than that of rice husk ash, indicating successful particle size reduction during synthesis.

The EDX technique characterizes the elemental composition of an examined volume by detecting the X-rays released when the sample is bombarded with an electron beam. Figure 3 (c) and 3 (d) display the EDX pattern for silica nanoparticles. The primary components are oxygen and silica, with their atomic and weight percentages determined through elemental analysis. The energy-dispersive X-ray spectroscopy (EDX) data for rice husk ash in Fig. 3 (c) revealed that oxygen constituted approximately 48.66% by mass and 62.46% by atom. Oxygen was the dominant element in rice husk ash, which may indicate the presence of oxides or oxidized organic compounds in the sample. Silicon (Si) was present at 51.34% by mass and 37.54% by atom. Silicon is commonly found in rice husk ash, primarily in silicates (such as SiO_2), the main component in rice husk.

Potassium was found to comprise 3.95% by mass and 1.96% by atom. Potassium is essential for various mineral compounds in rice husk ash, although its concentration is lower than that of oxygen and silicon. On the basis of these data, it can be concluded that rice husk ash is predominantly composed of oxygen (O) and silicon (Si), indicating the presence of silicates, most likely in the form of silica (SiO_2), and potassium (K), although in smaller amounts, suggesting the presence of potassium bound to other compounds or specific forms in the ash. On the basis of these data, rice husk ash is likely to contain silicate compounds with a high oxygen content, making it suitable for various industrial applications or as a material for absorption or purification.

In Fig. 3 (d), the EDX spectrum of nanosilica indicates that oxygen (O) is present, with a composition of approximately 45.95% by mass and 51.81% by atom. Silicon (Si) is present at approximately 38.35% by mass and 24.63% by atom. Silicon and oxygen are the primary elements in nanosilica, indicating the presence of dominant silica (SiO_2) in the sample. These results are consistent with expectations, as nanosilica typically consists of small silica particles. The EDX analysis revealed that nanosilica from rice husk ash consists primarily of

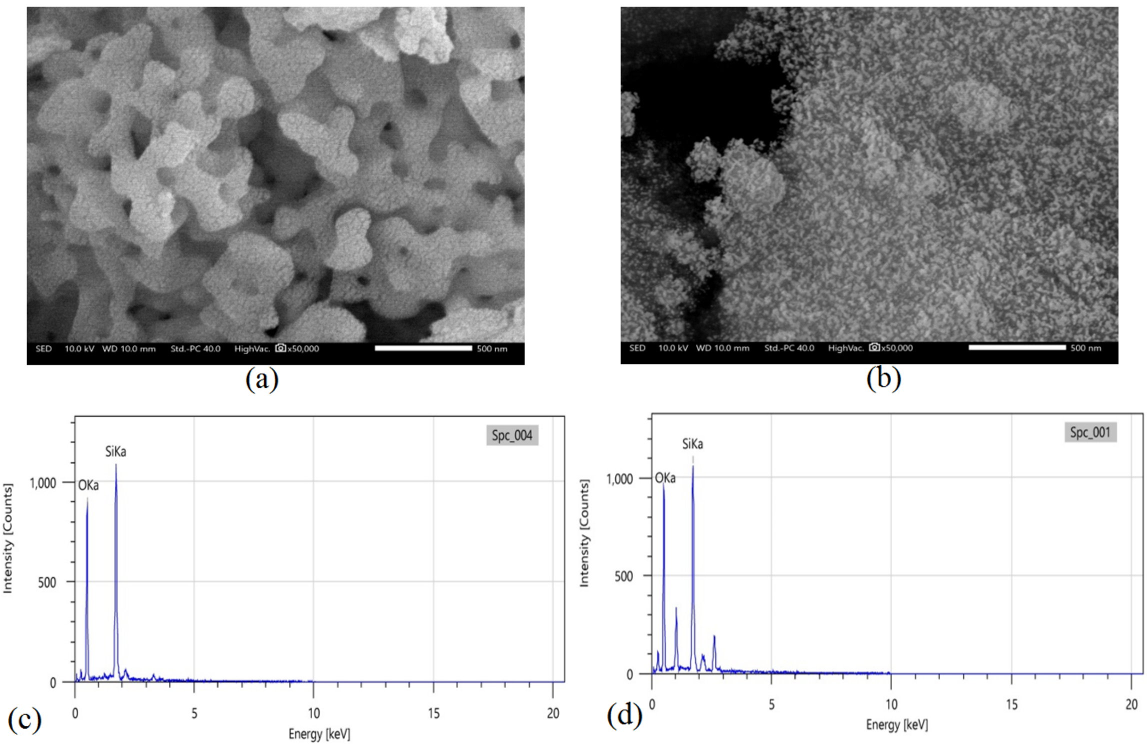

Figure 3. FESEM image of (a) Rice Husk Ash; (b) nanosilica and EDX Spectra from (c) Rice Husk Ash; (d) nanosilica powder.

silica (SiO_2). The total silica content of the resulting nanosilica was determined using XRF analysis.

Table 1 presents XRF analysis results detailing the elemental and oxide contents of rice husk ash and nanosilica powder. Rice husk ash calcined at 700 °C for 5 hours contained 82.3% silica as an element and 91.9% as an oxide (SiO_2). These results approach pure silica, which is approximately 99%, demonstrating that rice husk ash is a suitable starting material for producing nanosilica. The nanosilica powder synthesized via the sol-gel method contained 95.8% silica as an element and 97.9% SiO_2. The synthesized nanosilica had a higher silica content and fewer impurities than rice husk ash, confirming success of the synthesis process.

3.2 Characterization of nanopotassium sulfate powder

Nanopotassium sulfate powder synthesized from banana peel charcoal extract can be produced as potassium sulfate (K_2SO_4) powder through the following reaction: Synthesis K_2SO_4:

$$K_2CO_{3(s)} + H_2O_{(l)} \rightarrow KOH_{(aq)} + H_2CO_{3(g)} + (NH_4)_2SO_{(aq)} \rightarrow K_2SO_{4(aq)} + 2NH_{3(g)} + 2H_2O_{(l)} \xrightarrow{Drying} K_2SO_{4(s)}$$

Figure 4 (a) and 4 (b) show the surface morphology and EDX spectra of the synthesized K_2SO_4. Figure 4 (a), taken at a magnification of 5000×, reveals a less homogeneous surface morphology with visible agglomeration, resulting in larger and more distinct particles. The actual particle size can be observed in Fig. 5, which shows a transmission electron microscopy (TEM) analysis of K_2SO_4.

In Fig. 4 (b), the EDX spectrum of nanopotassium revealed that potassium (K) is present at a concentration of approximately 7.5% by weight (Wt.%), with a standard deviation (σ) of 0.1. This peak is located at approximately 1.5 keV, a characteristic feature of K. Oxygen (O) was also detected (0.5 – 2 keV), with a weight percentage of 63.1% and a standard deviation of 0.2. This peak was at approximately 0.5 keV, indicating the presence of O. Sulfur (S) was detected at 2 – 4 keV, with a sulfur content of approximately 29.3% by weight and a standard deviation of 0.1. Overall, this EDX spectrum revealed the primary elements present in the sample, including oxygen (O), sulfur (S), and potassium (K). On the basis of the peak intensities, oxygen was the dominant element in the sample. These peaks also suggest the presence of compounds such as potassium sulfate (K_2SO_4) due to the significant amounts of potassium and sulfur.

The relatively low potassium reading in the EDX analysis is attributed to the high-energy emission of electrons, which only probes one side of the sample, where the potassium concentration may have been lower; the other side likely had a higher potassium concentration [32]. Therefore, EDX is primarily used to verify the presence of desired elements, while XRF provides a more comprehensive determination of total material content.

Table 2 presents the XRF characterization results for banana peel powder, charcoal, and nanopotassium. Banana peel powder contained a relatively high potassium content of 72.8%. After washing at 500 °C, the potassium content increased to 86.7%, while the concentrations of other elements decreased. This confirms that calcination removes impurities, causing the banana peel to decompose and yield purer potassium [33, 34].

Nanopotassium sulfate synthesis was carried out after the potassium extraction process, with ammonium sulfate and sonication applied to reduce the particle size. Table 2 shows that the potassium content after nanopotassium synthesis was 50.1%. This meets the requirements for

Table 1. XRF Analysis of Rice Husk Ash and nanosilica powder.

Rice Husk Ash				Nanosilica powder			
Element	%	Oxide	%	Element	%	Oxide	%
Si	82.3	SiO_2	91.9	Si	95.8	SiO_2	97.9
P	1.8	P_2O_5	1.5	P	1.1	P_2O_5	0.9
K	11.0	K_2O	4.51	Ca	1.3	CaO	0.54
Ca	2.97	CaO	1.32	Mn	0.3	MnO	0.11
Ti	0.02	TiO_2	0.01	Fe	0.51	Fe_2O_3	0.21
Mn	0.52	MnO	0.20	Cu	0.38	CuO	0.12
Fe	0.804	Fe_2O_3	0.344	Zn	0.15	ZnO	0.051
Ni	0.02	NiO	0.007	Re	0.38	Re_2O_7	0.13
Cu	0.086	CuO	0.032				
Zn	0.02	ZnO	0.009				
Ba	0.2	BaO	0.06				
Eu	0.1	Eu_2O_3	0.04				
Yb	0.08	Yb_2O_3	0.03				
Re	0.1	Re_2O_7	0.05				

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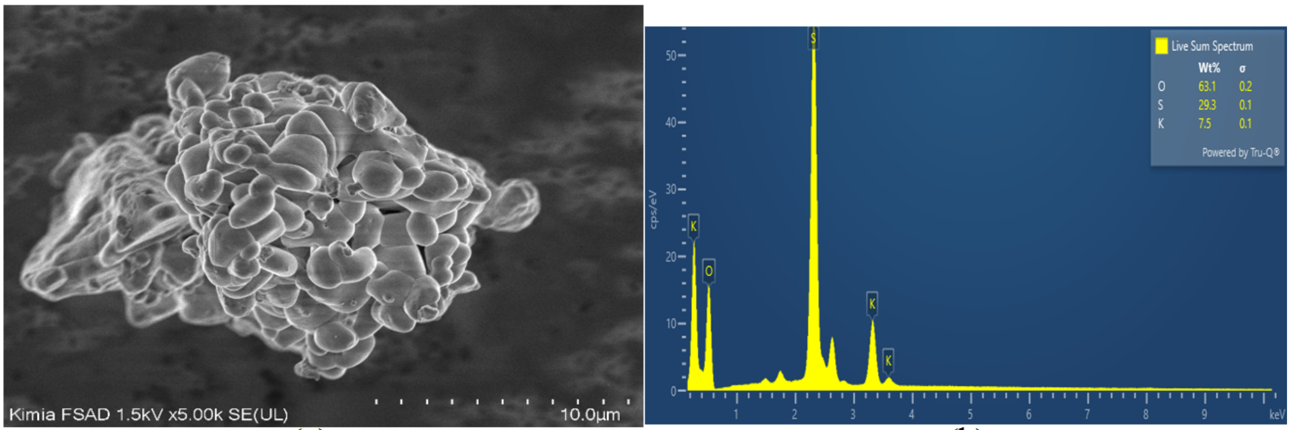

(a) (b)

Figure 4. (a) Surface morphology of K_2SO_4 using FESEM and, (b) EDX spectra of K_2SO_4.

a K_2SO_4 fertilizer, which specifies a minimum of 40% potassium and 17% sulfur [35]. Adding nanosilica to nanopotassium sulfate prevents leaching, allowing potassium to be maximally absorbed by plants. As the application of nanosilica fertilizer is more efficient in fluid form, this study further synthesized nanosilica and nanopotassium–silica to nanofluid form.

3.3 Characterization of particle size of nanosilica, nanofluid silica, nanopotassium, and nanofluid potassium-silica

TEM was used to determine the particle size of the synthesized nanosilica, as shown in Fig. 5. The particles of nanosilica synthesized via the sol–gel method are displayed in Fig. 5 (a), which shows clustered particles indicative of agglomeration. This agglomeration likely resulted from the addition of NaOH during synthesis, causing the particles to form inhomogeneous shapes. Figure 5 (b) shows nanosilica in liquid (nanofluid) form.

The nanofluid synthesis, aided by sonication, produced smaller and more uniform particle sizes. Comparing Fig. 5 (a) and 5 (b), the nanofluid silica exhibits more homogeneous and evenly distributed particles. The particle size analysis of nanosilica (Fig. 5 (a)), nanofluid silica (Fig. 5 (b)), nanopotassium (Fig. 5 (c)), and potassium–silica nanofluid (Fig. 5 (d)), performed using ImageJ, is summarized in Table 3. The data reveal that all materials and fluids had particle sizes below 100 nm, classifying them as nanomaterials (which are defined as having sizes between 1 and 100 nm). Table 3 also highlights that the particle size of nanofluids was smaller than that of nanopowders, which is attributed to ultrasonication during nanofluid preparation. When sonicating liquids at high intensities, sound waves create alternating high-pressure and low-pressure cycles based on frequency. Large particles experience surface erosion, speeding up diffusion, mass-transfer processes, and solid phase reactions due to changes in crystallite size and structure. Ultrasonication enhances precursor mixing and increases mass transfer at the particle surface, resulting in smaller particle sizes and greater uniformity [36].

The ImageJ application can determine the particle size distribution via TEM and particle size measurement data.

Table 2. Analysis of element and oxide content of banana peel, banana peel charcoal, and nano potassium using XRF.

Banana peel powder		Banana peel ash		Nano potassium sulfate	
Element	Content %	Element	Content %	Element	Content %
P	1.4	P	1.3	S	49.5
K	72.8	K	86.7	K	50.1
Ca	23.7	Ca	10.7	Cu	0.2
Mn	0.24	Mn	0.43	Rb	0.16
Fe	0.31	Fe	0.18		
Cu	0.55	Cu	0.16		
Zn	0.2	Zn	0.093		
Rb	0.18	Rb	0.36		
Sr	0.41	Sr	0.089		
Zr	0.02	Zr	0.009		
Re	0.4	Re	0.09		

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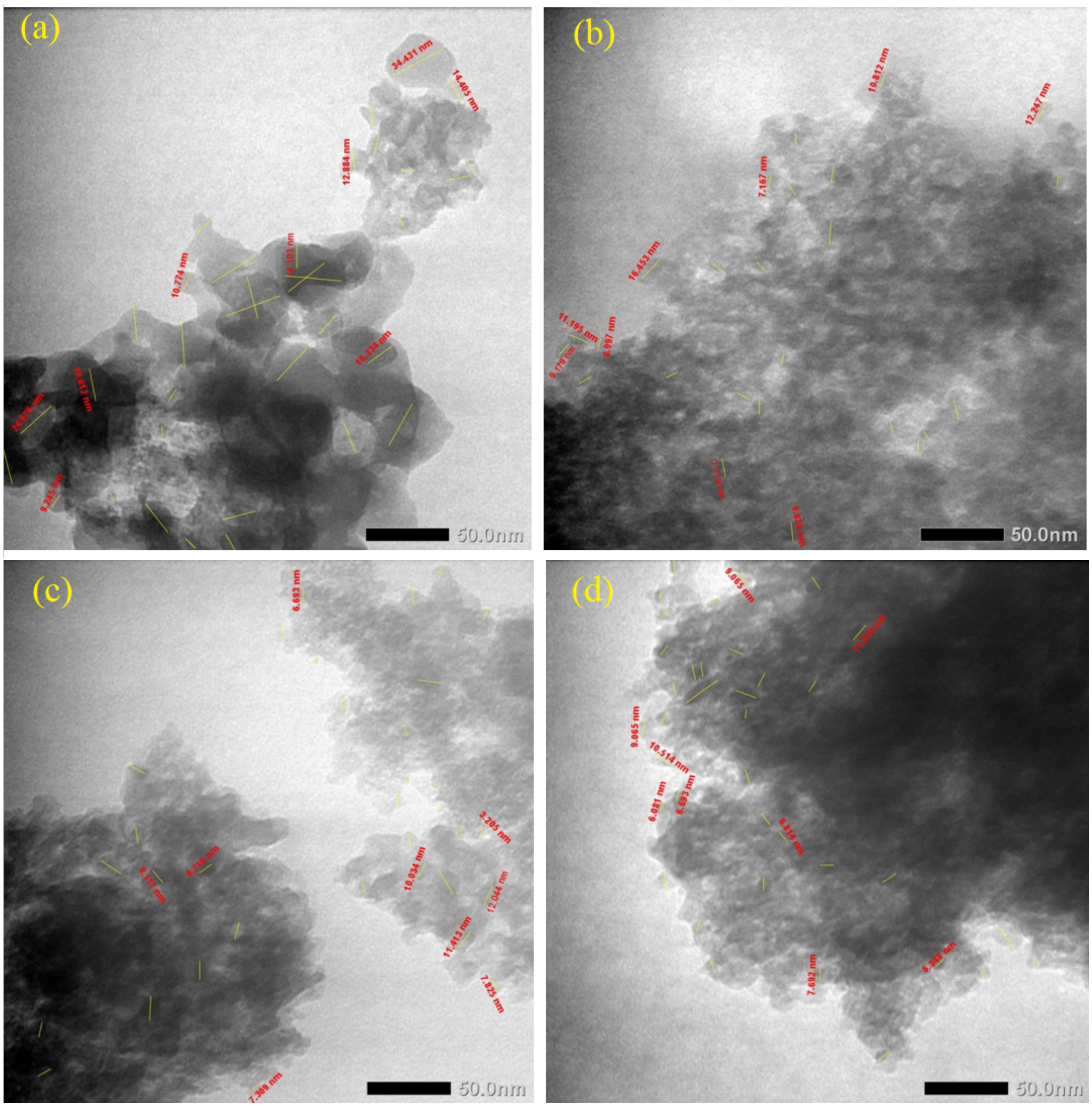

Figure 5. TEM Images of (a) Nanosilica; (b) Silica nanofluid; (c) Nanopotassium Sulfate; (d) Potassium-silica nanofluid.

Figure 6 shows the particle size distribution histograms of the nanosilica powder, silica nanofluid, nanopotassium sulfate, and potassium-silica nanofluid. The X-axis represents the particle size in nanometers (nm), and the Y-axis (vertical) represents the percentage of particles (counts %), indicating the relative percentage of particles in each size range. Figure 6 (a) shows that nanosilica powder has a narrow particle size distribution with a dominant size range between 20 – 25 nm and a few larger particles (> 30 nm). The distribution is slightly skewed to the right, which is typical for synthetic nanoparticles, indicating good powder quality and relative homogeneity.

Figure 6 (b) shows the distribution curve, indicating that the particle size is asymmetrically distributed, with a few larger particles that may be agglomerates or variations in the synthesis process. The most common particle size (highest frequency) was 8 – 10 nm, followed by 10 – 12 nm, with very few particles > 14 nm. These results indicate that the material has good homogeneity in terms of the nanoparticle size. On the basis of this analysis, it can be concluded that the nanofluid is smoother and well dispersed, which is consistent with its intended use for stability in liquids.

Figure 6 (c) shows the particle size distribution his-

Table 3. Results of particle size analysis of nanosilica powder, silica nanofluid, nanopotassium powder, and potassium-silica nanofluid.

Sample	Nanosilica powder	Nanofluid silica	Nanopotassium sulfate	Nanofluid Potassium-Silica
Particle size (nm)	22.508	10.173	8.860	8.616

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togram of the nanopotassium particles, indicating that the they are concentrated between 6 and 12 nm, with two dominant peaks at ~ 7 nm and 11 nm. The particle distribution is slightly bimodal, with a mixture of two subpopulations of particles, but still within a narrow range for the nanoparticles, indicating that the nanopotassium is well dispersed and relatively uniform in size.

Figure 6 (d) shows the particle size distribution histogram of the potassium–silica nanofluid, revealing that the most dominant particle size (mode) was 6 – 8 nm, with the highest number of particles (8 counts). The distribution is positively skewed, indicating a small number of larger particles (> 10 nm) relative to the majority of smaller particles. The particle size range was approximately 4 – 15 nm, indicating that the material has relatively small and concentrated particle sizes. These results suggest that the potassium-silica material has a smaller dominant particle size.

On the basis of the particle size distribution profiles of the nanosilica powder, silica nanofluid, nanopotassium, and potassium-silica nanofluid, it can be concluded that the nanosilica powder has the most significant and broadest particle distribution, indicating aggregation. Nanofluidization, the process of creating a solution, reduces particle size and improves homogeneity, as observed in silica nanofluids and potassium-silica nanofluids. Potassium-silica nanofluid and nanopotassium have the smallest and narrowest particle sizes, making them suitable for precision agriculture or biomedical applications because of their high surface area and good reactivity. This finding is supported by the average particle sizes shown in Table 3, as potassium–silica nanofluid and nanopotassium have smaller particle sizes, namely, 8.616 nm for potassium–silica nanofluid and 8.860 nm for nanopotassium.

The application of nanotechnology in agriculture significantly enhances crop productivity and quality. By integrating this technology, agricultural systems can achieve greater efficiency and profitability.

Compared with commercial fertilizers, nanosilica fertilizer, nanopotassium sulfate, and potassium–silica nanofluid synthesized using sol-gel and precipitation methods from rice husks and banana peels are more expensive. However, compared with commercial fertilizers, this process often yields products of more consistent quality [3, 37]. Nanofertilizers offer several advantages over commercial fertilizers, including enhanced efficiency, better control over nutrient release, and reduced environmental impact. However, the main challenges lie in their relatively high production costs and uncertainty about their long-term effects. On the other hand, conventional fertilizers are less expensive and more accessible, but they often pose a risk of causing environmental and health damage if used excessively. As a long-term solution, nanofertilizers have the potential to revolutionize sustainable agriculture, but further research is needed to ensure their safety and promote more economic development.

The use of nanofertilizers in real-world farming offers significant potential for improving crop yields, reducing environmental impact, and increasing nutrient efficiency [37]. However, the challenges associated with cost,

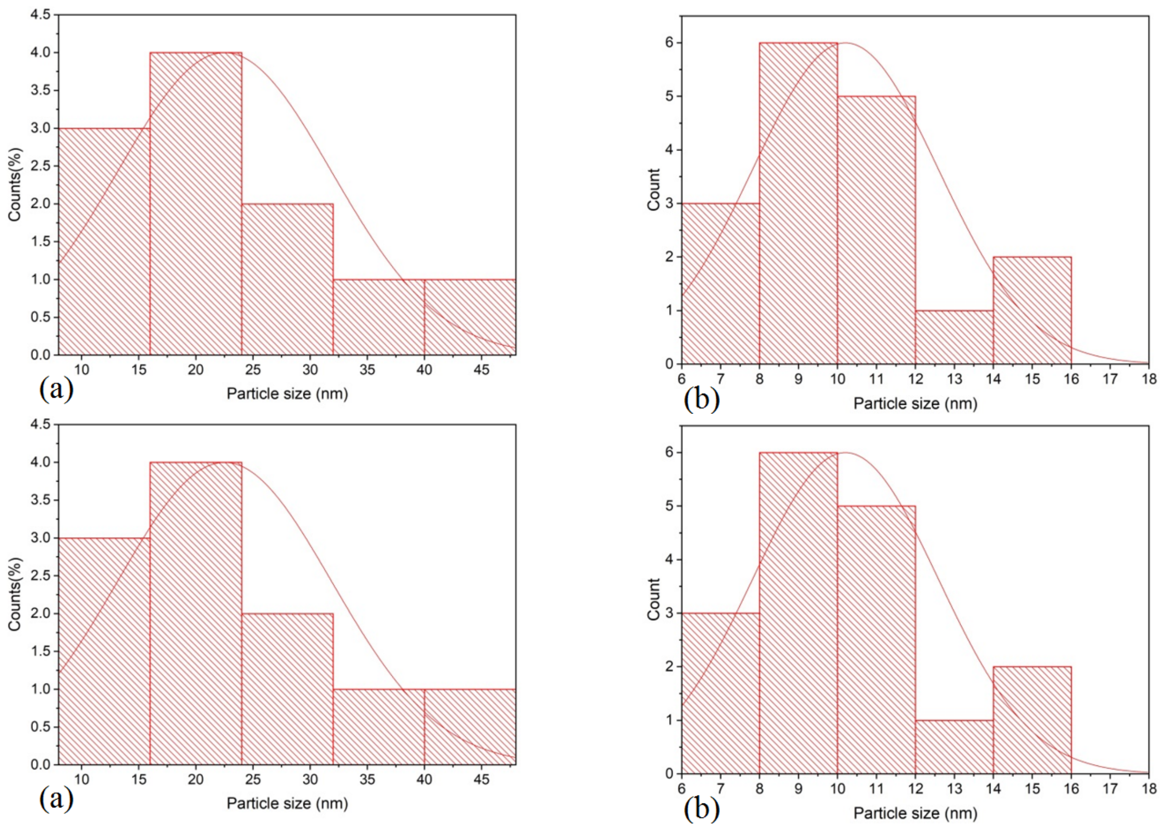

Figure 6. Particle Size Distribution Analysis: (a) Nanosilica Powder; (b) Silica Nanofluid; (c) Nanopotassium Sulfate; (d) Potassium-silica Nanofluid.

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safety, environmental concerns, regulatory frameworks, and adoption barriers must be addressed for nanofertilizers to achieve their full potential.

3.4 Application of nanofluid silica fertilizer to sweet corn plants

The height and leaf number of sweet corn plants were used to measure the effect of nanofertilizer application on their growth. Plant height plays a significant role in development, as it impacts the ability to compete for light, which is necessary for photosynthesis and general fertility. Crop production is also directly increased by it. The function of the leaves is to generate photosynthate, a source of energy for plant growth and development. The presence of more leaves might be due to increases in morphological traits such as height and branch count [38].

Ayman et al., (2020) suggested that using nanosilica increases the absorption of nutrients such as nitrogen, phosphorus, potassium, and silicon under salinity stress conditions, while sodium decreases with the increase of silicon in plant tissues [39]. In addition, nanosilica plays a role in improving resistance to pests and diseases.

The analysis of variance for average plant height and number of leaves (Table 4) indicated no interaction between silica size treatments and application times in sweet corn plants. However, a significant difference was observed in the single factor S (silica size). At three observation points 14, 28, and 42 days after sowing (DAS)—treatment S1 consistently showed the highest average plant height and number of leaves, significantly differing from treatment S2.

Based on the analysis of variance for the number of leaves, an interaction was observed between silica size treatments and application times at 21 DAS, as shown in Fig. 7. The best treatment combination was S1W2, which was significantly different from the other treatments. Silica is a beneficial, non-essential nutrient required by certain plant species. One of its primary functions is to straighten and strengthen leaves, optimizing photosynthesis and promoting robust vegetative growth [40].

In corn plants, silica supplementation accelerates photosynthesis, characterized by increased stomatal density and higher chlorophyll levels. This enhances yield by increasing the weight and productivity of corn kernels [40]. Advancements in nanosilica technology have enabled the production of silica fertilizers at nanometer scales. These particles are absorbed more efficiently, improving productivity, stability, and crop quality. Due to their rapid absorption, nanosilica fertilizers accelerate photosynthesis, leading to qualitative and quantitative production increases. This efficiency also compensates for the silicon lost due to various factors [41].

On the basis of the results of the analysis of variance on the number of leaves, the combination of silica size treatment and application time on sweet corn plants, there was an interaction effect at the age of 42 DAS, with the best treatment being S1W3, which was not significantly different from S1W1, S2W4, S1W2 and S2W1, and the lowest being S2W3, which was not significantly different from S2W2 and S1W4.

Determination of the average number of leaves yielded the results shown in Fig. 7 above, with a standard deviation of 0.63. Most of the values in the data were within ±0.63 of the average, indicating that the data distribution was relatively narrow. In other words, the data values tended to be close together and did not spread far from the average, making the data obtained reliable.

The results of this study demonstrate that applying nanosilica affected the average plant height and the number of leaves at 14, 28, and 42 days after sowing (DAS). These results align with the findings of Dung et al., (2016) who reported that nanosilica application significantly increased rice plant height compared with other treatments [42]. Their research indicated that nanosilica could increase plant height by over 30%. This improvement is attributed to increased photosynthetic efficiency and better nutrient absorption facilitated by silica.

During field research, corn plants treated with nanosilica exhibited better disease resistance than those without nanosilica treatment. Nanosilica can form a harder cell wall structure which damages the teeth of insects, especially the *Spodoptera exigua* caterpillar, and causes loss of appetite, leading to death [42]. Based on the research, applying silica at a dose of 0.3 g/L to leaves can reduce the occurrence of moler disease caused by *Fusarium spp*. Dung et al., (2016) also stated that nanosilica can inhibit the development of hyphae in cells, preventing changes to the cell wall structure [42]. Furthermore, the silica coating on the cell wall structure can reduce the ability of haustoria to penetrate the plant. Karunakaran et al.,(2013) showed that nanosilica could increase corn germination by 100% [43].

One notable function of silica is its ability to straighten

Table 4. Average plant height (cm) and number of leaves (strands) due to silica size treatment.

Treatment	Plant height (cm)			Number of leaves (strands)		
	14 DAS	28 DAS	42 DAS	14 DAS	28 DAS	42 DAS
S1	54.06 b	74.50 b	102.10 b	8.29 b	8.86 b	10.95 b
S2	48.85 a	69.79 a	94.14 a	7.68 a	8.26 a	10.48 a
LSD	3.92	3.72	6.99	0.36	0.72	0.53

Note: Numbers accompanied by the same letter within the same column and treatment group are not significantly different according to the LSD test

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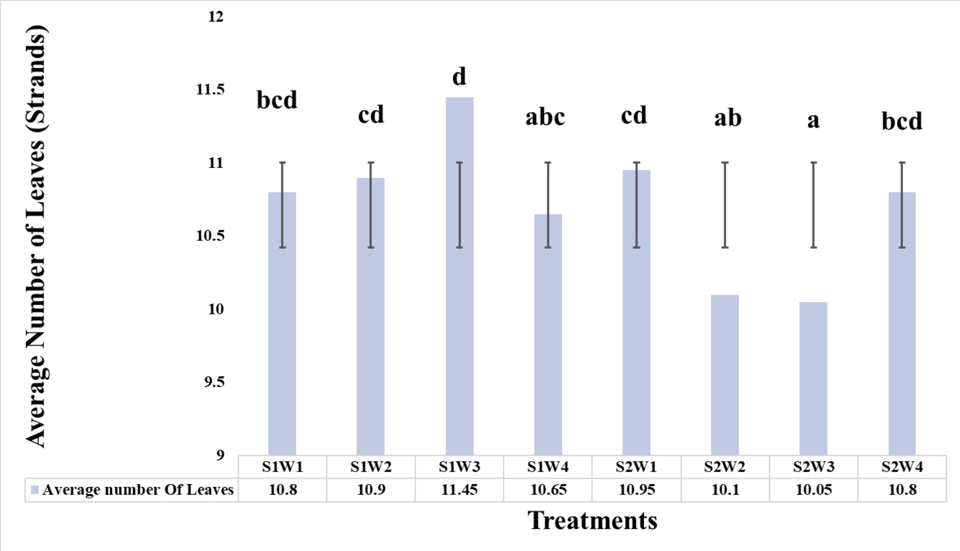

Figure 7. Average number of leaves (strands) resulting from silica size treatment and application time to sweet corn plants at the age of 42 DAS.

leaves, allowing them to absorb sunlight more effectively, and optimizing photosynthesis. The resulting photosynthates are used for growth, including increasing plant height and the number of leaves. Additionally, silica enhances root systems, improving nutrient absorption and positively impacting overall growth [44]. Suriyaprabha (2012) confirmed that nanosilica application resulted in superior corn plant height, significantly differing from other treatments [40]. Similar findings were reported by Aqaei et al., (2020) who noted that nanosilica application to sugarcane led to the best growth and yields, significantly outperforming other treatments [44]. Kumar et al.(2024) also found that applying nanosilica at the beginning of the vegetative phase provided better plant height data than other treatments [45].

Providing sufficient silicon in nano form to cereals can yield good harvest results, as the addition of nanosilica can increase cell strength and endurance. Providing nanosilica makes the leaves more upright, allowing for increased photosynthesis. Nanosilica plays a role in enhancing growth, increasing photosynthesis, and improving transpiration and evaporation efficiency, as well as increasing leaf strength, the chlorophyll concentration per leaf area, and product quality. The use of nanosilica fertilizer makes fertilizers more easily absorbed by plants and more efficient than conventional fertilizers [46]. Nanosilica is absorbed by plants in the form of monosilicic acid, which enters the plant through the xylem and is transported together with water. It is then translocated to the leaves, where evaporation occurs, and silica is stored in the epidermal layer of the leaves in the form of amorphous silica. The role of nanosilica in enhancing growth and production is attributed to the improvement of the photosynthesis system, as the leaves become more upright, allowing for photosynthesis to proceed smoothly and thereby increasing plant growth [47].

The use of nanotechnology in agriculture is believed to increase fertilizer efficiency. According to Dung et al. (2016) nanofertilizers (1 nm = 10^{-9} m) can directly target plants with minimal quantities [42]. This precision enables optimal results with smaller amounts of fertilizer compared with conventional methods, reducing production costs while maintaining efficiency and effectiveness.

The combination of silica size and application time in sweet corn plants only had an interaction effect at 42 DAS. The best combination of treatments was nanosilica applied at 21 DAS. This timing was effective, as it synchronized plant nutrient demands with the optimal release of nanosilica nutrients. The results of Ali et al., (2020) revealed that the application of nanosilica resulted in greater plant height and stem diameter than did the control with conventional silica [48] and the results of El-Naggar et al. (2020) revealed that the application of nanosilica resulted in greater plant height, chlorophyll content and harvest yields than did the control [49].

3.5 Application of nanopotassium sulfate fertilizer from banana peels on sweet corn plants

Nitrogen and phosphorus are primarily involved in forming parts of biomolecules, and potassium in living organisms is mostly in the form of free cations (K^+). K^+ is the most abundant inorganic chemical in leaf biomass after nitrogen, which underscores its essential contribution to plant functioning [50]. K^+ has a fundamental role in stomata, namely controlling stomata opening and facilitating adequate gas and water flux. Adequate K^+ concentrations in chloroplasts are necessary to maintain well-structured stroma lamellae, thus supporting chloroplast integrity and efficient light absorption. K^+ plays a complex role in photosynthetic activity and plant growth through various direct and indirect mechanisms; adequate K^+ supply can increase photosynthetic assimilation, increase nutrient uptake, and maintain cell turgor control [50]. Elevated photosynthetic assimilation rates also increase plant height and leaf formation. The various functions of K+ highlight its role as the center of

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plant homeostatic control, which includes internal transport of substances and energy, response mechanisms to biotic and abiotic stresses, and control of growth and metabolism.

Sweet corn plant height significantly varied due to the combination of potassium fertilizer treatments and application timing. The LSD test (Fig. 8) indicated that plant height increased significantly. The combination of treatment S3W1, where nanopotassium sulfate was applied at the beginning of the vegetative growth stage (7 DAS), demonstrated the highest and most significant effect (Fig. 8). The average number of leaves is shown in Fig. 8, with a standard deviation of 0.83. Most of the values in the data were within ±0.83 of the average, indicating that the data distribution was relatively narrow. In other words, the data values tend to be close together and do not spread far from the average, making the data obtained reliable.

In root science, phosphorus and nitrogen have somewhat eclipsed potassium, an essential macronutrient. K^+ functions in root growth, root system architecture development, cellular processes, and particular plant reactions to K^+ deficiency [51]. Therefore, in the presence of potassium, the absorption of nitrogen nutrients is more effective. Nitrogen affects vegetative growth, significantly affecting plant height and leaf number. Potassium plays a role in photosynthesis and the production and translocation of carbohydrates to the meristematic growth area.

Nanofertilizers also enhance plant growth through direct application methods or foliar application, making them a suitable option for improving nutrient efficiency. They release nutrients gradually, providing nutrients slowly over an extended duration, which helps increase efficient use without side effects, significantly reduces nutrient loss, and ensures environmental safety [3]. Nanofertilizers consist of nutrients encapsulated or coated in nanomaterials, allowing for controlled release and slow diffusion into the soil. Their use minimizes nutrient losses via leaching or runoff, reduces rapid degradation and volatility, and enhances nutrient quality, soil fertility, and crop productivity over the long term [3] Potassium is a critical nutrient for plants, supporting osmotic regulation, water use efficiency, nitrogen uptake, protein synthesis, and assimilate translocation. K_2SO_4 is particularly vital in sulfur-deficient soils. Studies, such as those by Wilmer (2022), have shown that potassium sulfate improves various quality characteristics in vegetable crops [52].

According to other studies, nano-K is a useful tactic for enhancing the photosynthetic and antioxidant machinery, reducing oxidative stress biomarkers and Na^+ levels, increasing salt stress tolerance, and improving yield quality under salt stress [53]. The use rate of conventional potassium fertilizers has increased significantly with the use of potassium-based nanomaterials, which have a utilization rate of over 80%. Additionally, the activities of soil peroxidase and catalase were efficiently increased by potassium-based nanomaterials [54].

The timing of K_2SO_4 application significantly has been influenced plant height during the early vegetative period, particularly at 28 DAS (Fig. 8). Application during the generative phase had no significant effect. Fitriyah et al., (2024) also reported that potassium fertilizers, such as KNO_3, significantly impact plant growth during the vegetative period [55]. Neither nanopotassium sulfate nor potassium sulfate fertilizer had a significant effect on the number of leaves at any observation stage. Leaf number increases are primarily driven by nitrogen, which is critical for metabolic processes involving protein synthesis. Optimal nitrogen levels enhance photosynthesis, leaf area production, and net assimilation rates, but do not directly influence leaf numbers [56]. Conversely, potassium plays a more pivotal role in the later stages of plant growth, such as ripening, where it supports photosynthesis, chlorophyll formation, seed filling, and carbohydrate synthesis [50]. Thus, the effects of K_2SO_4 on leaf number in sweet corn growth remain

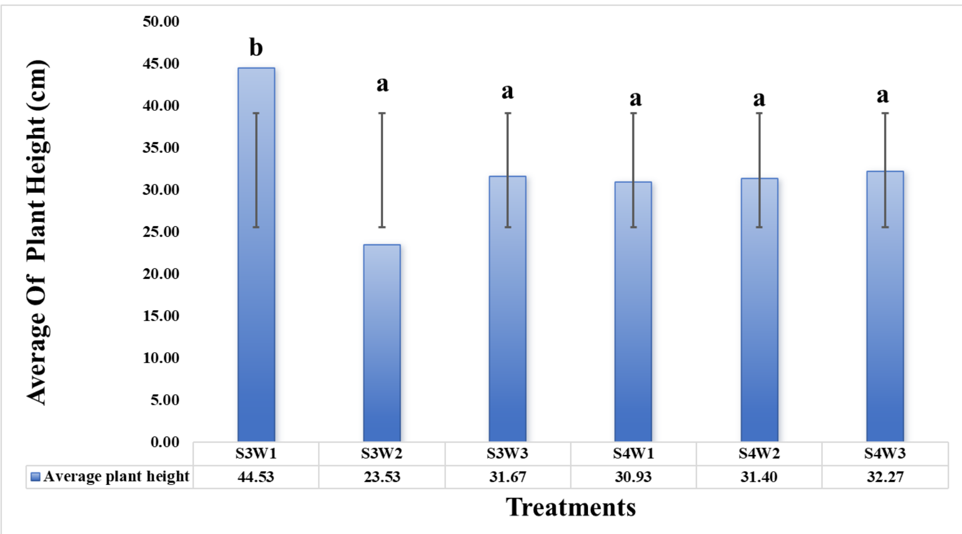

Figure 8. Average plant height (cm) and number of leaves (strands) due to the combination of potassium sulfate nano fertilizer with different application times on sweet corn plants at the age of 28 DAS.

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unobservable in the current study.

3.6 Application of potassium silica nanofluid fertilizer on sweet corn plants

Potassium silica nanofluid fertilizer is a compound fertilizer composed of two elements: potassium and silica. Potassium is obtained from organic materials such as banana peel waste, and silica is obtained from rice husk waste. Potassium silica nanofluid fertilizer is produced using nanotechnology methods.

Based on variance analysis results, a significant interaction was found between the application timing and concentration of potassium-silica nanofluid fertilizer on plant height at 42 days after sowing (DAS). A significant effect was also observed for the single application of potassium-silica nanofluid fertilizer concentration (K) at 28 days after sowing (DAS) on plant height. The results of the LSD further test are presented in Fig. 9.

As shown in Fig. 9, the best interaction was observed in treatment K3W3 (5 mL/plant concentration with fertilization at 35 DAS). This interaction suggests that the nutrients were absorbed optimally, supporting growth in plant height. Plants easily absorb nanofertilizers and bind to nano-dimensional adsorbents, enabling more efficient nutrient uptake compared to conventional fertilizers [2].

In SI units, a nanometer is defined as 10^{-9} meters [57]. Compared with compound particles, nanoparticles work faster than larger fertilizers because nanoparticles have superior properties, especially in terms of the particle size, chemical structure, surface coverage, and reaction speed [58]. The use of nano fertilizers encourages the maximization of nutrient absorption by plant roots and minimizes the occurrence of leaching or groundwater pollution, which has the potential to cause environmental harm [59, 60]. This result aligns with the finding of Zulfiqar et al., (2019) that, compared with conventional fertilizers, nanofertilizers are more readily absorbed by corn plants [2]. In the control treatment (K0), i.e., without the addition of potassium silica nanofluid fertilizer, the growth results of the sweet corn plants were lower than those when potassium silica nanofluid fertilizer was used (Fig. 9).

The LSD test (Table 5) indicated that the application timing of the single treatment did not significantly affect plant height increases. However, the addition of potassium–silica nanofertilizer significantly influenced plant height, with best results obtained at a concentration of 5 mL/plant. Precise fertilizer application timing and the use of fertilizers with smaller particle sizes facilitate nutrient absorption, leading to increased productivity, stability, and quality of crop yields [3, 4, 51].

The analysis showed no interaction or significant effect between the combination of treatments and the single effects of application timing and potassium-silica nanofertilizer concentration on the number of leaves at 14, 28, and 42 DAS. The average number of leaves is presented in Table 5. This lack of effect may be due to

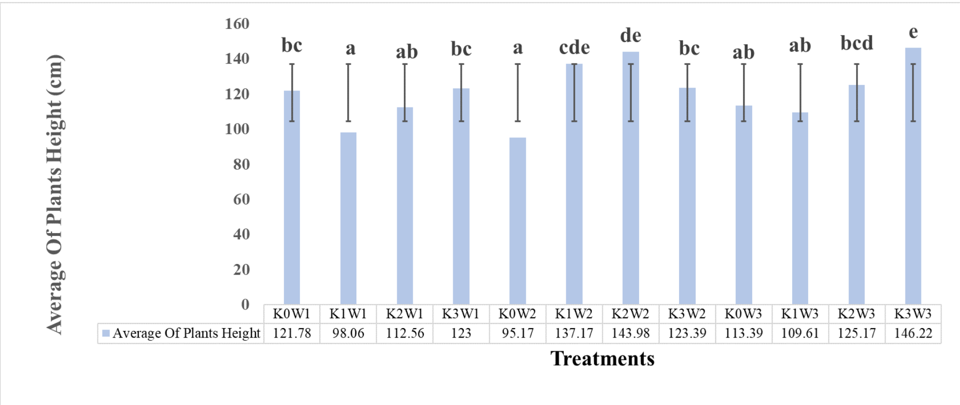

Figure 9. Average plant height (cm) due to variations in the concentration of potassium–silica nano fertilizer with application time on sweet corn plants at the age of 42 DAS.

Table 5. Average plant height (cm), number of leaves (strands), and stem diameter (cm) due to variations in the concentration of potassium-silica nano fertilizer.

Treatment	Plant height (cm)			Number of leaves (strands)			Stem diameter (cm)		
	14	28	42	14	28	42	14	28	42
K0	11.80 a	29.36 a	44.39	5.20	6.58	8.00	4.37	7.84	11.07
K1	14.29 ab	33.00 ab	47.81	5.14	6.58	8.00	4.32	7.70	11.08
K2	14.65 ab	30.78 ab	51.53	5.08	6.92	8.58	4.35	7.52	11.14
K3	17.32 b	37.49 b	50.72	5.46	7.50	8.35	5.17	8.39	10.79
LSD	4.87	8.13	NS	NS	NS	NS	NS	NS	NS

Note: Numbers accompanied by the same letters in the same column and treatment do not show significant differences in the LSD test.

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the fertilizer concentration being too low to significantly increase leaf growth, and when corn is planted, there is a rain almost every day so that nutrients are leached into the soil, which can reduce the nutrient content of fertilizers. According to Assaha et al., (2017) a high accumulation of Na^+ in plants due to salinity stress can cause damage, such as leaf dryness and shedding [61, 62]. Similarly, Magalhães et al., (2023) reported that inadequate nitrogen availability could hinder the growth of plant leaves and stems [63]. In this study, the particle size of the potassium silica nanofluids was 8.616 nm, allowing for easy absorption by plants. The fertilizer contained mineral elements such as P, K, Ca, Mg, Fe, Cu, Mn, Zn, and, Rb which are essential for sweet corn development.

Fig. 9 shows that the K3W3 treatment resulted in the greatest average plant height, which was 146.2 cm. The K1W1 treatment produced the lowest average height, which was 98.06 cm. Overall, plants treated with K3 (in combination with W1, W2, and W3) presented a greater average height. The error bars in Fig. 8 show the variation in the data from the average value. The longer the error bar is, the greater the variation in the data for that treatment. Treatments K0W1 and K2W1 have shorter error bars, indicating that the data for this treatment were more consistent and less varied. In contrast, treatments K3W2 and K2W3 have longer error bars, indicating that the data had greater variation.

The average plant height data are shown in Fig. 9, with a standard deviation of 0.93. Most of the values in the data were within ±0.93 of the average, indicating that the data distribution was relatively narrow. In other words, the data values tended to be close together and did not spread far from the average, making the data obtained reliable.

The ANOVA test indicated no interaction between application timing and potassium–silica nanofertilizer concentration on stem diameter. The application of potassium-silica nanofertilizer at 14, 28, and, 42 DAS increased stem diameter; however, the differences between the treatments were not statistically significant. Efficient fertilization is achieved by applying the correct dose, in the right manner, and at the appropriate time, tailored to the plant's nutrient requirements [64]. The application of potassium-silica fertilizer enhances photosynthesis and strengthens cell walls, making plants more robust and less susceptible to pests and diseases. The findings of Zhang et al., (2023) support these results, demonstrating that potassium fertilizer promotes the growth of sweet corn plants by increasing plant height and stem diameter [65].

Potassium is essential for the growth and development of corn. About 25% of potassium is found in corn kernels after harvest; the rest is found in the stems and cobs. Young plants do not need much potassium, but the need increases rapidly, especially when panicles are about to emerge [66]. The optimal application time is when the plants are 35 days old, at the end of the vegetative period and at the beginning of the generative phase, which is marked by the emergence of panicles. The optimal application time was when the plants are 35 days old, at the end of the vegetative period and at the beginning of the generative phase, which is marked by the emergence of panicles. This occurs because when the plant enters the generative growth phase, it produces flowers and fruits until the fruit ripen. In this phase, the nutrients required by plants include phosphate and potassium, so the provision of potassium silica fertilizer at the beginning of the generative phase has a real effect on the growth of sweet corn plants.

4. Conclusion

In this study, potassium–silica nanofluid fertilizer with an optimal particle size of approximately 8.6 nm was successfully synthesized from banana peels and rice husk waste. The application of nanofertilizer significantly enhanced the vegetative growth of sweet corn, particularly when 5 mL was applied at 35 DAS. These findings demonstrate the potential of organic waste-derived nanofertilizers to improve nutrient efficiency and crop performance. Moreover, this research highlights the value of converting agricultural waste into high-efficiency fertilizers, offering an environmentally friendly alternative to conventional fertilizers and contributing to sustainable agriculture. Further research should explore long-term environmental impacts, cost-effectiveness in large-scale applications, and effects on different crop varieties under various soil conditions.

Funding
Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia through the Domestic Collaborative Research Scheme (master contract no. 109/E5/PG.02.00PL/2024 and subsidiary contract no. 029/SP2H/PT/LL7/2024 and no. 01/040.1/PN.02.01/VI/2024.

Authors contributions
All authors contributed equally to the conception, design, execution, and writing of this work. All authors read and approved the final manuscript.

Availability of data and materials
The authors declare that the data supporting the findings of this study are available within the paper.

Conflict of interests
The authors assert that they do not have any identifiable conflicting financial interests or personal relationships that might be perceived to influence the work presented in this paper.

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