



Research Article

Fabrication of Urea with Amorphous Silica to Increase Rice Growth in Saline Soils

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Abstract

In recent decades, the decrease in rice cultivation areas in Vietnam, particularly in the Mekong River Delta, caused by climate change and soil salinization, has posed serious challenges for sustainable development. In addition to irrigation and agronomic practices, fertilizers that sustain rice growth under saline conditions play a crucial role in improving crop productivity. Amorphous silica has been reported to increase plant tolerance to drought, salinity, and heavy metal stress. In this study, nanosilica-coated urea (UCS) fertilizers were synthesized by coating urea granules with 1–5 wt% amorphous silica. The products were characterized by SEM, XRD, FTIR, TG–DSC, and EDX to confirm their structural and chemical features. Laboratory-scale experiments on saline soils revealed that UCS reduced total dissolved salt (TDS) content by up to 40% after 30 days, increased soil organic nitrogen and silicon contents by more than 15%, and promoted stable rice growth. After 30 days, the height of the rice treated with UCS1 reached 42–44 cm, which was 124% greater on average than that with conventional urea (18–30 cm), and higher survival rates were maintained (up to 90% vs. 40%). The growth stages of rice under mild to moderate salinity conditions were evaluated throughout a 120-day cultivation period. These results highlight the strong potential of urea–silica fertilizers for sustainable rice cultivation in saline soils (0.5%–1% NaCl).

ARTICLE HISTORY

Received: 7 Oct. 2025

Revised: 27 Apr. 2026

Accepted: 5 May 2026

Published: 17 Jul 2026

KEYWORDS

Soil salinity;
Urea-based fertilizer;
Amorphous nanosilica-modified urea;
Saline soil remediation;
Plant growth enhancement

Introduction

Soil salinity has emerged as a critical threat to global food security, affecting more than 4 million km² of land worldwide, and is projected to threaten nearly half of arable land by 2050. In saline soils, excessive accumulation of sodium (Na⁺) and chloride (Cl⁻) ions impairs osmotic regulation, disrupts nutrient uptake, and induces oxidative stress by stimulating the overproduction of reactive oxygen species (ROS). Saline soil has an EC greater than 4 dS m⁻¹ or 40 mM NaCl (Stavridou et al., 2017). These physiological disturbances reduce photosynthesis, delay flowering, and ultimately suppress crop

yields (Gong et al., 2015; Ma et al., 2022; Pirasteh-Anosheh et al., 2016; Salekdeh et al., 2002).

Nitrogen (N) remains the most important nutrient for rice production, with urea being the dominant N fertilizer because of its high nutrient density (46% N) and ease of application (Azeem et al., 2014; Uzoh et al., 2026). However, the efficiency of urea is often constrained in saline soils because of enhanced leaching and volatilization and reduced uptake efficiency. Studies have demonstrated that compared with nonfertilized controls, urea application significantly improves rice growth,

chlorophyll content, and yield (Li et al., 2025). For instance, in Vietnam, field trials reported that compared with unfertilized controls, urea fertilization increased chlorophyll levels in rice leaves by 11.76%, grain yield by 20.8%, and nitrogen use efficiency (Thao et al., 2016; Zhang et al., 2018). Similar positive effects have been observed in maize, where plant height increased by 14.9% and fresh ear weight by 93% with optimal urea fertilization (VIRAC Data Factory, 2023). These findings underscore the critical role of nitrogen in improving crop resilience and productivity, particularly under saline stress.

In addition to nitrogen, silicon (Si) has been identified as a beneficial element that enhances plant tolerance to abiotic stresses. Although not considered essential, Si contributes to cell wall reinforcement, ion balance regulation, and ROS detoxification, ultimately improving plant vigor under saline stress (Ma et al., 2004; Rizwan et al., 2015; Sourì et al., 2021). Recent advances in nanotechnology have introduced silica nanoparticles (SiNPs), which provide higher bioavailability and more efficient uptake than conventional silica amendments do. The application of SiNPs has been shown to increase rice yield by up to 33.3%, increase antioxidant enzyme activity, and reduce Na^+ accumulation under saline irrigation (Jin et al., 2024). These findings indicate that integrating Si with nitrogen fertilizers could offer a synergistic approach to improving plant stress tolerance.

In Vietnam, several efforts have been made to develop improved fertilizer formulations for saline soils. A notable example is the industrial production of N46. Plus, a urea-based fertilizer coated with N-dual protection technology was launched by PetroVietnam Ca Mau (PVCFC) in 2016. This product, containing 46% N with urease and nitrification inhibitors, has demonstrated >7% yield increases and 20–30% fertilizer savings, reflecting both economic and environmental benefits (PVCFC, 2021). Moreover, compared with unfertilized controls, field experiments combining urea (100 kg N ha^{-1}) with potassium chloride (KCl, up to $120 \text{ kg K}_2\text{O ha}^{-1}$) in salt-tolerant rice varieties such as OM 8104 and MRN 3 resulted in yield increases of 24.7% and 22.29%, respectively, and improved K^+/Na^+ ratios in plant tissues (Sen, 2018). These findings highlight the importance of integrated nutrient management for saline agriculture in Vietnam.

Rice is among the most important staple crops in Vietnam, not only serving as the primary food source for more than 90 million people but also acting as a major contributor to the country's agrarian economy and export earnings. Vietnam consistently ranks among the world's top three rice exporters (Thi et al., 2022), with annual production exceeding 40 million tons of paddy rice, cultivated mainly in the Mekong River Delta

(responsible for nearly 50% of national output) and the Red River Delta (Food and Agriculture Organization of the United Nations, 2023; Tu et al., 2021). Although these deltas offer rich alluvial soils and favorable weather, they are under threat from sea level rise, saline intrusion, and erratic rainfall caused by climate change. It is estimated that many hectares of rice-growing land in the Mekong Delta may be affected by salinity, which poses a severe risk to yield stability and food security (Minh et al., 2022; Thach et al., 2023). Salinity stress not only reduces rice productivity but also alters grain quality, thereby undermining both domestic consumption and export competitiveness.

The management of soil fertility and nutrient use efficiency plays important roles in sustaining rice production. Among fertilizers, urea is the predominant nitrogen source in Vietnam, with domestic production reaching 2.8 million tons in 2023, exceeding the national demand of 2.2 million tons and ensuring a surplus for export (General Statistics Office, Agriculture, Forestry and Fishing, 2023). Urea has been shown to significantly increase rice growth parameters, including the chlorophyll content and grain yield, while increasing nitrogen use efficiency under saline conditions. Moreover, combined nutrient strategies such as the application of urea with potassium chloride have demonstrated substantial yield improvements in salt-tolerant rice cultivars such as OM8104 and MRN3 (Trinh et al., 2024). At the industrial level, advanced products such as the coated urea N46. In addition, Ca Mau Fertilizer Company has been introduced to reduce nitrogen losses, improve plant vigor, and promote yield gains exceeding 7% when fertilizer inputs are cut by 20–30% (Xu et al., 2024; Zhu et al., 2025).

In soils, traditional urea fertilizers still face the challenges of volatilization, leaching, and inefficient nutrient use (Lin et al., 2007; Shoji et al., 2001). This restriction urges the development of innovative nitrogen fertilizers that can improve crop resilience to salinity stress, provide controlled nutrient release, and improve nitrogen retention (Naz and Salaiman, 2016; Tayade et al., 2022; Yan et al., 2024). The creation of urea–silica composites presents a viable approach to maintain rice yield, enhance soil quality, and support the long-term climate change resilience of the rice industry in Vietnam (Sahu et al., 2022; Wanyika et al., 2012).

In this study, urea fertilizer was fabricated with amorphous nanosilica using the coating method. The obtained products were carefully characterized by scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and thermogravimetric (TGA) methods before being tested for salinity resistance in soil and laboratory-scale rice growth.

Materials and methods

1) Chemicals

Chemical reagents, including sodium silicate (Na_2SiO_3 , 99%), ammonia (NH_4OH , 25%), hydrochloric acid (HCl , 36%), and hydrogen peroxide (H_2O_2 , 3%), were purchased from Xilong Scientific Ltd. (China). Granular urea was purchased from Ninh Binh Nitrogenous Fertilizer Ltd. Company (Vietnam). All the reagents were used without further purification.

The OM5451 rice variety (Research and Seed Production Center, Loc Troi Group) was used for the test. It has a growth period of approximately 90 days and yields approximately 7–8 tons ha^{-1} . OM5451 was officially recognized as a national rice variety by the Ministry of Agriculture and Rural Development (Decision No. 711/QD-TT-CLT, December 7, 2011) and is currently widely cultivated across the Mekong Delta. In addition to its relatively good salt tolerance, the variety is characterized by vigorous tillering, rapid leaf development, and stable resistance to major pests and diseases, including brown planthopper, blast, and yellow dwarf disease. Owing to its high yield, stress tolerance, and desirable eating quality, OM5451 is well accepted in both domestic and export markets, particularly in the Philippines (Nguy, n.d.). The soil used in this study was used for the analysis of soil parameters.

2) Preparation of nanosilica and urea-silica fertilizers

Preparation of nanosilica: First, 30 mL of Na_2SiO_3 was dispersed in 30 mL of distilled water in a 100-mL beaker on a magnetic stirrer. Afterward, 3 mL of 25% NH_4OH solution was slowly added to the mixture. Afterward, 36 wt% HCl was gently added to the beaker until the precipitate appeared, and the pH was adjusted to 4.5. The mixture was isolated by centrifugation and neutralized by washing several times with distilled water. Next, the silica gel was obtained by stirring the precipitate and heating it to 80 °C for three hours. The silica gel was subsequently dried and calcined at 450 °C in a furnace for 30 minutes to obtain the final nanosilica product.

Preparation of nanosilica-coated urea (USC) fertilizer: Urea–silica fertilizers were prepared by the coating method. First, granular urea was mixed well with various nanosilica contents of 1.0, 3.0, and 5.0 wt%, denoted as UCS1, UCS3, and UCS5, respectively. After that, the corresponding mixtures were dried at 80 °C for 2 hours before being calcined at 100 °C for 30 minutes to produce the corresponding USC products.

3) Materials characterization

A SEM S4800 Hitachi instrument (Japan) coupled with energy-dispersive X-ray spectroscopy (EDX) at 10 kV was used to study the morphology and elemental analysis of the synthesized catalysts. A D8 Advance X-

ray diffractometer (Bruker, Germany) with a Cu K α radiation source was used to examine the crystal structure and phase purity of the catalysts. Thermal gravimetric analysis (TGA) was carried out using SETARAM (France) Labsys Evo. The functional groups of the materials were examined by using FTIR spectroscopy with a Shimadzu spectrometer.

Crystallographic characterization techniques commonly apply Bragg's law to interpret XRD data. In this context, the crystallite size (D , nm) can be estimated using the Scherrer equation (Eq. 1) (Muniz et al., 2016).

$$D = k \cdot \lambda / \beta \cdot \cos \theta \quad (\text{Eq. 1})$$

where K represents the dimensionless Scherrer constant, λ is the X-ray wavelength (nm), β denotes the full width at half maximum (FWHM, in radians), and θ is the Bragg diffraction angle (in radians).

4) Experimental design

4.1) Soil preparation

Urea-based saline-resistant fertilizer was tested on artificial saline soil at the laboratory scale. First, the initial soil had an average salinity of 0.03 wt%. NaCl salt solution was added (soaked in salt solution for 14 days) to increase the soil salinity to between 0.5 wt% (0.86 dS m^{-1}) and 1.0 wt% (1.71 dS m^{-1}). Afterward, 500 g of each group of saline soil was weighed into a 1000 mL beaker, and 500 mL of distilled water was added. Each group of saline soil was supplemented with saline-resistant fertilizer at a ratio of 0.100 to 0.150 g per 1 kg of soil (Table 1). After a certain period (3, 7, 14, 21, and 30 days), the soil was taken to determine the soil salinity according to the TCVN 12615:2019 standard (Figure 1). Soil treatments were prepared for rice cultivation at two salinity levels (0.5% and 1%) with different fertilizer application rates. Treatments M1 and M2 consisted of soils amended with 0.1 g kg^{-1} UCS at salinities of 0.5% and 1%, respectively, while the corresponding controls (N1 and N2) received 0.1 g kg^{-1} urea at the same salinity levels. Similarly, in treatments M3 and M4, 0.125 g kg^{-1} UCS was applied at 0.5% and 1% salinity, respectively, with N3 and N4 serving as urea-based controls. Treatments M5 and M6 used 0.15 g kg^{-1} UCS at 0.5% and 1% salinity, respectively, with N5 and N6 as the corresponding urea controls.

Fertilizer efficacy testing of samples UCS1, UCS3, and UCS5 was conducted as follows: soil sample M1 with a salinity of 0.5% and a corresponding fertilizer application of 0.1 g kg^{-1} . After 3, 7, 14, 21, and 30 days, the total dissolved salt content was checked according to the TCVN 12615:2019 standard.

The total dissolved salt (TDS) in the soil, expressed as a percentage of the dry soil mass, is determined according to the following principle (Lin et al., 2007). All soluble salts in the soil are extracted with distilled water

without CO₂. The extract is filtered through fine filter paper, followed by the oxidation of the included organic substituents with H₂O₂. The extract was evaporated and dried to constant mass, the residue was weighed, and the results were determined by the following equation (Eq. 2).

$$\% \text{ TDS} = (m_1 - m_0) \times k \times 100/m \quad (\text{Eq. 2})$$

Where m_0 , m_1 represents the mass of the initial beaker and the beaker with dry residues, in grams (g); m represents the mass of soil in grams (g), which corresponds to the volume of filtrate removed for analysis; and k represents the soil dryness coefficient, which is determined according to the TCVN 4048:2011 standard.

4.2) Simulation of rice cultivation on a laboratory scale

Urea-based salinity-resistant fertilizer was tested for use in the cultivation of artificial saline soil at the laboratory scale (Figure 2). First, soil with salinities of 0.5 and 1.0 wt% was prepared according to the procedure in section 2.4.1. Moreover, the selected rice seeds were soaked in a 100-mL beaker at 50 °C to germinate for 2 days. After that, ten germinated seeds were sown in the as-prepared saline soil in each cylindrical hole ($d = 10$ cm, $h = 14$ cm). Afterward, the growth of the rice was monitored for a certain time (3,

7, 14, 21, and 30 days), whereas the soil salinity was measured according to the TCVN 12615:2019 standard.

The experiment was arranged in a completely randomized design consisting of different fertilizer treatments, including control and urea-based formulations. Each treatment was conducted with three independent replicates, where each replicate corresponded to one experimental unit (one pot containing ten rice plants). The pots were randomly distributed under uniform environmental conditions to minimize experimental bias.

Growth parameters, including plant height, survival rate, and developmental stage, were recorded at different time intervals (e.g., 14, 30, 62, and 84 days after sowing). The collected data are expressed as the mean $\pm$ standard deviation.

Statistical analysis was performed using one-way analysis of variance (ANOVA) to evaluate the differences among treatments. When significant differences were detected ($p < 0.05$), a post hoc multiple comparison test was applied to identify statistically significant differences between treatments. All the statistical analyses were carried out using standard software such as Microsoft Excel. Prior to ANOVA, assumptions of normality and homogeneity of variance were checked.

Table 1 Soil preparation before texting

Samples	Initial soil (g)	Distilled water (mL)	Ratio of salt-resistant fertilizer/1 kg of saline soil	Initial salinity (%)
M1, N1	500	500	0.100	0.5
M2, N2	500	500	0.100	1.0
M3, N3	500	500	0.125	0.5
M4, N4	500	500	0.125	1.0
M5, N5	500	500	0.150	0.5
M6, N6	500	500	0.150	1.0



Figure 1 Salt resistance experiments at the laboratory scale.

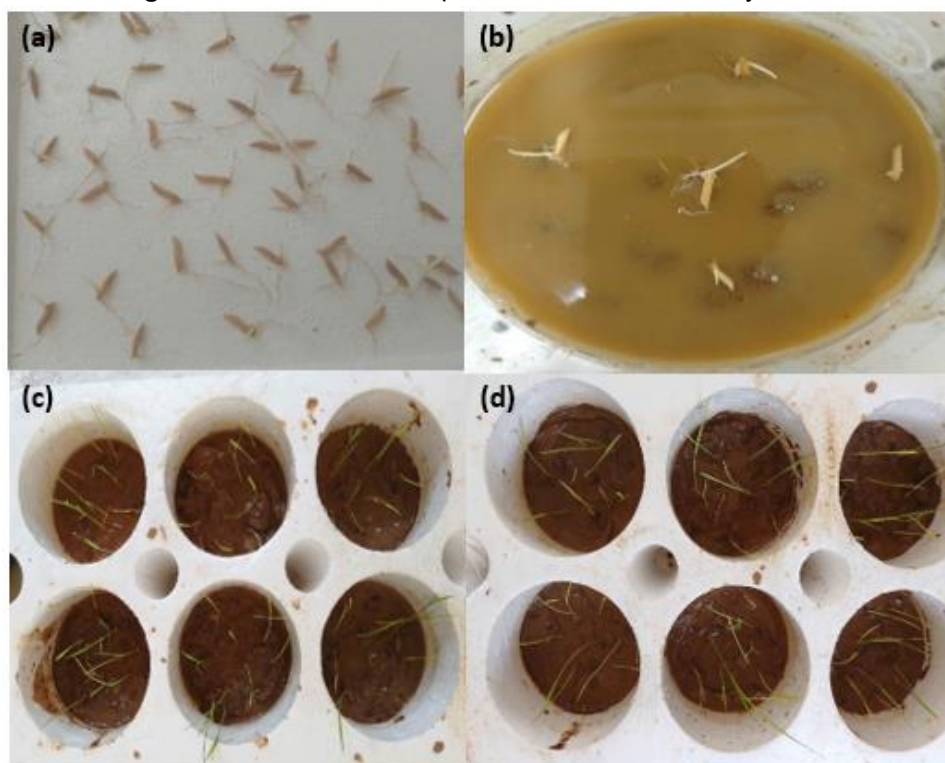


Figure 2 Simulation of rice cultivation at the laboratory scale. (a) Germinated rice seeds, (b) sown rice seeds, and (c, d) planted holes.

Results and discussion

1) Materials characterization

TG–DSC analysis of pure urea and nanosilica-coated urea (Figure 3) revealed that both samples exhibit a sharp endothermic peak at approximately 140 °C, corresponding to the phase transformation of urea (Nguy, n.d.). For pure urea, the TG curve remained nearly constant at approximately 100%, indicating negligible mass loss during the melting process, which is characteristic of the thermal behavior of unmodified urea (Tischer et al., 2019). In contrast, the mass of the silica-

encapsulated urea decreased slightly after melting, which can be attributed to the release of adsorbed moisture and carbonaceous residue from the silica matrix and the restricted volatilization of urea (Zhuravlev, 2000). Moreover, the encapsulated sample exhibited a sharper and more defined endothermic peak, suggesting that the silica shell stabilized the melting process by reducing heat dissipation and limiting urea decomposition or evaporation. These results demonstrate that while silica encapsulation does not alter the melting point of urea, it significantly enhances its thermal stabi-

lity after melting by acting as a diffusion barrier, thereby slowing volatilization and decomposition (Azeem et al., 2014; Ghosh et al., 2024).

The surface morphologies of pristine urea and nanosilica-coated urea were investigated by SEM (Figure 4). The initial urea granule (Figures 4a, 4e) exhibited a smooth and spherical morphology with an intact surface, which is typical for commercial urea. Upon coating with 1% silica (Figures 4b, 4f), the granules retained their spherical structure, although the surface became slightly rougher because of the deposition of a thin and nonuniform silica layer. Figure 4b is a photograph of the salinity-resistant fertilizer particles with a size of approximately 1 mm, and Figure 4f is a surface photograph showing the dispersion of small nanosilica particles with a size of <100 nm in the urea matrix. At 3 wt% silica loading (Figures 4c, 4g), the spherical morphology of urea was no longer preserved. The granules were completely covered by silica, resulting in the formation of multiple cracks and a honeycomb-like porous structure,

indicating the formation of a thick and continuous coating. With a further increase to 5% silica (Figures 4d, 4h), the original granule shape completely disappeared, and the surface displayed extensive fractures along with a dense silica network. Such morphological modifications are highly relevant for agricultural applications. The thin silica layer at 1 wt% loading is likely to significantly influence the dissolution behavior of urea in soil.

The EDX results were used for elemental analyses of the prepared samples. The EDX results revealed the presence of Si in all the prepared nanosilica-modified samples, whose atomic mass ranged from 0.75–4.37 wt%, corresponding to the increase in the nanosilica precursor during the preparation step, which was close to the theoretical theory of the product. The remaining elements appearing on the EDX data were typically N, O, and C, suggesting the high purity of the prepared UCS materials.

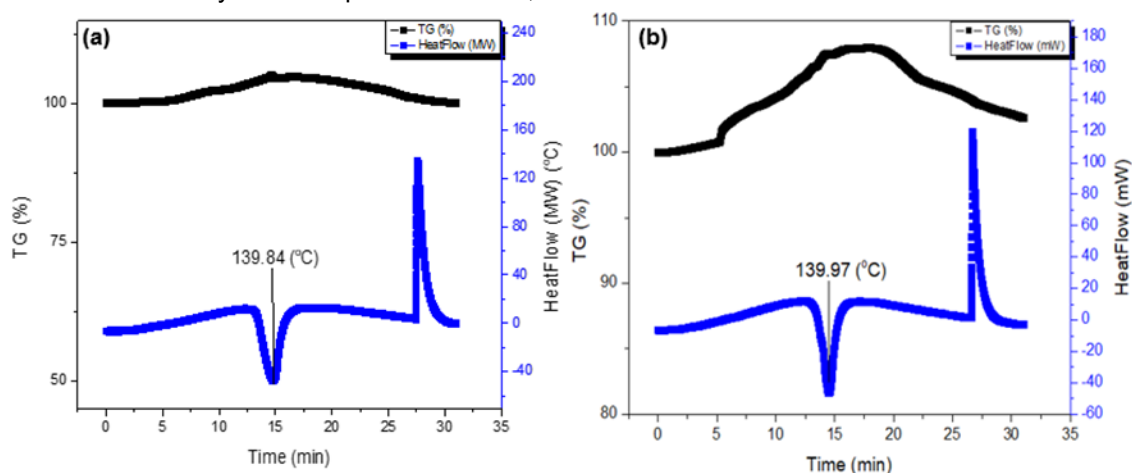


Figure 3 TGA curves of (a) initial urea and (b) UCS1

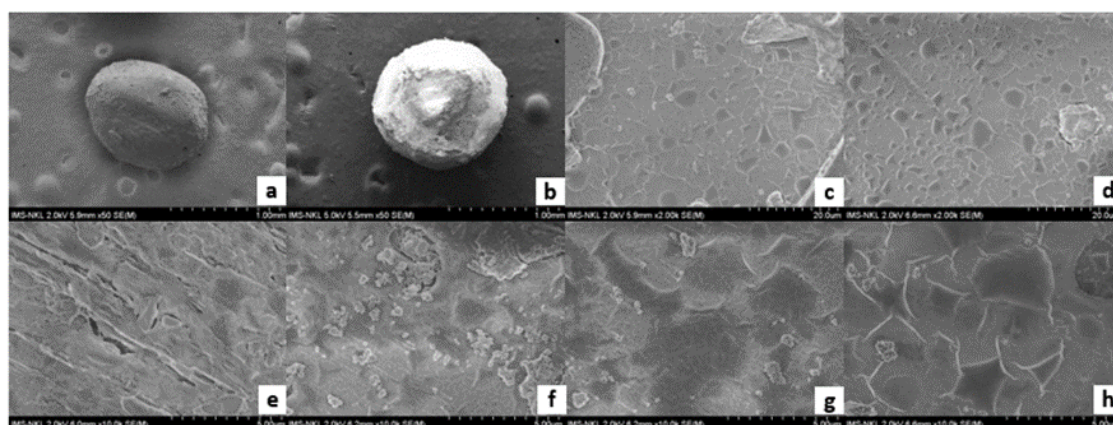


Figure 4 SEM images of (a, e) initial urea, (b, f) UCS1, (c, g) UCS3, and (d, h) UCS5.

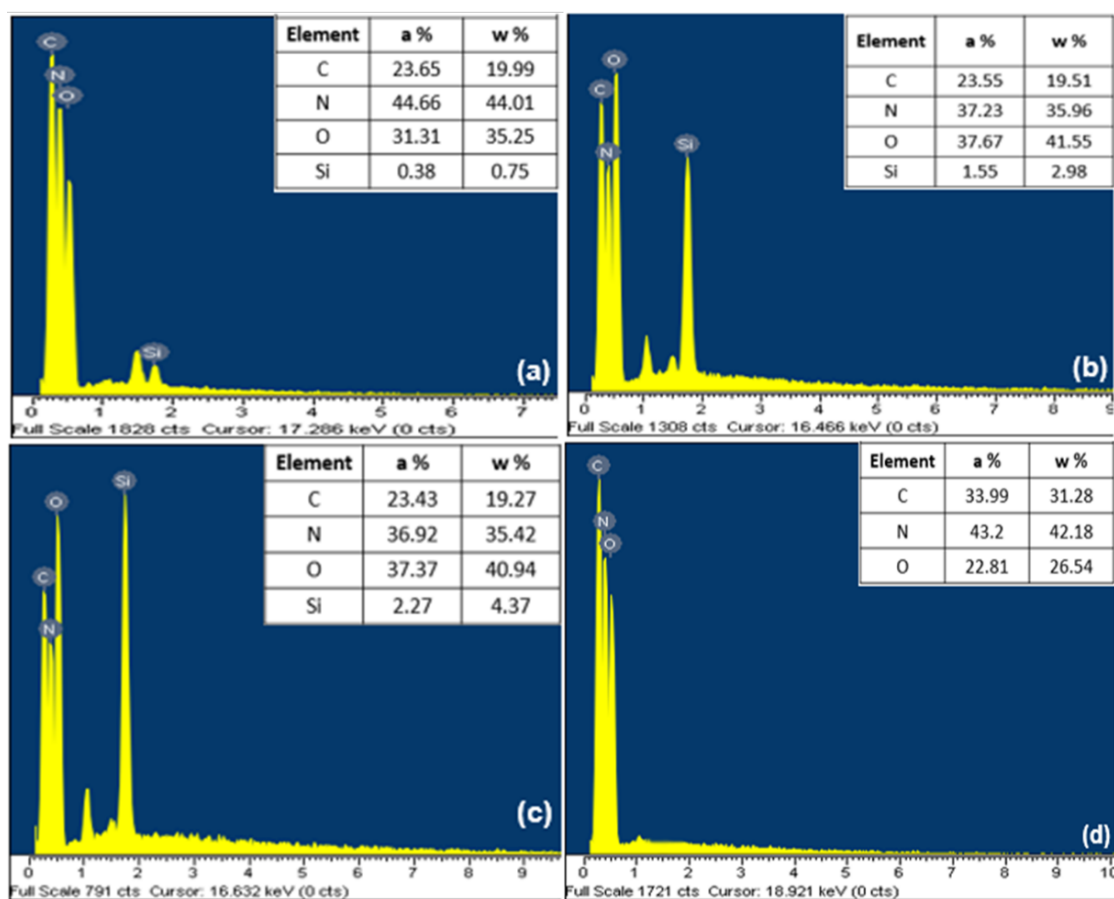


Figure 5 EDX spectra of (a) UCS1, (b) UCS3, and (c) UCS5 (d) U0 (inset tables: elemental composition).

XRD curves of U0 and UCS with various coated nanosilica samples are shown in Figure 6. The pattern of the U0 sample exhibited sharp and intense diffraction peaks corresponding to the tetragonal structure of urea (PDF #00-037-1464) (Fahmi et al., 2022). After coating with silica, the characteristic peaks of urea were still observed; however, their intensity decreased progressively with increasing silica content. The results indicated that the silica layer partially covered the crystalline domains of urea (Dere et al., 2025). Notably, no additional peaks corresponding to crystalline silica were detected. According to Vegard's law, because of the low content of the fertilizer, the peak area or peak intensity for amorphous nanosilica is much smaller than that of urea, with a slight shift in the diffraction angle. Hence, observing the presence of the corresponding peaks of amorphous nanosilica in the XRD curves of UCS samples was difficult. Compared with the curve of U0, the peak intensity of UCS1 decreased slightly but remained distinct, indicating that the thin silica layer did not disrupt the crystalline integrity of the urea core. On the other hand, UCS3 and UCS5 exhibited broader and less intense peaks, reflecting a reduction in crystallinity due to the formation of thicker amorphous silica coatings on the urea particles. Moreover, the change can be due to cracking and disruption of the initial urea morphology (Inoue and Hirasawa, 2013). These results are in agreement with the results of the SEM images. While a higher silica loading (3–5 wt%) resulted in

significant morphological changes and loss of granule integrity, the 1 wt% silica produced a thin but effective coating without altering the urea crystal structure. Furthermore, the characteristic peak of the U0 sample at 22.2° was slightly positively shifted, suggesting a change in bond length in the tetragonal structure due to modification with amorphous silica (Phillips et al., 2021).

The crystallite size of the urea and nanosilica-coated urea samples was calculated using the Scherrer equation (Muniz et al., 2016), with a diffraction peak at 22.2° . U0, UCS1, UCS3, and UCS5 had average crystallite sizes of 43.85 nm, 44.77 nm, 48.21 nm, and 41.92 nm, respectively. After coating with a silica content ≤ 3 wt%, the crystallite size slightly increased, indicating that the urea particles were shielded by the thin silica, which contributed to stabilizing the crystalline domains (Ding et al., 2012). However, a greater silica content (5 wt%) can lead to the collapse of the urea structure, as clearly illustrated by the SEM images.

The distinctive functional groups of silica and urea in the composite fertilizers are clearly visible in the FTIR spectra (Figure 7). The wide band at $3,200\text{--}3,400\text{ cm}^{-1}$ is ascribed to hydrogen-bonded O–H and N–H stretching of urea; this band is still discernible and reasonably strong in UCS1, suggesting that amino groups are retained, but it weakens in UCS3 and UCS5 because of the thicker silica coating. The sharp peak at $1,670\text{ cm}^{-1}$, corresponding to the C=O stretching vibration

of urea, is clearly observed in UCS1 but becomes weaker and broader in UCS3 and UCS5, indicating partial signal suppression by the silica shell. Similarly, UCS1 exhibits stronger N–H bending and C–N stretching absorption bands at 1500–1300 cm^{-1} , which progressively decrease as the silica content increases. Conversely, the broad and strong region at 1,000–1,212 cm^{-1} , which is indicative of Si–O–Si asymmetric stretching, is dominant in the UCS3 and UCS5 spectra, indicating a higher silica contribution but is relatively weak in UCS1. Stronger peaks can be seen in the

heavily coated samples at 950 cm^{-1} (Si–OH), 800–700 cm^{-1} (Si–O–Si symmetric stretching), and 470 cm^{-1} (Si–O bending) (Dere et al., 2025). Overall, UCS1 presents a balanced spectral profile where the urea-related bands (N–H, C=O, and C–N) are still sharp and intense, whereas silica signals are present but not excessive, suggesting that the stability of the silica coating is sufficient to increase without masking the nutrient core, thereby making UCS1 the most favorable material compared with UCS3 and UCS5.

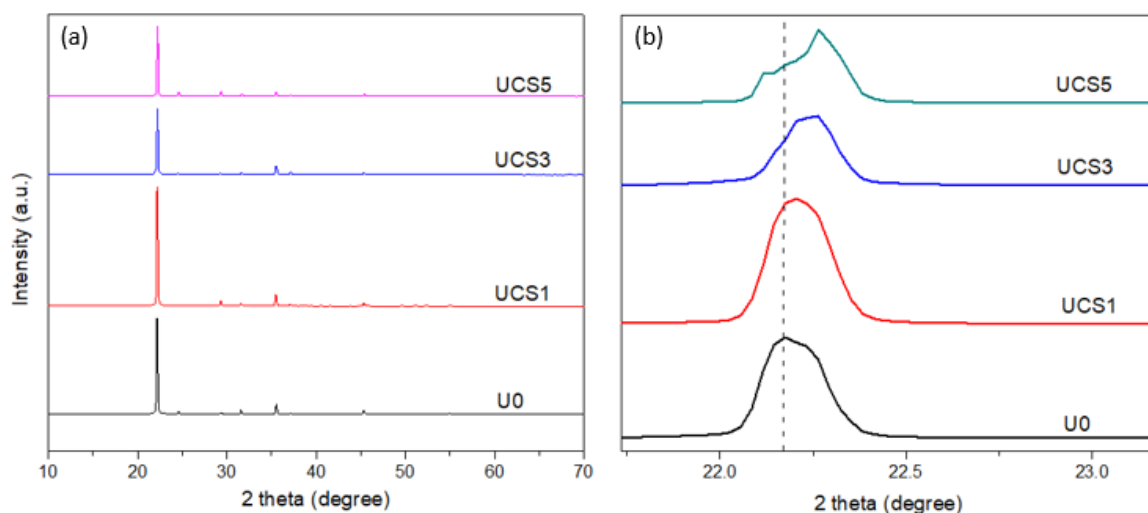


Figure 6 (a) XRD pattern with (b) a certain magnified view of UCS samples.

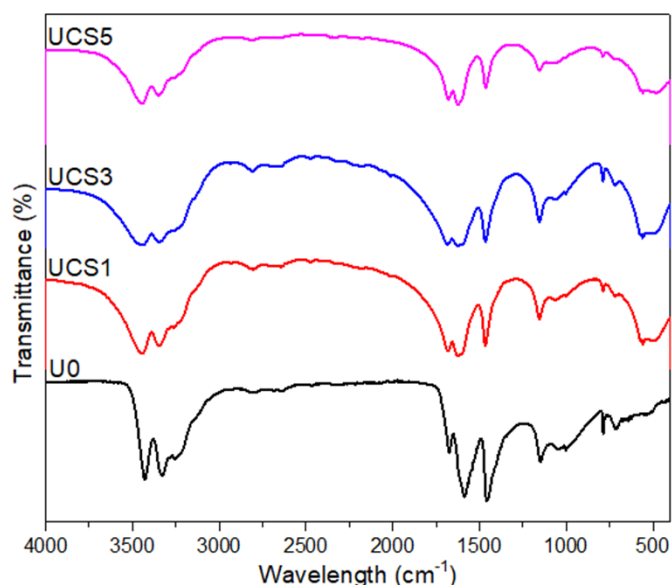


Figure 7 FTIR spectra of UCS samples.

2) Salt resistance experiments at the laboratory scale

The TDS content decreased consistently across all the treatments (UCS1, UCS3, and UCS5) throughout the 30-day growth period, but the extent of the reduction varied among the formulations (Figure 8). UCS1 demonstrated the most stable and sustained decrease, from 0.5368% on day 3 to 0.3216% on day 30, indicating a strong capacity to regulate salinity over time. UCS3 also showed a downward trend (0.5671% to 0.3371%), although the reduction was less pronounced,

suggesting a weaker ion-trapping efficiency than UCS1. Interestingly, UCS5 achieved the lowest final salt content (0.3014%), with a relatively rapid decline during the early stages, but such behavior may imply faster nutrient release and reduced long-term stability. These differences can be explained by the surface chemistry of the urea–silica composites: as reported, Na^+ ions can be immobilized on hydroxylated silica surfaces via coadsorption with water molecules (Wang et al., 2020), while other authors highlighted the controlled nitrogen release capability of silica-based carriers (Lawrencina et al., 2021; Shen et al., 2019). Together, these findings indicate that UCS1 provides the most balanced performance, combining effective salinity reduction with sustained nutrient management, making it the most promising candidate for saline soil applications.

Initial laboratory-scale salinity test results revealed that urea-based salinity-resistant fertilizer can reduce soil salinity specifically (Figure 8). After 30 days, the soil salinity decreased from 0.40 to 0.21 wt%, and the soil pH decreased progressively from 6.10 (0.1 g kg^{-1} of saline soil) to 5.24 (0.125 g kg^{-1} of saline soil) and 4.73 (0.150 g kg^{-1} of saline soil). After 30 days, the soil salinity decreased from 0.65 to 0.39 wt%, and the soil pH decreased progressively from 6.24 (0.10 g kg^{-1} of saline soil) to 5.45 (0.15 g kg^{-1} of saline soil) and 4.97 (0.10 g kg^{-1} of saline soil).

The test results in Table 2 show that the product has a clear anti-salinity effect on saline soil from 1.0 wt% to

0.39 wt%, and the soil pH decreased from 6.24 to 4.97. The results of evaluating the content of silicon and OM (total organic N) in the soil before and after the anti-salinity fertilizer was applied on a urea basis are shown in Table 2.

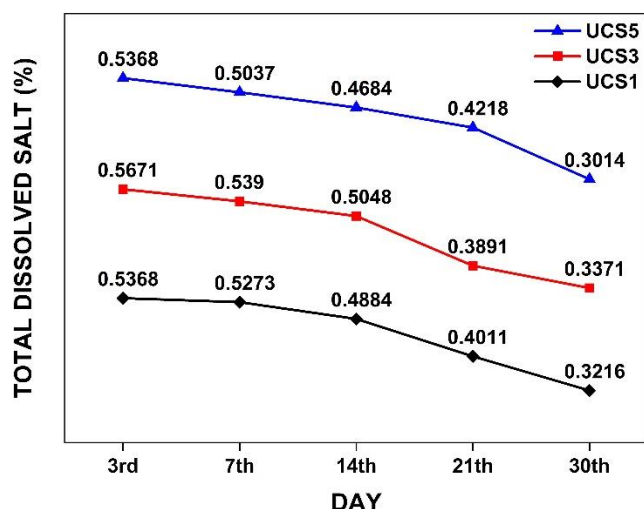
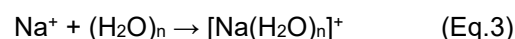


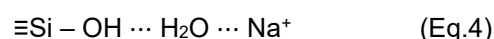
Figure 8 Comparison chart of the effects of UCS1, UCS3 and UCS5 on TDS in soil sample M1.

The test results in Table 3 show that the Si and organic N indices both increased by >15%.

It is possible that the salt-resistant fertilizer silanol group absorbs Na^+ through the H_2O bridge, preventing plants from absorbing Na^+ from the environment, which explains why the soil salinity gradually decreases after it is used (Lunevich et al., 2016; Newton et al., 2016; Rimsza et al., 2018). The hydroxylated silica surface contains abundant silanol groups ($\equiv\text{Si}-\text{OH}$), which participate in ion exchange and hydrogen bonding with water. When Na^+ ions are present in saline soils, they are first hydrated (Eq. 3).



The hydrated Na^+ complex interacts with the silica surface through hydrogen bridges between water molecules and silanol groups (Eq. 4).



This process, known as outer-sphere adsorption, keeps Na^+ at a distance from the root zone, thereby reducing ionic stress. Additionally, ion-exchange reactions may occur (Eqs. 5–6).

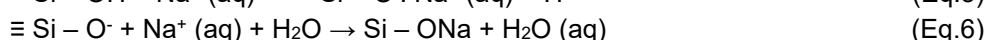
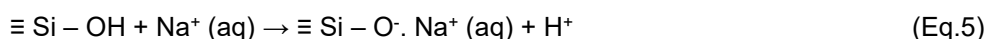


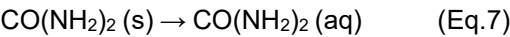
Table 1 Soil salinity and pH in the urea-based salinity-tolerant fertilizer application trial

Samples	Ratio of salt-resistant fertilizer per 1 kg of saline soil	Initial salinity (wt%)	Initial pH_{KCl}	Salinity after 14 days (wt%)	pH_{KCl} after 14 days	Salinity after 30 days (wt%)	pH_{KCl} after 30 days
M1	0.100	0.5	6.10	0.47	5.61	0.40	5.24
M2	0.100	1.0	6.24	0.96	5.79	0.65	5.45
M3	0.125	0.5	6.11	0.41	5.47	0.35	5.16
M4	0.125	1.0	6.24	0.79	5.61	0.45	5.28
M5	0.150	0.5	6.10	0.37	5.31	0.21	4.73
M6	0.150	1.0	6.25	0.78	5.45	0.39	4.97

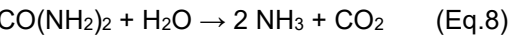
Table 2 Concentrations of Si and OM-organic matter (total N) in soil before and after the addition of salinity-resistant fertilizer based on urea

Evaluation criteria	Sand (%)	Limon (%)	Clay (%)	OM (%)	Si (mg kg^{-1})
Initial M1	27.82	22.98	49.2	0.96	<45
M1 after fertilizing				2.46	53.46
Initial M2				0.96	<45
M2 after fertilizing				2.50	53.47
Initial M3				0.96	<45
M3 after fertilizing				3.08	58.81
Initial M4				0.96	<45
M4 after fertilizing				3.12	58.82
Initial M5				0.96	<45
M5 after fertilizing				3.70	70.57
Initial M6				0.96	<45
M6 after fertilizing				3.74	70.58

Moreover, when urea is coated with a silica layer, the coating acts as a diffusion barrier, controlling the dissolution rate (Eq. 7).



Ammonia is then converted into NH₄⁺ in soil solution (Eq. 8), ensuring a prolonged nitrogen supply while reducing losses through volatilization and leaching.



Together, these mechanisms allow urea–silica composites to simultaneously mitigate salt stress by adsorbing Na⁺ and to provide controlled nutrient release, leading to enhanced growth and survival under saline conditions.

3) Simulation of rice cultivation on a laboratory scale

The experimental results revealed clear differences in plant performance between UCS1–nanosilica–coated urea (M1–M6) and U0–pure urea (N1–N6) under saline conditions (Tables 4 and 5). With respect to UCS1, the plants maintained stronger growth, reaching 42–44 cm after 30 days. The best treatments, M5 and M6, preserved up to 9 living plants. They also maintained relatively low salt accumulation, ranging from 0.1909% to 0.3719%. In contrast, the urea-only controls performed much worse. In some treatments, such as N1 and N3, similar plant heights of 30 cm were reached at 30 days. However, survival decreased sharply, with only 1–4 plants remaining alive. In N5 and N6, all the plants perished by day 30. The total dissolved salt concentration in the control group

also remained high, with values reaching 0.8973%. These findings indicated the ineffective regulation of salt stress. Overall, the urea–silica formulations clearly outperformed conventional urea. They supported better plant growth, reduced salt accumulation, and improved survival rates, as observed in the captured images (Figures 9 and 10). These findings highlight their potential as an effective fertilizer strategy for rice cultivation in saline soils.

Assessment of the appearance of rice plants cultivated in saline soil conditions revealed notable differences between those treated with ordinary urea (N1–N6) and those treated with nanosilica-coated urea fertilizers (M1–M6) (Figure 10). The plants treated with ordinary urea (N1–N6) presented diminished and abbreviated root systems with restricted lateral branching, indicating that salt stress significantly inhibited root growth and cellular proliferation. Conversely, plants treated with nanosilica-coated urea UCS (M1–M6) presented more vigorous root systems, marked by increased branching, fiber density, and structural integrity. These morphological enhancements demonstrate that the nanosilica coating efficiently alleviated salt-induced stress by facilitating root elongation and fortifying the overall root structure, thereby increasing the water and nutrient absorption efficiency. Compared with plants in the standard urea treatment group, those in the UCS treatment group exhibited increased root growth and overall vitality. These data collectively provide compelling evidence that nanosilica-coated urea improves the robustness and adaptive performance of rice grown under saline conditions.

Table 3 The growth of the plants and TDS (%) in soil before and after the addition of salinity-resistant fertilizer based on urea were observed

Samples	14 days			30 days		
	Plant height (cm)	TDS (%)	Survival ratio (%)	Plant height (cm)	TDS (%)	Survival (%)
M1	18.4 ± 1.80	0.4578	90%	43.0 ± 0.60	0.3816	40%
M2	15.7 ± 1.80	0.7851	80%	37.0 ± 1.70	0.5563	20%
M3	15.8 ± 2.20	0.3972	90%	42.0 ± 0.90	0.2988	60%
M4	14.85 ± 2.90	0.8675	100%	44.0 ± 1.00	0.7137	70%
M5	17.2 ± 1.20	0.3457	100%	42.9 ± 1.90	0.1909	90%
M6	14.3 ± 2.50	0.6743	100%	42.0 ± 1.00	0.3719	90%

Table 4 The growth of the plants and TDS (%) in the soil before and after the addition of pure urea (U0) were observed

Samples	14 days			30 days		
	Plant height (cm)	TDS (%)	Survival ratio (%)	Plant height (cm)	TDS (%)	Survival (%)
N1	13.16 ± 0.85	0.4601	80%	30.0 ± 2.00	0.4087	10%
N2	12.25 ± 0.87	0.8972	60%	27.0 ± 3.00	0.8074	20%
N3	14.70 ± 0.38	0.5258	90%	30.0 ± 3.16	0.4780	40%
N4	12.85 ± 1.00	0.8794	80%	20.0 ± 3.00	0.8076	30%
N5	14.00 ± 1.00	0.4498	90%	0	0.4215	0
N6	12.10 ± 1.12	0.9907	70%	0	0.8973	0



Figure 9 Pictures of (a, b) plants in M1–M6 and (c, d) plants in N1–N6 after 30 days.

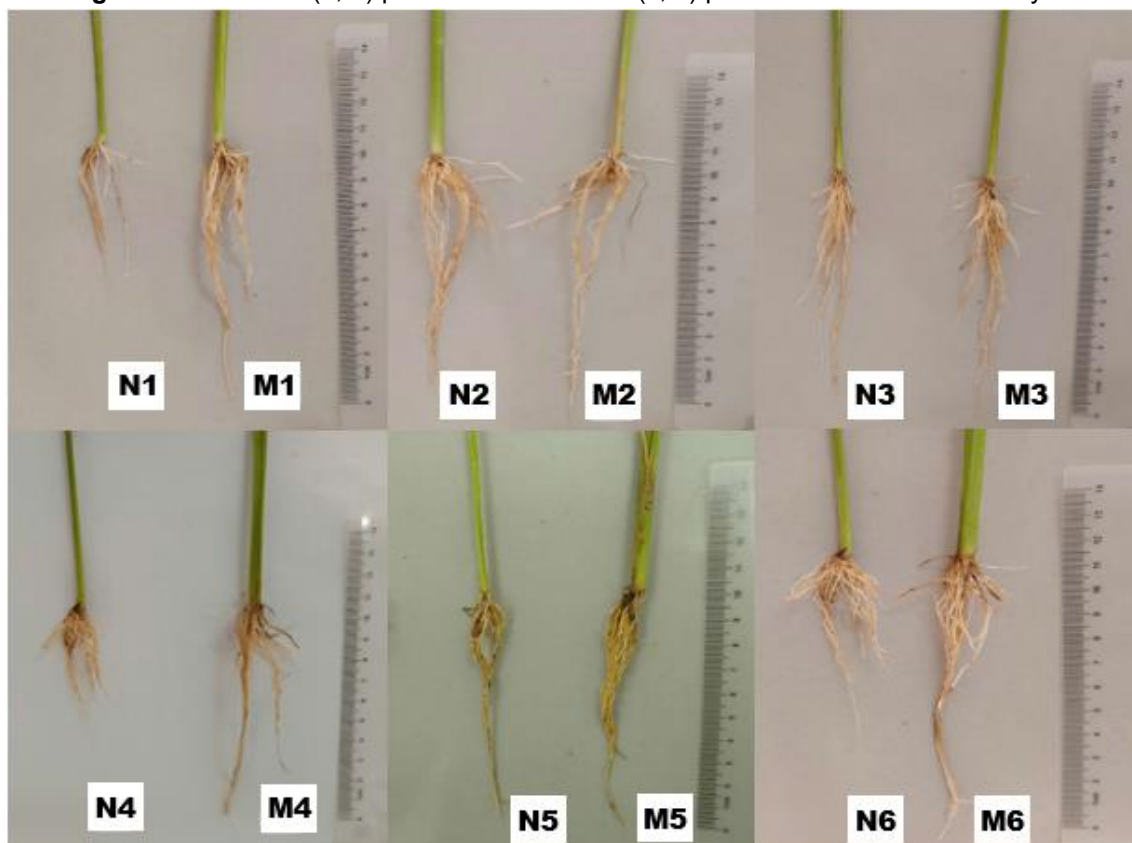


Figure 10 Images of root plants in M1–M6 and in N1–N6.

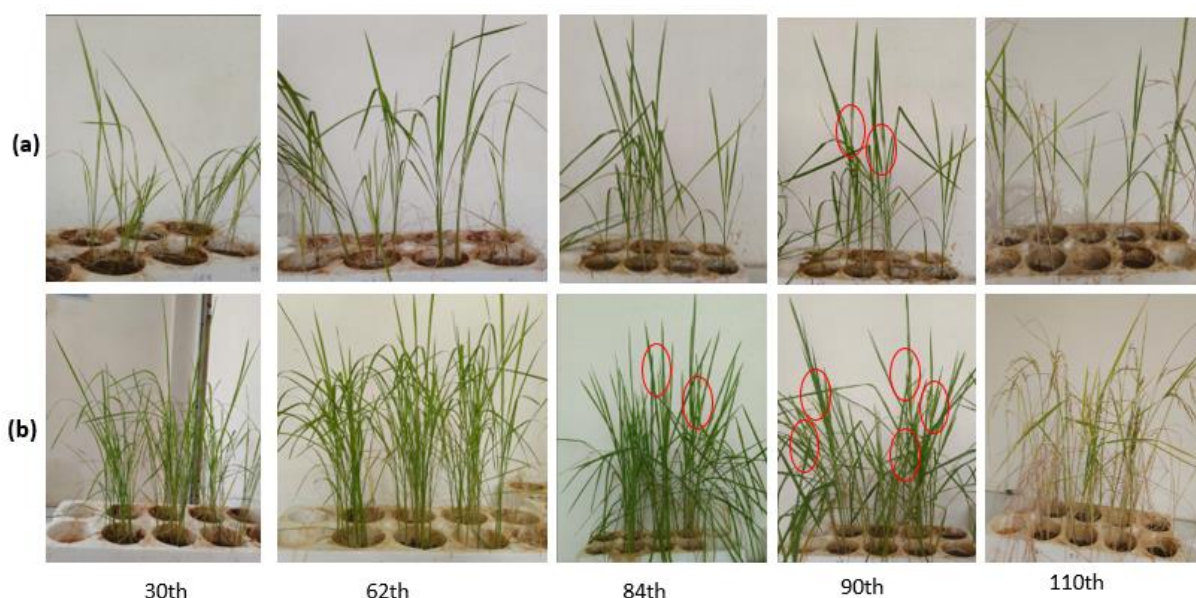


Figure 11 Pictures of the growth stage of rice plants on saline soil: (a) urea (b) UCS1.

Compared with those treated with regular urea at the same salt levels, the main roots and total root lengths of the rice plants treated with UCS were significantly longer, and more side roots were present. The best results were observed with a nanosilica-coated urea concentration of 0.125 g kg^{-1} . The greatest improvement was observed with 0.125 g kg^{-1} UCS, indicating that this amount of silica coating is best for helping roots grow longer and branch out more when facing salt conditions. Excessive silica loading (0.15 g kg^{-1}) resulted in marginal reductions in root density, indicating a saturation effect. These results show that UCS helps reduce the negative effects of salt on roots by encouraging a larger and more flexible root system.

Conclusions

In this study, nanosilica-coated urea fertilizers were synthesized using a simple coating method. Material characterization confirmed that nanosilica formed an effective protective layer around urea, enhancing thermal stability and modifying dissolution behavior. Laboratory experiments demonstrated that UCS formulations reduced soil salinity by up to 40% and increased silicon and organic nitrogen contents by more than 15%. Among the treatments, UCS1 provided the most balanced performance, combining effective salinity reduction, improved nutrient retention, and enhanced plant survival. Compared with conventional urea, UCS fertilizers promoted greater rice growth (124%) and resilience under saline stress. These results highlight the potential of nanosilica-coated urea as a promising strategy for sustainable rice production in salinity-affected regions.

Acknowledgements

This study was supported by the Vietnam Academy of Science and Technology under grant number UDPTCN.08/25-27.

Data availability statement

Information and data used in the study will be disclosed upon request.

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Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

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