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Enhancing Nitrogen Use Efficiency, Growth, and Biomass Yield of Pak Choy on Coastal Entisols with a Combination of Reduced Nitrogen Fertilizer and Zeolite-Based Slow-Release Fertilizer

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ABSTRACT

Coastal sandy soil has a low capacity to hold water and nutrients, trigerring high doses of fertilizer application. Therefore, this study aims to determine the optimal mixture of urea and zeolite-based slow-release fertilizers (SRF) that can reduce application of inorganic fertilizer while improving nitrogen use efficiency (NUE), growth dynamics, and yield of pak choy cultivated on coastal Entisols. This research was conducted from October to December 2023 in the Plant and Soil Research field on the outskirts of the Bengkulu University campus. The treatments used were a combination of urea and SRF, consisting of 0% N-urea, 100% N-urea, 75% N-urea + 25% N-SRF, 50% N-urea + 50% N-SRF, 25% N-urea + 75% N-SRF, and 100% N-SRF. The study was set up in a completely randomized design with five replications. The results demonstrated that the treatments enhanced the growth and biomass yield of pak choy, as well as NUE. The combination of 50% N-urea + 50% N-SRF (equal to 200 kg urea ha^{-1} + 608.5 kg SRF ha^{-1}) resulted in higher leaf area, fresh shoot weight, dry shoot weight, fresh plant weight, N- uptake, and NUE compared with the application of 100% N-urea (400 kg urea ha^{-1}). The NUE for the combination of 50% N-urea + 50% N-SRF was 36.36%, which was 13.63% compared to 100% N-urea with an NUE of 34.09%. Therefore, using this SRF allows for a reduction in urea requirements by up to 50%.NUE and nitrogen uptake show a very high positive association ($r=0.941$, $p<0.01$).

INTRODUCTION

Pak choy cultivation is practiced in Bengkulu, among other things, on sandy saline land in the coastal areas. According to Costa et al. (2019), sandy soils have distinctive characteristics including low soil fertility, low water retention, and moderate to high soil salinity. Low water retention coupled with high rainfall (which is common in Bengkulu) can lead to high nitrogen (N) losses through leaching. According to Vlek and Byrnes (1986), in passive soils it is estimated that about 80-84% of urea is lost to the environment. This loss of fertilizer that is not absorbed by plants can have a negative impact on the environment, such as algal blooms in lakes and rivers, mainly caused by fertilizer runoff (Paerl et al., 2020).

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Due to these high N losses, N fertilizers are applied at much higher doses than recommended doses in an effort to ensure high yields. For instance, a recent study conducted on sandy soils reported that fertilisation from 178 to 255 kg ha-1 N increased cabbage yield (Barrett et al., 2018). This higher dose of N fertilizer is unavoidable because, for cabbages, including pak choy (*Brassica rapa* L.) and other leafy vegetables, N is the main macro-nutrient most needed for plant growth and development, especially leaves (Yousaf et al., 2021). However, this practice is unsustainable, and alternative solutions are needed.

Slow-release fertilizer (SRF) has been recognized as an appropriate solution to solve the main coastal sandy soil problems, which are high nutrient (including N) loss and low water retention which makes cultivated plants vulnerable to water stress (Wang et al., 2019). SRF can not only reduce N loss but also ensure a stable N supply for crops as stated by Ye et al. (2020). However, there are some studies in which SRF application provided less or no benefit than other forms of fertilizer in reducing nitrogen leaching and improving nitrogen use efficiency (NUE) in all types of soils. For example, Shuman et al. (2023) demonstrated the efficacy of SRF in minimizing nitrogen loss in various soil environments. However, a more recent study by Li et al. (2021a) indicated that the effectiveness of SRFs may be limited in saline sandy soils, mainly due to their low water retention capacity, which increases water stress in plants.

Additionally, saline sandy soils not only offer common challenges such as high N loss but also low water retention and high salt stress, which have significant impacts on crop growth and yield (Wang et al., 2019). Although SRF is designed to gradually release nutrients, its ability to enhance water retention and alleviating salinity stress is still unclear, especially in coastal sandy soils. Several reports, such as that by de Holanda et al (2023), explain that SRF can increase soil water content, but there is no agreement on its ability to significantly increase water retention in highly permeable sandy soils.

Furthermore, there is still a considerable gap in the literature regarding the integration of materials such as zeolite into SRFs to simultaneously address N loss and water retention. Zeolite, known for its high cation exchange capacity (CEC) and water holding capacity, has the potential to enhance the effectiveness of SRF in saline sandy soils. A recent study by Soltys et al. (2020) has shown positive results for the use of zeolite to reduce salinity stress and enhance nutrient retention. The application of zeolite-based SRF in coastal saline soils has not been thoroughly studied, especially in the context of pak choy cultivation. Extensive research has shown that while SRF and zeolite individually provide benefits, their combined application for the formulation of slow-release fertilizers applied in marginal environments such as saline sandy soils, remains under-researched. This gap reinforces the need for research exploring the synergistic effects of SRF and zeolite on enhancing nitrogen use efficiency (NUE), improving soil water retention, and reducing salinity stress in crops such as pak choy.

Zeolite, which is a mineral rock composed mainly of aluminum silicate compounds and other metal ions such as K, Mg, Ca, and Fe, can be used as a material to make SRFs that have both characteristics. The manufacture of SRF can be performed by the batch impregnation method (Purnomo and Saputra, 2021). Zeolites can fulfill both SRF characteristics for the following reasons. First, zeolites have pores and a cation exchange capacity (CEC) so that ammonium (NH_4^+) and nitrate (NO_3^-) resulting from urea hydrolysis are strongly bound within its pores (Soltys et al., 2020). In addition, with a high CEC, zeolite's exchange capacity for Na^+ cations found in saline soils and toxic to pak choy plants is high, so it can significantly reduce salinity stress. The results of research by Romadhan et al. (2022) showed that amelioration of saline soil with inactivated natural zeolite clinoptilolite by as much as 0.06 kg/m^2 can reduce soil salinity levels and increase pak choy growth and yield. Second, zeolite has a high surface area and porosity, so its water-holding capacity is also high (Lateef et al., 2016).

The surface area, CEC, and pores of zeolite can be increased even further through thermal activation into activated zeolite (Pich et al., 2010). By using activated zeolite in the production of SRF, it is expected that (1) the absorption and binding capacity of zeolite to ammonium (NH_4^+) and nitrate (NO_3^-) resulting from urea hydrolysis will be much higher, so that N losses are expected to be smaller, and (2) the water retention ability will also be higher. The effectiveness of slow-release fertilizer was tested by Geng et al. (2016) on cotton and the results showed that SRF application can increase cotton yield and reduce the amount of N dose required by 30%, increase soil N content by 16% (Cordeiro et al., 2022) and can reduce leaching of inorganic N fertilizer (Lawrencia et al., 2021).

Despite having low fertility and other disadvantages (Costa et al., 2019), coastal sandy soil has the potential to be developed as agricultural land, including for the expansion of pak choy planting areas because this plant can grow on light textured soils such as sand (Sindesi et al., 2021). In addition, potentially saline land in Indonesia is quite extensive, approximately ± 27.4 million ha, consisting of tidal and coastal plains, dry climate drylands, and tidal swamps (BBSDLP, 2012). The tidal and coastal plains reaches 12.020 million ha or 6.20% of the total land in Indonesia (Karolinoerita and Annisa, 2020). This area is widespread throughout Indonesia, including Bengkulu province, which has a coastline of 525 km.

Pak choy was chosen as the test crop in this study because (1) the cultivation of cabbage on sandy soil with high yields requires very high N fertilization between 178 and 255 kg ha^{-1} N (Barrett et al., 2018) and (2) pak choy is classified as an export commodity for Japan, Malaysia, Taiwan, Singapore' United Arab Emirates. According to the Central Bureau of Statistics and the Directorate General of Horticulture 2019, the export volume reached 24,600 tons in 2018. In addition, this plant is sensitive to salinity stress, so it will experience significant damage when grown in salt-affected soil (Shannon and Grieve, 1998). Salinity stress in Brassica species reduces growth and yield by up to 60% (Ashraf and McNeilly, 2004). Therefore, it is necessary to use new innovative N fertilizers that can provide N nutrients according to the needs of pak choy plants and prevent pak choy plants from water and Na^+ salt stress cultivated in sandy saline land. The use of activated zeolite-based slow-release fertilizer is an alternative solution. This study aimed to determine the optimal mixture of urea and zeolite-based slow-release fertilizers that can reduce the use of inorganic N fertilizer while improving nitrogen use efficiency, growth dynamics, and biomass yield of pak choy cultivated on coastal Entisols.

MATERIALS AND METHOD

Experimental Site and Treatment

This research was carried out from October to December 2023 in a plastic house in the Plant and Soil Research field located on the outskirts of the Bengkulu University campus with an altitude of ± 10 m above sea level.

This study used a completely randomized design (CRD) involving six treatments and each of them was replicated five times. The

Table 1. The combined application of urea fertilizer (U) and activated zeolite-based slow-release fertilizer (SRF) at different proportions as treatments in the study.

Treatment		Fertilizer application			
Code	Proportion	g $polybag^{-1}$		kg ha^{-1}	
		urea	SRF	urea	SRF
B0	No fertilizer	0.00	0.00	0.00	0.00
B1	100% N-urea	0.95	0.00	400	0.00
B2	75% N-urea + 25% N-SRF	0.71	0.72	300	304.25
B3	50% N-urea + 50% N-SRF	0.48	1.40	200	608.50
B4	25% N-urea +75% N-SRF	0.24	2.20	100	912.75
B5	100% N-SRF	0.00	2.90	0.00	1217.00

Note: Electrical Conductivity (EC), Cation Exchange Capacity (CEC), not determined (nd) treatments combined urea fertilizer (U) and activated zeolite based slow- release fertilizer (SRF) at different proportions (Table 1). The combination was made based on a dose of 184 kg N ha^{-1} (Barrett et al., 2018). SRF has an N content of 15.12%. The amounts of urea and SRF used per polybag or per hectare was made accordingly. The fertilizer doses applied are presented in Table 1.

The six treatments were repeated 5 times to obtain 30 experimental units. Each experimental unit contained 3 polybags, giving a total of 90 polybags. Fertilizers were applied at a dose of 184 kg ha^{-1} N or 400 kg urea ha^{-1} as recommended by Barrett et al. (2018) or equal to 1217 kg SRF ha^{-1}, 89.8 kg P_2O_5 ha^{-1}, and 121 kg K_2O ha^{-1}, Slow-release fertilizer (SRF) prepared for this study had an N content of 15.12%.

Soil and SRF Analysis

Soil samples were collected from the coastal area in Bengkulu City in a zigzag method. These samples were mixed, dried, crushed, and sorted to produce one kilogram of samples. Subsequently, the samples were tested for base saturation (BS), phosphorus (P), potassium (K), accessible nitrogen (N), cation exchange capacity (CEC), electrical conductivity (EC), and aluminum saturation (Al saturation). A variety of standard laboratory techniques described in Balai Penelitian Tanah (2009) were employed to assess the chemical properties of soil.

A sample of SRF was also analyzed for its chemical characteristics, such as total-N. The Soil Analysis Handbook of Reference Methods published by Balai Penelitian Tanah (2009) provides common protocols for recording the SRF chemical characteristics.

Activated Zeolite-based SRF Preparation

Zeolite activation was carried out following the method (Pich et al., 2010) through various stages: (1) zeolite was filtered first with a filter size of 1 mm to remove impurities, (2) filtered zeolite was put into a furnace with a temperature of 250^0C for one hour, (3) after cooling, zeolite was powdered with a food kitchen blender. The powdery zeolite was then used to prepare SRF using a modified hydrothermal batch impregnation method (Catli et al., 2020).

Field Management

The planting media was made from a mixture of soil and compost in a ratio of 1:1. Seeding using trays with seed varieties of Nauli F1 pak choy. The sown seeds were watered daily until they were ready to transplant at 14 days of age. The soil used for planting was coastal sandy soil. The soil weighing 5 kg was filled in polybags with a size of 40 cm x 25 cm, manure was also added into the media in a ratio of 4:1 (v: v). Then, each polybag was set to a distance of 30 cm x 30 cm in the plastic house.

Urea fertilizer was given twice, one day before planting for the first application and the rest was given when the plants were at age of 14 days after transplanting (DAT). SRF was administered once on one day before transplanting together with half dose of urea, SP-36, and KCl. Fertilizers were applied at 84.0 kg N ha^{-1} for urea, 89.8 kg P_2O_5 ha^{-1} for SP-36, dan 121.0 kg K_2O ha^{-1} for KCl. The application was performed by perforating the planting media around the roots (± 7cm in depth) of the plants.

Table 2. Soil, zeolite, and slow-release fertilizer (SRF) characteristics used in this study

Treatment		Fertilizer application			
Code	Proportion	g $polybag^{-1}$		kg ha^{-1}	
		urea	SRF	urea	SRF
B0	No fertilizer	0.00	0.00	0.00	0.00
B1	100% N-urea	0.95	0.00	400	0.00
B2	75% N-urea + 25% N-SRF	0.71	0.72	300	304.25
B3	50% N-urea + 50% N-SRF	0.48	1.40	200	608.50
B4	25% N-urea +75% N-SRF	0.24	2.20	100	912.75
B5	100% N-SRF	0.00	2.90	0.00	1217.00

Note: Electrical Conductivity (EC), Cation Exchange Capacity (CEC), not determined (nd)

The 14-day-old seedlings were transferred carefully into the polybags at a 4 cm deep. Before transplanting, the planting medium was watered to facilitate the planting process. Watering was performed every morning and evening using a watering can to maintain soil moisture at a field capacity. Replanting was performed at 7 DAT by replacing abnormal plants. Weed control was performed manually by pulling them out directly. To manage diseases and pests, 500 g L^{-1} of insecticides, including profenofos, were administered in addition to 3% carbofuran.

Harvesting was performed at 30 DAT when the bottom leaves began to turn yellow, whereas the leaves on top were bright green. Harvesting was performed by cutting the base of the stem on the plant so that it only leaves the roots in the polybag.

Data Collection and Analysis

Plant growth parameters, consisting of plant height, leaf number, leaf area, leaf greenness, root dry weight, and shoot dry weight, as well as biomass yield attributes, including shoot fresh and plant weight, were observed in order to gather the data. Using standard protocols described by Cornelissen et al. (2003) with a minor modification, all plant growth and biomass yield measurements were carried out on five randomly selected plant samples. Such medication was applied to measure leaf greenness level, which was done when the plants were 14 DAT using SPAD meter. The measurement was performed on selected leaves that had opened completely on the lower, middle, and upper parts. The N content in leaf tissue, N-uptake, and NUE were also measured according to the procedures described by Weih et al. (2018). NUE was calculated using the following formula:

The collected data were analyzed using analysis of variance (ANOVA) with F test at 5% level to determine the effect of the treatments using IBM SPSS version 21.0 for Windows. If there was a significant difference from the treatment, further test (the LSD) was

$$NUE = \frac{Uf - Uo}{Na} \times 100$$

where:
U_f: nitrogen uptake in the fertilized plot (kg ha^{-1})
U_0: nitrogen uptake in the unfertilized control plot (kg ha^{-1})
Na: amount of nitrogen applied (kg ha^{-1})

conducted at the 5% level. Pearson correlation analysis was conducted using JASP (0.19.0) software.

RESULTS AND DISCUSSION

Based on the soil characteristics shown in Table 2, the study area used in this experiment was not ideal for the optimal mustard growth and yield. The low organic matter, coupled with very low nitrogen, insufficient phosphorus and potassium, sandy texture, and medium salinity creates a suboptimal environment for mustard cultivation. These factors indicate that without the application of slow- release fertilizer made from zeolite and bentonite as soil amendments, the growth and yield of mustard greens on this land will most likely be disrupted. Consequently, emphasizing this experiment on improving nutrient use efficiency and growth dynamics is well suited to overcome these soil limitations.

The growth and yield potential of pak choy may be restricted by specific soil features. The fertility and structure of the soil used in this study, as well as water and nutrient retention by adding zeolite-based SRF. Zeolite as a matrix for SRF has high CEC and porosity, which are important for retaining nutrients (especially N from urea) and water. SRF is rich in nutrients, particularly nitrates (N). These characteristics make SRF an excellent amendment for improving the overall productivity of agricultural soils, particularly those used to grow pak choy.

For plant growth measured by plant height and number of leaves, the values of these two variables increased significantly from 7 DAT to 21 DAT (Table 3). The increase in plant height each week was consistent at 5 cm, as well as the number of leaves, which increased by 5 leaves per week, except without fertilizer (B0). However, in the 21 DAT, the average plant height was comparable to that reported by Romadhan et al. (2022), but did not match the description of the variety which should be

Table 3. Effect of a combination of urea fertilizer and slow release fertilizer with activated zeolite matrix on the growth of pak choy

Soil characteristics	Value	Criteria	Characteristics	Zeolite	SRF
C-organic (%)	0.24	low	pH H2O (1:5)	6.48	
Total-N (%)	0.07	Very low	pH KCl (1:5)	5.24	
P-available (ppm)	2.7	low	CEC (cmol.kg-1)	110.57	
$K_{exchangeable}$ (cmol (+) kg^{-1})	0.17	low	N-Total (%)	nd	15.12
$Ca_{exchangeable}$ (cmol (+) kg^{-1})	0.35	low	$K_{exchangeable}$ (cmol (+) kg^{-1})	20.11	
$Mg_{exchangeable}$ (cmol (+) kg^{-1})	0.22	Very low			
pH (H_20 1 :2.5)	7.8	basic			
EC (dSm^{-1})	5.02	medium			
$Al_{exchangeable}$ (cmol (+) kg^{-1})	1.43	Very low			
Texture 3 fractions		sandy			
Sand (%)	92.70				
Clay (%)	4.23				
Dust (%)	3.07				

Note: Numbers in the same column followed by the same lowercase letter mean not significantly different at the 5% LSD test

25 cm - 28 cm. In this study, the plant height ranged from 21 cm - 23 cm. The possible cause for the different results was the contrasting growing conditions in this study and in the description.

At 21 DAT, the average plant heights for treatments B1 (100% N-urea), B2 (75% N-urea + 25% N-SRF), B3 (50% N-urea + 50% N-SRF), B4 (25% N-urea + 75% N-SRF), and B5 (100% N-SRF) were higher than those of the plants that were not fertilized (B0) (Table 3). Treatments B1, B2, B3, B4, and B5 resulted in plant heights comparable to the recommended 100% urea dose (B1). These results indicate that both urea and SRF fertilizers provide comparable levels of nutrient availability and absorption efficiency in saline sandy soil conditions.

The similar pattern was also followed in the number of leaves, where treatments B1 to B5 produced more leaves compared to the treatment without fertilizer (B0). This indicates that both fertilizer types are effective in increasing plant height and leaf number in pak choy. The nutrient release profile of SRF using active zeolite matrix may be similar to standard urea, resulting in comparable results. The findings in this study are consistent with studies on the effectiveness of SRF reported by Smith et al. (2020). They found that SRF were as effective as conventional urea fertilizers in promoting lettuce growth. This suggest that the SRF used in this study was potentially applicable for various crops.

Further test results showed that the treatment without fertilizer (B0) produced the lowest leaf area (518.31 cm²), which was statistically significantly different from all fertilizer treatments. This shows that fertilizer application greatly influences the increase in pak choy leaf area. Treatment B1 with 100% N -urea produced a leaf area of 1074.68 cm², significantly higher than B0 but lower than the treatments of B2, B3, B4, and B5. The B2 treatment (75% N-urea + 25% N-SRF) produced a leaf area of 1138.92 cm², which was not significantly different from B1 but lower than treatments B3, B4, and B5. Treatments B3 (50% N-urea + 50% N-SRF), B4 (25% N-urea + 75% N-SRF), and B5 (100% N-SRF) produced almost the same leaf area, at 1419.13 cm², 1415.35 cm², and 1451.21 cm², respectively. These three treatments were not significantly different from each other, but were significantly higher than B0, B1, and B2.

The result of analysis of variance showed that the treatment without fertilizer (B0) produced the lowest SPAD index value (37.97), which was significantly lower than all fertilizer treatments. The B1 treatment (100% N-urea) produced a SPAD index value of 45.41, but was lower than several combinations of Urea and SRF (B3, B4, and B5). Treatment B3 (50% N-urea + 50% N-SRF) produced the highest SPAD index value of 48.46, which was significantly higher than all other treatments. Treatments B4 (25% N-

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urea + 75% N-SRF) and B5 (100% N-SRF) produced similar SPAD index values of 47.14 and 47.22, respectively, significantly higher than B0 and slightly higher than B1 and B2.

Data on root dry weight showed that all treatments involving fertilizer application (B1, B2, B3, B4, and B5) increased pak choy root dry weight higher than the control (B0). The lowest root dry weight average of 0.15 g was produced by treatment B0 (no fertilizer application), indicating that the plants needed nutrient supply for optimal root development. While treatment B1 (100% N-urea) increased the root dry weight to 0.49 g, lower than the combination treatment of Urea and SRF (B2, B3, B4 and B5). Treatments B3 (50% N-urea + 50% N-SRF) and B4 (25% N-urea + 75% N-SRF) showed the same root dry weight of 0.63 g, while B5 (100% N-SRF) showed slightly lower results, but still higher than B0, B1, and B2 (Table 4).

The results of analysis of variance showed that the combination treatment of urea and SRF had a significant effect on shoot dry weight (Table 4). Treatment B3 (50% N-urea + 50% N-SRF) showed the highest result in shoot dry weight. The treatment without fertilizer (B0) produced the lowest shoot dry weight of 4.01 g which was significantly lower than all fertilizer treatments. The B1 treatment with 100% N-urea produced a shoot dry weight of 6.32 g. This result suggests that treatments with higher proportions of SRF (B2, B3, B4, and B5) gave better results than 100% N-urea (B1), indicating that SRF can partially replace urea without reducing plant growth. The significant increase in plant dry weight in the combined treatment of SRF and urea was also reported by Li et al. (2022) and Huang et al. (2022). They said that balanced nutrient availability from SRF was the cause for the increase in dry matter accumulation in various plants.

Similar results were also reported by Banik et al. (2023), who stated that the SRFs (with biochar as a matrix fertilizer) are comparable to and even better than traditional urea in promoting maize growth, and increasing shoot, and root biomass yields. According to Latifah et al. (2017), the sufficient availability of N from urea with the addition of zeolite is a factor in increasing the growth. The ample of N supply from urea-impregnated zeolites is due to the blockage of zeolite pores by urea and causes a reduction in urea exposure to water (Maghsoodi et al., 2020; Schmidt et al., 2017).

The results of ANOVA showed that the combination treatment of urea and SRF had a significant effect on pak coy biomass yield with indicators of shoot fresh and plant fresh weight (Table 4). The treatment without fertilizer (B0) produced the lowest shoot fresh weight and plant fresh weight of 57.42 g and 58.30 g, respectively, which were significantly lower than the other treatments. The B1 treatment with 100% N-urea produced a shoot fresh weight of 133.10 g and a shoot dry weight of 6.32 g, respectively. Treatments with higher proportions of SRF (B2, B3, B4, and B5) gave better results than 100% N-urea (B1), indicating that SRF can partially replace urea without reducing plant growth (Huang et al., 2022).

Table 4. Effect of a combination of urea fertilizer and slow release fertilizer with activated zeolite matrix on biomass yield, N leaf, N uptake, and nitrogen use efficiency (NUE) in pak choy

Treatments		Dry biomass yield		Fresh biomass yield		N leaf (%)	N up-take (g kg^{-1})	NUE (%)
Code	Proportion	Root dry weight (g)	Shoot dry weight (g pot^{-1})	Shoot fresh weight (g pot^{-1})	Plant fresh weight (g pot^{-1})			
B0	No fertilizer	0.15 c	4.01 c	57.42 c	58.30 c	2.15 c	0.09 c	-
B1	100% N-urea	0.49 b	6.32 b	133.10 b	136.80 b	2.77 ab	0.19 b	22.73 c
B2	75% N-urea + 25% N-SRF	0.56 a	7.46 ab	175.85 a	180.18 a	2.97 a	0.24 a	34.09 a
B3	50% N-urea + 50% N-SRF	0.63 a	8.42 a	173.04 a	176.89 a	2.74 ab	0.25 a	36.36 a
B4	25% N-urea + 75% N-SRF	0.63 a	6.80 ab	181.28 a	186.10 a	2.89 a	0.22 ab	29.55 b
B5	100% N-SRF	0.62 a	7.24 ab	193.38 a	197.29 a	2.43 bc	0.19 b	22.73 b

Note: Numbers in the same column followed by the same lowercase letter mean not significantly different at the 5% LSD test

These results indicate that SRF, either alone or in combination with urea, significantly increased pak choy fresh biomass production (Table 4). The prolonged availability of nutrients provided by SRF most likely contributes to sustained plant growth, reducing leaching and volatilization of nutrients, especially in sandy soils (de Campos Bernardi et. al., 2020; Wang et al., 2020). The superiority of SRF treatment in increasing plant fresh weight is in line with studies by Wang et al. (2020), which reported increased biomass production in plants due to the steady release of nutrients from SRF.

Treatment B2 (75% N-urea + 25% N-SRF) showed the highest total nitrogen content, significantly higher than the control (B0) and 100% N-SRF treatment (B5). Combination treatments (B2, B3, B4) generally showed increased nitrogen uptake compared to single applications of urea or SRF. The highest total nitrogen content was observed in the 75% N-urea + 25% N-SRF (B2) treatment at 2.97%, indicating optimal nitrogen uptake and utilization. The control (B0) had the lowest nitrogen content at 2.15%, emphasizing the need for nitrogen supplementation for optimal growth. This finding suggests that combining urea with SRF (B2, B3, B4) improves nitrogen uptake efficiency compared to using urea or SRF alone (Chen et al., 2020). The highest nitrogen content observed in the 75% N-urea + 25% N-SRF (B2) treatment was consistent with the findings from (Chen et al., 2020; Liu et al., 2023), suggesting that combining urea with SRF can improve the efficiency of nitrogen uptake and utilization.

The treatment without fertilizer (B0) showed the lowest plant fresh weight. The treatment with 100% N-SRF (B5) showed the highest yield compared to all other treatments, including B1, B2, B3 and B4. The plant fresh weight in treatment B5 was lower than the weight range in the description (400 - 500 g per plant). Treatment B1 (100% N-urea) showed a higher average plant fresh weight than B0, but was still lower than treatments B2, B3, B4, and B5 (Table 4). This indicates that nitrogen fertilizer application, especially in combination with SRF, greatly affects plant growth.

The highest nitrogen uptake was obtained in treatment B3 (50% N-urea + 50% N-SRF) with a value of 0.25%, followed by B2 (75% N-urea + 25% N-SRF) (0.24%) and B4 (25% N-urea + 75% N-SRF) (0.22%). Treatments B1 (100% N-urea) and B5 (100% N-SRF) showed lower N uptake values (0.19%), although B5 produced the highest fresh weight. This suggests that SRF makes an important contribution in increasing nitrogen availability in the long term, although N uptake efficiency may not always be higher compared to the combination of urea and SRF. The results of plant fresh weight and N uptake are in agreement with the study by Li et al. (2021), which showed that SRF can improve plant growth and N uptake better than urea alone. These results are also consistent with (Wang et al., 2020) who reported that the combination of urea with SRF gave the best results in terms of plant fresh weight.

The highest nitrogen use efficiency (NUE) was obtained in treatment B3 (50% N-urea + 50% N-SRF) with a value of 36.36%, followed by B2 (34.09%) and B4 (29.55%). The 100% N-urea and 100% N-SRF treatments showed lower nitrogen use efficiency (22.73%), although 100% N-SRF gave the highest fresh weight. This indicates that the combination of urea and SRF increased NUE to about 160% (at B3) compared to the use of urea or SRF alone. This finding is in line with previous research (Li et al., 2021a) which showed that the use of SRF can increase NUE by up to 22.2% at similar nitrogen levels, particularly on sandy soils. The finding that treatments with a combination of SRF and urea had higher NUE compared to the use of urea or SRF alone supports the results of (Li et al., 2021b), which showed that SRF can improve NUE by providing nutrients gradually.

SRF have several mechanisms that improve NUE in crops, especially in soils with special characteristics such as coastal passive soils. SRFs are designed to release nitrogen gradually according to crop needs. This process reduces fluctuations in nitrogen levels in the soil and avoids wastage due to leaching. Numerous studies have shown that SRF increases long-term nitrogen availability, which can improve nitrogen use efficiency (Jiang et al., 2019; Huang et al., 2022).

SRF reduces the risk of excessive nitrogen leaching into aquatic systems, which often occurs with conventional water-soluble nitrogen fertilizer applications. With slow release, nitrogen can be taken up more efficient -ly by plants before it is lost from the soil system (Li et al., 2020). SRF ensures nitrogen is continuously and evenly available, which helps plants maximize nitrogen uptake. Several studies have shown that crops receiving SRF show increased nitrogen uptake and better yields compared to crops receiving only conventional nitrogen fertilizer (Chen et al., 2021). With the slow release of nitrogen, SRF reduces the frequency of fertilizer application required, thereby reducing costs and labor.

The results of this study further suggest that slow-release fertilizer can be a viable alternative to conventional nitrogen fertilizer. Nutrient release pattern of these fertilizers matches the nutrient uptake requirements of pak choy, ensuring optimal plant growth and biomass yield. Activated zeolite has a high ability in cation exchange which enables it to absorb and exchange nutrient ions such as ammonium (NH_4^+) from urea. This property increases nitrogen retention in the soil, reduces leaching, and makes nutrients available to plants over a longer period of time. The porous structure of zeolites facilitates the slow and controlled

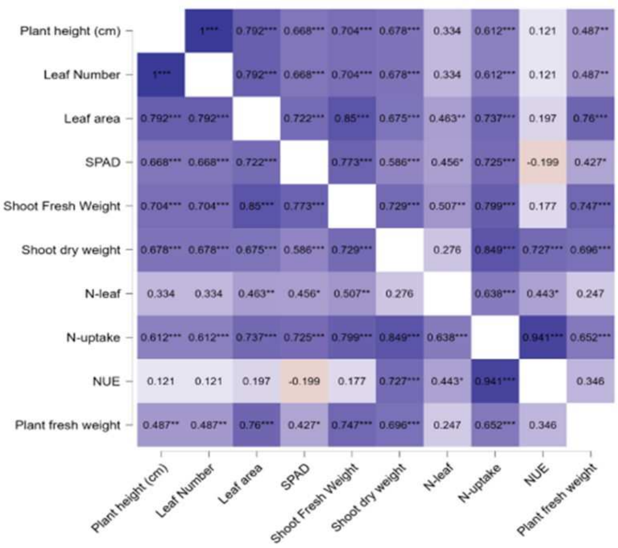

Figure 1. Pearson's correlation matrix of various growth and yield traits in pak choy treated with the combination of reduced urea fertilizer with zeolite-based slow-release fertilizer.

release of urea. Urea intercalated in the zeolite matrix slows down the hydrolysis process and its release into the soil solution, thereby providing nitrogen in a stable manner to plant growth requirements (Li et al., 2021b).

Activated zeolites also improve soil physical properties by increasing water retention and aeration, which contributes to optimal root development and overall plant health. These improvements in soil structure also help maintain soil moisture balance, which is important for consistent nutrient release from fertilizers (Gao et al., 2022). The ability of zeolites to absorb ammonium ions effectively reduces nitrogen loss through soil evaporation and leaching. By retaining more nitrogen in the root zone, zeolite-containing fertilizers increase nitrogen use efficiency and reduce the negative impact of nitrogen fertilizers on the environment (Mahjoor and Ehsan., 2019). Active zeolites play a role in supporting sustainable agricultural practices by reducing the frequency of fertilizer application and reducing the risk of nutrient runoff. Improved nutrient use efficiency also contributes to reducing the overall carbon footprint of agricultural activities (Guo and Zhou., 2023).

Figure 1 shows that the most important association is between NUE and nitrogen uptake, showing a very high positive association ($r=0.941$, $p<0.01$). This suggests that increasing the plant's capacity for efficient nitrogen absorption should be the main goal of efforts to increase NUE. The positive correlations were also observed between NUE with shoot dry weight ($r=0.727$, $p<0.001$) and with leaf N content ($r=0.443$, $p<0.05$), although to a lesser extent. The weak correlations with plant height, leaf number, and SPAD suggest that NUE has relatively small direct effects on these growth characteristics.

CONCLUSIONS

The use of SRF as part of a balanced fertilization strategy increased growth and yield of pak choy and efficiency of nitrogen use. The combination treatment of N-urea and SRF (50% N-urea + 50% N-SRF) produced leaf area, root dry weight, shoot fresh weight, plant fresh weight, and NUE superior to those resulted from urea alone. The other combination treatments were comparable to urea alone on inducing plant height, leaf number, leaf greenness, N-leaf, and N-uptake. By using SRF, the need for urea can be reduced by up to 50% without reducing the growth and yield of pak choy. Increasing the plant's capacity for efficient nitrogen absorption should be the main goal of efforts to increase NUE.

Based on the research results, future studies need to investigate the long-term consequences and its effects on various types of crop to fully understand the potential benefits of using SRF with an activated zeolite matrix.

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