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Encapsulation of NPK in snake fruit peel biochar (*Salacca edulis*) and activated natural zeolite as a slow-release fertilizer for water spinach (*Ipomoea reptans* Poir)

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ABSTRACT

The declining of efficiency of chemical fertilizer and rapid nutrient leaching in tropical soils shows the need for affordable slow-release systems based on agricultural waste and natural minerals. Therefore, this study aims to investigate the use of biochar from snake fruit peel as a slow-release fertilizer (SRF) and evaluate the effectiveness of the combination with activated natural zeolite. The process was carried out by drying the snake fruit peel at 70°C, activating it with HNO_3 for 4 hours, and pyrolyzing it at 200°C for 2 hours. Activated natural zeolite was prepared using NaOH concentrations of 4, 6, and 8 M for 1.5 hours, then characterization was conducted through atomic absorption spectroscopy (AAS), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), gas sorption analysis (GSA), and scanning electron microscopy coupled with energy-dispersive X-ray analysis (SEM-EDX). The results showed that AAS had a potassium content of 7.175 mg g^{-1} in 100 mL and 358.785 mg g^{-1} in 500 mL of snake fruit peel. FTIR analysis showed the presence of O–H and Si–O functional groups, while sharp XRD peaks were consistent with the JCPDS data. GSA characterization identified the optimal zeolite concentration as 6 M, and SEM-EDX confirmed the presence of essential NPK elements. The NPK-Biochar-Zeolite SRF fertilizer was found to contain nitrogen (1786.40 ppm), phosphorus (3151.67 ppm), and potassium (15.06 me%), showing superior potassium retention compared to other nutrients. In terms of plant growth, the NPK-Biochar-Zeolite SRF significantly increased water spinach, locally known as "kangkung" in Indonesian, plant height by 2.2% and leaf width by 0.3% compared to other treatments. These results suggest that biochar from snake fruit peel, in combination with activated zeolite, can enhance fertilizer efficiency and support optimal plant growth for sustainable agricultural practices.

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1. INTRODUCTION

According to FAO projections, the world population is estimated to reach 9.7 billion by 2050. This rapid population growth will significantly increase global food demand. Meanwhile, agriculture remains the main sector supplying food, and a large proportion of production significantly relies on inorganic fertilizer, particularly NPK, to achieve optimal yields (Chen et al., 2025; Wang et al., 2022). However, continuous use of chemical fertilizer may lead to various negative impacts, such as soil acidification, compaction, and structural degradation, which in turn result in nutrient loss and reduced crop yield and quality (Chen et al., 2025). Poor agricultural practices and environmental factors, such as high rainfall, irrigation, erosion, and fertilizer volatilization, also contribute to the leaching of essential nutrients, including nitrogen (N), phosphorus (P), and potassium (K), from the soil, subsequently causing water pollution and increased greenhouse gas emissions (Tahery et al., 2022).

One promising approach is the development of slow-release fertilizer (SRF). In general, SRF is engineered to release nutrients gradually according to crop demand, showing a low nutrient-release rate, which extends soil nutrient availability for plant uptake and reduces leaching or dissipation into the

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environment, ultimately improving fertilization efficiency (Priyadi & Mangiring, 2019; Rafique et al., 2025; Wang et al., 2022). Several types of SRF have been developed, including polymer-based (El-Aziz et al., 2022), biochar-based (Wang et al., 2022), and zeolite-based (Legese et al., 2024) fertilizers. Polymer-based fertilizers, such as polyurethane, polyolefin, and polyvinylidene chloride, can effectively slow nutrient release but are difficult to degrade, may accumulate in the environment, and have relatively high production costs. On the other hand, biochar and zeolite, which are derived from natural and environmentally friendly sources, have been identified as more sustainable alternatives for SRF. These materials also offer significant advantages, including enhanced functional activity and improved performance in promoting soil and nutrient-release processes (Ramesh & Raghavan, 2024).

Biochar, a carbon-based material, offers numerous advantages when used as a soil amendment, including the ability to enhance nitrogen recycling in soil-plant systems. The high surface area, porous structure, and diverse functional groups allow biochar to adsorb various nutrient ions such as ammonium, nitrate, phosphate, and potassium (Rashid et al., 2025). Biochar can also retain and gradually release nutrients, thereby reducing nutrient leaching, lowering fertilizer application frequency, and increasing nutrient use efficiency (Jia et al., 2021). Previous studies have shown that biochar derived from rice husks, empty fruit bunches of oil palm, or other organic materials effectively slows nitrogen loss due to leaching, enhances nutrient retention, and supports plant growth (Dong et al., 2020; Setyawan et al., 2022). Among various feedstocks, snake fruit peel (*Salacca edulis*) shows high potential as biochar due to the high carbon content, large surface area, and good sorption properties (Maneesri et al., 2024). However, a major limitation of biochar-based fertilizer is the insufficient slow-release capability, largely driven by the weak interfacial binding forces that affect nutrient retention on the biochar surface (Dong et al., 2025). To overcome this limitation, composite biochar fertilizers have increasingly been engineered to enhance nutrient stabilization, regulate diffusion pathways, and prolong the availability of nutrients in the soil system (Luo et al., 2021; Ramesh & Raghavan, 2025).

Recent advancements have shown that incorporating mineral phases into biochar matrices can substantially reinforce nutrient adsorption and slow surface desorption kinetics. Among these minerals, zeolite, as a crystalline aluminosilicate mineral, is distinct due to its ion-exchange capacity and uniform microporous channels, which are highly effective for trapping fertilizer ions (Ginting et al., 2025; Sharma et al., 2022). Zeolite also improves soil aeration, enhances soil structure, and promotes root growth by reducing soil compaction. Studies have shown that combining zeolite with biochar or natural polymers slows nitrogen release, improves fertilizer efficiency, and maintains nutrient availability in the soil (Dong et al., 2025; Permana et al., 2023; Suci et al., 2025). For example, (Dong et al., 2025) developed a nanozeolite-coupled biochar-based phosphorus fertilizer (ZEO/BC-PSRF) using a simple disc granulation process with kaolinite as a binder. The controlled-release performance of this fertilizer was evaluated through water release testing, indicating that ZEO/BC-PSRF showed the slowest phosphorus release, with only 29.4% released after 24 h (Dong et al., 2025). The use of coconut shell biochar (matrix) and activated natural zeolite (slow-release agent) in fertilizer successfully increased red onion yields (Permana et al., 2023). However, the potential of snake fruit peel biochar combined with activated natural zeolite in NPK-based fertilizer remains underexplored.

Water spinach (*Ipomoea reptans* Poir) was selected as the test crop due to the high consumption and cultivation popularity in Indonesia, along with a strong nutritional profile, particularly the high vitamin, mineral, and iron content (Peng et al., 2024). The rapid growth and substantial nutrient requirements make it a responsive model for assessing fertilizer efficiency. Due to the short cultivation cycle as a leafy vegetable, brief nutrient deficits quickly influence biomass, chlorophyll levels, and leaf quality, enabling a clear comparison between slow-release and conventional nutrient delivery (Mohd Noor et al., 2022). Additionally, the frequent cultivation near water bodies and role in nutrient-rich environments are directly associated with concerns of nutrient runoff and eutrophication, supporting the relevance for evaluating controlled-release biochar–zeolite fertilizer systems. Previous studies have shown that the incorporation of biochar or zeolite as an SRF matrix enhances plant growth, improves nutrient retention, and increases fertilizer use efficiency (Fistarani & Handayani, 2023; Pohan, 2021). Therefore, this study aims to develop an NPK-based SRF using snake fruit peel biochar and activated natural zeolite, and to evaluate the effectiveness in promoting the growth as well as productivity of water spinach. The results are expected not only to improve fertilization efficiency but also to provide an environmentally friendly, sustainable, and cost-effective alternative for tropical agriculture.

2. MATERIALS AND METHODS

2.2. Materials

Snake fruit peel waste used in this study was collected from local fruit shops in Yogyakarta, Indonesia. The materials used for fertilizer production included activated natural zeolite (DS Top Seller, Bandung, Indonesia), molasses (Laksana Berkah Tani, Bandung, Indonesia), humic acid (60%; POWERSOIL, Mitra Bertani, Indonesia), clay (CV. Rajakayubekasi, Bekasi, Indonesia), analytical-grade sodium hydroxide (NaOH; Merck), and distilled water. The nutrient sources comprised urea (46% N; Petro, PT. Petrokimia Gresik, Indonesia), diammonium phosphate (DAP; 12% N and 60% P_2O_5; Sarana Kimia Mandiri, Nganjuk, Indonesia), ammonium sulfate (ZA; 21% N and 24% S; Agrofarm, Malang, Indonesia), and potassium chloride (KCl; 60% K_2O) and magnesium oxide (MgO; 16% MgO), both branded Pak Tani and purchased from Saprotan Utama, Indonesia.

2.2. Material synthesis

2.2.1. Snake fruit peel preparation

Snake fruit peel was washed using distilled water and dried in an oven at 70 °C. The dried peel was then ground using a blender and sieved to obtain a particle size of 100 mesh. Subsequently, the snake fruit peel was stored in a desiccator.

2.2.2. Activation and pyrolysis of snake fruit peel into biochar

A total of 500 grams of snake fruit peel was soaked in 500 mL of 0.1 M HNO_3 for 2 hours. The mixture was then filtered and rinsed twice with distilled water. The sample was dried in an oven at 100 °C for approximately 4 hours until completely dry. The activated snake fruit peel powder was then furnace-treated at 200 °C for 2 hours. The resulting biochar was placed in a desiccator, ground, and sieved to 100 mesh. The final product was weighed and characterized using FTIR, SEM-EDX, and XRD. The filtrates from the HNO_3 soaking and distilled water rinsing were analyzed using AAS to determine the potassium content in the snake fruit peel biochar.

2.2.3. Zeolite activation

2.2.3.1. Natural zeolite preparation

The natural zeolite was ground and sieved to 100 mesh. After being soaked in distilled water for 24 hours, it was filtered and dried in an oven at 120°C.

2.2.3.2. Zeolite activation process

A total of 250 grams of the prepared zeolite was mixed with 100 mL of NaOH at concentrations of 4, 6, and 8 M. The zeolite activation process was carried out for 1.5 hours at 70°C. Subsequently, the zeolite was filtered and rinsed with distilled water until a neutral pH was reached. The activated zeolite was then characterized using BET to determine the surface area. The NaOH concentration that produced the largest surface pore area of the natural zeolite was selected for use as the activating agent in the zeolite preparation process for fertilizer production.

2.2.4. Fertilizer production

2.2.4.1. Fertilizer formulation

The NPK-Zeolite SRF (NPK 7.5-5-5-1.5-2) was specifically formulated for water spinach as an SRF. This formulation contained 7.5 % nitrogen, 5 % phosphate, 5 % kalium, 1.5 % sulphure, and 2 % magnesium. To produce 1 kilogram of NPK-Zeolite SRF, the required materials were 91.98 grams of urea, 108.70 grams of DAP, 23.53 grams of MgO, 62.50 grams of ammonium sulfate (ZA), 314.99 grams of zeolite, 314.99 grams of soil, and 83.33 grams of KCl. Meanwhile, to produce 1 kilogram of activated NPK-Biochar SRF for water spinach, the required materials were 91.98 grams of urea, 108.70 grams of DAP, 23.53 grams of MgO, 62.50 grams of ZA, 314.00 grams of zeolite, 314.99 grams of soil, 83.33 grams of KCl, and 209.98 grams of biochar. Table 1 shows the material composition to produce NPK-Zeolite SRF and NPK-Biochar SRF.

2.2.4.2. Granulation

The granulation process of the fertilizer was carried out by gradually mixing the finely ground raw materials into a container according to the predetermined formulation. After all the materials were added, the granulation started, during which the components were thoroughly mixed until homogeneous. In the granulation process, a binder solution or molasses solution with a concentration of 20 % was sprayed onto the mixture. The process continued until the fertilizer formed into small granules or round-shaped particles.

Table 1. Composition of NPK-Zeolite SRF and NPK-Biochar SRF

Material	Weight (gram)	
	NPK-Zeolite SRF	NPK-Biochar SRF
Urea	91.98	91.98
DAP	108.70	108.70
KCl	83.33	83.33
ZA	62.50	62.50
MgO	23.53	23.53
Zeolite	314.99	209.98
Clay	314.99	209.98
Biochar	-	209.98
Total	1000	1000

2.2.4.3. Drying and Screening

After the granule fertilizer became half-dried, humic acid was used to coat the surface. This was carried out by spraying a 20 % humic acid solution onto half-dried granules until the surface was evenly covered, then the fertilizer was dried again. The dried granule fertilizer was further ground to produce a uniformly-sized coarse powder fertilizer.

2.2.4.4. Characterization and analysis of fertilizer

The NPK-Biochar, NPK-Zeolite, and NPK-Biochar-Zeolite SRF were characterized using FTIR (Spectrum Two Perkin Elmer), XRD (Bruker D2 Phaser), and SEM-EDX (JSM-6510LA-EX-3618OD3A; JEOL). SEM-EDX was used to analyze the morphology and surface structure of the fertilizer, map the elemental distribution, and determine the percentage of each element. FTIR identified the functional groups and chemical bonds present in the fertilizer, providing insight into possible interactions between NPK, biochar, and zeolite. Meanwhile, XRD was conducted to determine the crystalline phases, assess the degree of crystallinity, and confirm the structural composition of the synthesized SRF.

2.2.4.5. Analysis of NPK content

The analysis of NPK content in water spinach was carried out by mixing the prepared fertilizer with soil and stirring until homogeneous. After 14 days of planting, the soil-fertilizer mixture was collected and taken to the Soil Laboratory of the Faculty of Agriculture, Universitas Gadjah Mada, for NPK analysis.

2.2.5. Plant growth test

The planting of water spinach (*Ipomoea reptans* Poir) was carried out using upland water spinach seeds. These seeds were soaked for 6–12 hours until germination occurred, showing viability. The planting medium was prepared by mixing soil with compost in polybags. Five different treatments were applied, including (A0) without fertilizer, (A1) commercial fertilizer (Phonska), (A2) NPK-Biochar SRF, (A3) NPK-Zeolite SRF, (A4) NPK-Biochar-Zeolite SRF, and (A5) Commercial water spinach. For each fertilizer treatment, one plant grown in a single pot was used. All pots were placed uniformly to ensure equal sunlight exposure, and each received the same volume of water. Each polybag was treated with 20 grams of fertilizer. Fertilizer was applied in several stages, namely when the plant started to grow (around day 7), at 14 days, and 25 days after planting. The upland water spinach plants were harvested 25 days after planting (DAP).

Table 2. The Potassium Content in the Soaking Solution Sample of Snake Fruit Peel

Volume (ml)	Potassium content (mg g^{-1})
100	7.175
500	358.785

Table 3. The surface area of the activated natural zeolite

Sample	BET surface area (m^2 g^{-1})
Activated natural zeolite-4M	25.6670
Activated natural zeolite-6M	34.7306
Activated natural zeolite-8M	19.8108

The observed parameters included plant height (cm) and leaf width (cm), each of which was measured three times for each plant.

3. RESULT

3.1. Characterization

Based on the AAS analysis in Table 2, the potassium content in 100 mL of solution was 7.175 mg g^{-1}, while in 500 mL it reached 358.785 mg g^{-1}. These results show that snake fruit peel is an effective alternative to KCl and can be used as a matrix in the production of SRF.

The surface area of the activated natural zeolite was determined using the BET method, and the results are shown in Table 3. Among the treatments, activation with 6M NaOH produced the largest surface area, reaching 34.7306 m^2 g^{-1}. In contrast, activation with 4M and 8M NaOH resulted in lower surface areas.

FTIR spectra of biochar, NPK-Biochar SRF, NPK-Zeolite SRF, and NPK-Biochar-Zeolite SRF are shown in Figure 1. The FTIR spectrum of activated snake fruit peel biochar shows absorption peaks at wavenumbers of 3187 cm^{-1}, 2079 cm^{-1}, 1605 cm^{-1}, 1242 cm^{-1}, 1034 cm^{-1}, corresponding to O-H stretching, C≡C, C=O, C-O, and Si–O functional groups, respectively (Shah et al., 2025).

The XRD diffractograms of biochar, NPK-Biochar SRF, NPK-Zeolite SRF, and NPK-Biochar-Zeolite SRF are shown in Figure 2. The XRD analysis of biochar showed distinct peaks at 2θ = 28.1°, 29.7°, 30.8°, 34.0°, and 40.5°, which are primarily attributed to the crystalline structures of sylvite (KCl) and calcite ($CaCO_3$). These minerals are commonly present in biochar, suggesting the potential for soil amendment applications (Sahoo et al., 2021). After loading with NPK fertilizer, the NPK-Biochar sample showed new diffraction peaks at 2θ = 22.1°, 24.0°, 31.8°, 42.9°, and 45.2°, indicating the successful incorporation of NPK into the biochar matrix. This shift in the XRD pattern signifies a modification in the crystalline structure of the biochar due to the NPK loading (Priya et al., 2024). In the case of NPK-zeolite, a prominent peak at 2θ = 26.7° was observed, corresponding to quartz minerals, as per JCPDS 05-0490. Sharp peaks at 2θ = 10.0°, 12.0°, and 20.8° were also identified as clinoptilolite minerals, in accordance with JCPDS 25-1349, while peaks at 2θ = 16.7°, 22.4°, 26.7°, 28.3°, and 29.0° are characteristic of mordenite, based on JCPDS 11-0155 (Betriani et al., 2023).

The surface morphology of biochar, NPK-biochar SRF, NPK-zeolite SRF, and NPK-Biochar-Zeolite SRF is shown in Figure 3. Snake fruit peel biochar surface demonstrated irregular rock-like shapes with non-uniform particle sizes separated from each other, as presented in Figure 3a. SEM analysis in Figure 3b shows that natural zeolite activated with NaOH forms irregular particle aggregates with relatively small sizes stacked and closely packed, indicating the successful activation of the zeolite (Ates & Akgül, 2016). The surface morphology of NPK-Zeolite SRF (Fig. 3d) shows irregular rock-like crystals that are closely arranged. In fertilizer containing biochar (Fig. 3c & 3e), the surface appears coarse with irregular crystal-like structures, and small particles form aggregates that adhere to each other.

Energy Dispersive X-Ray (EDX) analysis was carried out to determine the elemental composition of snake fruit peel biochar as well as the synthesized zeolite–biochar-based fertilizer. The EDX results showed that snake fruit peel biochar consisted of 32.83 % carbon, 12.92 % nitrogen, 33.70 % oxygen, 1.00 % magnesium, 0.76 % silica, and 9.33 % potassium.

The EDX characterization of the fertilizer showed differences among the formulations. The NPK–Biochar SRF contained 16.03 % nitrogen, 3.20 % phosphorus, 7.73 % potassium, and magnesium at concentrations of 2.78 % and 1.42 %. In comparison, the NPK–Zeolite SRF contained 13.96 % nitrogen, 3.26 % phosphorus, 10.89 % potassium, and 5.83 % sulfur, while magnesium was not detected.

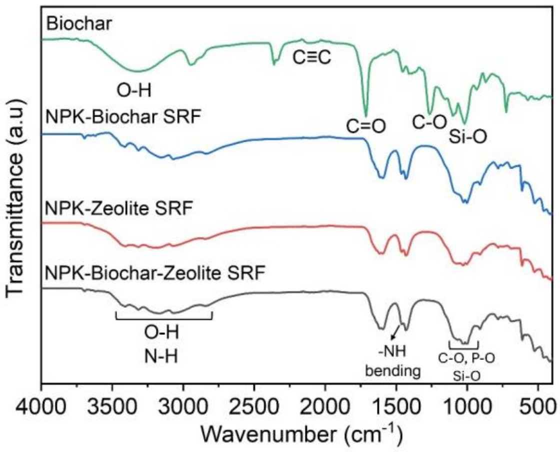

Figure 1. FTIR Spectra of Biochar, NPK-Biochar SRF, NPK Zeolite SRF, and NPK-Biochar-Zeolite SRF

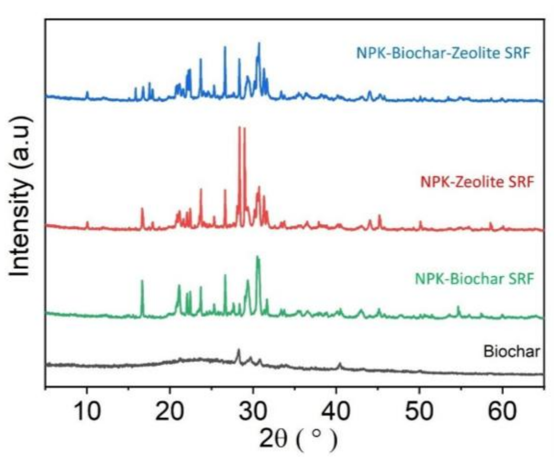

Figure 2. Diffractogram of Biochar, NPK-Biochar SRF, NPK-Zeolite SRF, and NPK-Biochar-Zeolite SRF

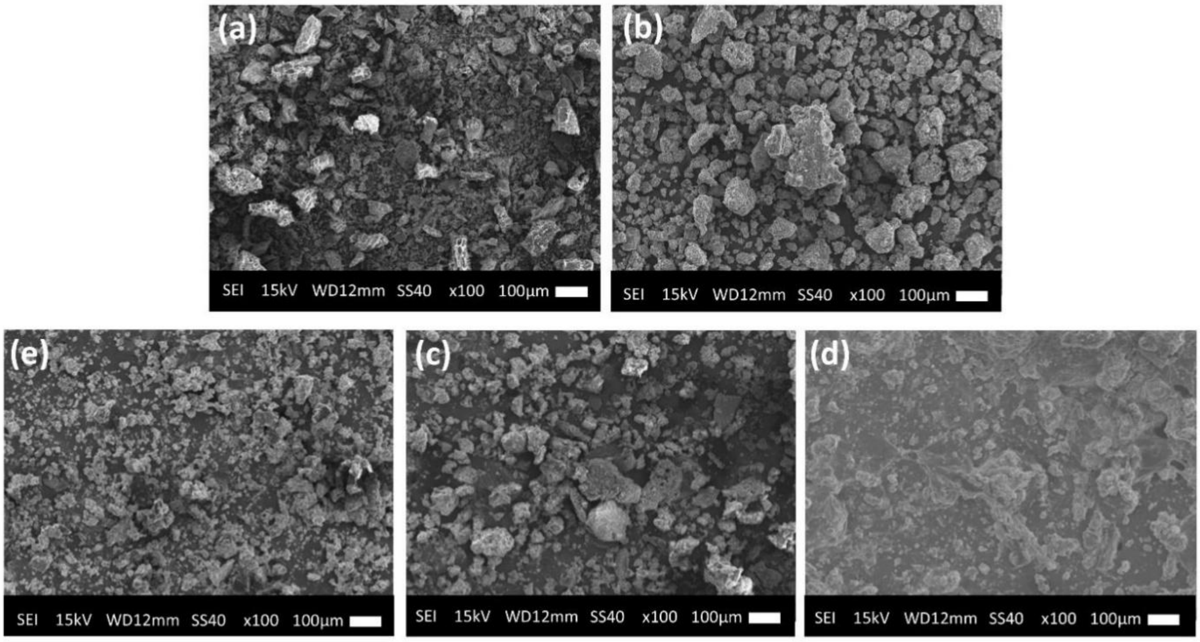

Figure 3. SEM Images of (a) Biochar, (b) Zeolite, (c) NPK-Biochar SRF, (d) NPK-Zeolite SRF, and (e) NPK-Biochar-Zeolite SRF

3.2. Plant growth test

The average plant height observed for treatments A0, A1, A2, A3, and A4 was 6 cm, 16.7 cm, 16.8 cm, 16.5 cm, and 18.5 cm, respectively, while the commercial water spinach (A5) reached a height of 20 cm. Among the treatments, the SRF A4 (NPK zeolite–biochar SPK) was the most effective, increasing the plant height of water spinach by 2.2 % compared to A1, A2, and A3. In contrast, water spinach without fertilizer (A0) only reached a height of 6 cm and did not show further growth until harvest. The average leaf width of water spinach for treatments A0, A1, A2, A3, and A4 was 0.1 cm, 0.9 cm, 0.8 cm, 0.9 cm, and 1.2 cm, respectively, while commercial water spinach (A5) had an average leaf width of 0.5 cm. Water spinach without fertilizer (A0) had a leaf width of only 0.1 cm and showed no change until harvest, indicating that the absence of nutrient supply limited plant growth and development.

Soil analysis was conducted at the Environmental Studies Center (PSLH), Faculty of Agriculture, UGM, in the Department of Soil Science. Post-harvest soil samples were analyzed to evaluate the effectiveness of nutrient release from the synthesized NPK fertilizer, and the results are presented in Table 5. The analysis showed that for NPK SRF with activated natural zeolite, the soil contained 4004.28 ppm of nitrogen (N), 5155.26 ppm of phosphorus (P), and 11.54 me% of potassium (K). For NPK SRF Biochar, the values were 1084.26 ppm N, 3388.66 ppm P, and 11.7 me% K. Meanwhile, NPK-Biochar-Zeolite SRF contained 1786.40 ppm N, 3151.67 ppm P, and 15.06 me% K. For the commercial Phonska fertilizer, the NPK content in the soil after water spinach cultivation was more balanced in retaining nutrients. Specifically, nitrogen (N) was 2390.09 ppm, phosphorus (P) 2063.63 ppm, and potassium (K) 10.51 me%.

4. DISCUSSION

The major discovery of this study is that the combination of activated natural zeolite and snake fruit peel biochar as a matrix for NPK SRF significantly enhances nutrient retention in soil and improves water spinach growth. Among the treatments, NPK-Zeolite–Biochar SRF (A4) showed the highest plant height increase (2.2 % higher than other SRF formulations) and indicated superior performance in retaining potassium, while NPK-Zeolite SRF excelled in nitrogen and phosphorus retention. These results show that the integration of biochar and zeolite not only provides a controlled nutrient-release system but also optimizes soil nutrient availability for plant uptake.

The observed enhancement can be attributed to the physicochemical properties of both materials. Activation of natural zeolite with 6M NaOH resulted in the largest surface area, reaching 34,7306 $m^2\ g^{-1}$. This shows that zeolite treated with 6M NaOH is suitable for use as a matrix in the preparation of SRF fertilizer. A similar study by Permana et al. (2023) reported that activation improved the surface area of zeolite-based SRF fertilizer (Permana et al., 2023). The increase in surface area is mainly attributed to the removal of impurities from the zeolite framework during the NaOH treatment, which exposes more pores and active sites (Hong & Um, 2021). In contrast, activation with 4M and 8M NaOH resulted in lower surface areas. The decline may be associated with agglomeration, where individual zeolite particles cluster into larger masses, thereby blocking access to the internal pores. During surface area analysis, gas adsorption tends to occur on these aggregates rather than on isolated particles, which potentially leads to inaccurate surface area measurements (Hong & Um, 2021). Furthermore, at higher concentrations, such as 8M, NaOH treatment can damage the zeolite framework. Strong alkaline conditions promote the dissolution of silica, and under more extreme conditions, aluminum atoms are also released from the structure. This leaching effect weakens the framework and reduces the material porosity. Previous studies have also shown that excessive NaOH concentrations cause partial removal of Al^{3+}, significantly decreasing the surface area.

Table 4. Elemental Composition of Biochar, Zeolite, NPK-Biochar SRF, NPK-Zeolite SRF, and NPK-Biochar-Zeolite SRF

Element	Elemental composition of the material (%)				
	Biochar	Zeolite	NPK-Biochar SRF	NPK-Zeolite SRF	NPK-Zeolite-Biochar SRF
C	32.83	8.29	8.49	8.47	9.42
N	12.92	-	16.03	13.96	21.20
O	33.70	53.52	40.09	43.94	34.61
Na	-	24.63	-	1.97	1.48
Mg	1.00	-	1.42	-	-
Al	-	1.41	5.13	-	2.62
Si	0.76	9.61	6.73	3.89	3.22
P	-	-	3.20	3.26	-
S	-	-	2.78	5.83	5.20
Cl	-	-	4.01	5.33	8.00
K	9.33	0.33	7.73	10.89	11.52
Cu	-	1.83	2.21	0.96	1.33
Ca	-	0.37	-	-	-

Beyond chemical changes, NaOH activation also alters the surface morphology of the zeolite, further influencing the structural and textural characteristics (Permana et al., 2023).

The presence of O–H and C–O bonds in the FTIR spectra shows the successful activation of snake fruit peel biochar, which possesses polar characteristics and is suitable for use as a slow-release agent in fertilizer formulations. The Si–O stretching vibration of siloxane observed in the sample shows the formation of a stable silica framework. The broad absorption band in the wavenumber region of 1100-1000 cm^{-1} is attributed to the internal and external asymmetric stretching vibrations of tetrahedral Si–O from siloxane, which is a characteristic feature of silica-based materials (Liu et al., 2019). The FTIR spectra of NPK-Biochar, NPK-Zeolite, and NPK-Biochar-Zeolite SRF showed remarkable differences compared to the spectrum of biochar alone, including the appearance of new peaks and peak shifts. Compared to biochar, the granulated NPK-Biochar, NPK-Zeolite, and NPK-Biochar-Zeolite SRF show higher intensity absorption bands associated with aliphatic –OH and –NH groups from primary amines or amides, observed around 3410 cm^{-1} and 3070 cm^{-1}. These chemical bonds show that both biochar and zeolite have reacted with urea and ammonium (Tahery et al., 2022; Wang et al., 2022). Additionally, peaks observed around 1430 cm^{-1} and 1460 cm^{-1} correspond to the presence of carbonate and NH bending vibrations from ammonium and or urea. The peak near 1000 cm^{-1} may show the stretching vibrations of aromatic C–O, Si–O, and P–O bonds (Shi et al., 2020). Absorption bands in the wavenumber range of 910 cm^{-1} to 740 cm^{-1} are associated with phenolic –OH, C–H bending, and the presence of various inorganic or mineral components such as Al–O–Si and Fe–O groups (Liu et al., 2019).

The XRD diffractograms of biochar, NPK-Biochar SRF, NPK-Zeolite SRF, and NPK-Biochar-Zeolite SRF showed distinct peaks at 2θ = 28.1°, 29.7°, 30.8°, 34.0°, and 40.5°, which are primarily attributed to the crystalline structures of sylvite (KCl) and calcite ($CaCO_3$). These minerals are commonly present in biochar, suggesting the potential for soil amendment applications (Sahoo et al., 2021). After loading with NPK fertilizer, the NPK-Biochar sample showed new diffraction peaks at 2θ = 22.1°, 24.0°, 31.8°, 42.9°, and 45.2°, indicating the successful incorporation of NPK into the biochar matrix. This shift in the XRD pattern signifies a modification in the crystalline structure of the biochar due to the NPK loading (Priya et al., 2024). In the case of NPK-zeolite, a prominent peak at 2θ = 26.7° was observed, corresponding to quartz minerals, according to JCPDS 05-0490. Additionally, sharp peaks at 2θ = 10.0°, 12.0°, and 20.8° were identified as clinoptilolite minerals, in accordance with JCPDS 25-1349, while peaks at 2θ = 16.7°, 22.4°, 26.7°, 28.3°, and 29.0° are characteristic of mordenite, based on JCPDS 11-0155 (Betriani et al., 2023). The presence of these distinct mineral phases in the NPK-Zeolite sample reflects the stability of the zeolite structure even after NPK loading. Finally, the XRD pattern of NPK-Biochar-Zeolite showed characteristic peaks from all three materials, confirming the successful combination of NPK, biochar, and zeolite. This synergy suggests the potential for a novel composite material combining the nutrient delivery capabilities of NPK, the adsorptive properties of biochar, and the ion-exchange characteristics of zeolite, which may offer enhanced soil fertility and sustainable agricultural applications (Dong et al., 2025).

SEM analysis in Figure 3b shows that natural zeolite activated with NaOH forms irregular particle aggregates with relatively small sizes stacked and closely packed, indicating the successful activation of the zeolite (Ates & Akgül, 2016). The surface morphology of the fertilizer is relatively rough due to the adherence of micronutrients on the surface, which can influence the gradual release of nutrients. This shows that the incorporation of snake fruit peel biochar and activated natural zeolite into NPK SRF fertilizer produces a more porous surface, enhancing the capacity to absorb and retain nutrients (Shao et al., 2025). On the other hand, the nutrients contained in the fertilizer contribute to a slower release.

The EDX results showed that snake fruit peel biochar consisted of 32.83 % carbon, 12.92 % nitrogen, 33.70 % oxygen, 1.00 % magnesium, 0.76 % silica, and 9.33 % potassium. These values indicate that the biochar not only serves as a carbon source but also contributes macro- and micronutrients essential for plant growth (Omokaro et al., 2025). For the activated natural zeolite, the EDX analysis showed that NaOH treatment significantly altered the elemental composition. The desilication process removed part of the silica from the zeolite framework, increasing mesoporosity while maintaining micropore size and acidity. The reduction of silica content created more space for accommodating particles and enhanced adsorption capacity. Additionally, the desilication treatment resulted in an increased sodium (Na) content within the zeolite structure.

The addition of snake fruit peel biochar had a significant effect compared to zeolite SRF fertilizer. The NPK–Zeolite–Biochar SRF in Table 4 contained 9.42 % carbon, 34.61 % oxygen, and 11.52 % potassium. The use of activated natural zeolite enhanced the retention of essential nutrients, resulting in higher elemental contents than those observed in other synthetic fertilizer (Suci et al., 2025). However, the presence of residual impurities blocking some zeolite pores during activation may have reduced the capacity of the zeolite to capture specific elements, which explains the loss of certain nutrients in the final product.

The plant growth test results in Figure 4 showed that fertilizer application can positively affect plant height. Among the treatments, SRF A4 (NPK zeolite–biochar SPK) was the most effective, increasing water spinach plant height by 2.2 % compared to A1, A2, and A3. The significant increase in plant height observed in the biochar and zeolite treatments can be explained by the ability to enhance nutrient uptake and increase soil organic matter, which helps reduce leaching of nitrogen, potassium, and phosphorus (Kamrunnahar et al., 2024; Suraya et al., 2023). In contrast, water spinach without fertilizer (A0) only reached a height of 6 cm and showed no further growth until harvest. These results show that the application of SRF can enhance leaf expansion in water spinach (Yang et al., 2021).

Soil analysis results indicated that NPK SRF with activated natural zeolite was most effective in retaining nitrogen and phosphorus in the soil compared to other synthetic fertilizer shown in Table 5. On the other hand, NPK SRF Zeolite–Biochar showed superior potassium retention, while NPK SRF Biochar performed better in retaining phosphorus and potassium. Overall, all three synthetic fertilizer showed good ability to maintain soil NPK levels.

Despite these differences in nutrient retention, harvested water spinach showed uniform shape and size across all treatments. With commercial Phonska, the NPK content in the soil after water spinach cultivation was more balanced in retaining nutrients. Conversely, soil without synthetic or commercial Phonska fertilizer had lower NPK levels due to the lack of a substance that could inhibit nutrient release. Water spinach grown in this soil was smaller and less nutritious.

Regarding the NPK-Biochar-Zeolite SRF, the comparison among the three synthesized fertilizer shows that the N and P contents were lower compared to those in the NPK SRF with activated natural zeolite. The biochar included in the NPK-Biochar-Zeolite SRF formulation helped prevent nutrient loss. Additionally, the dosage of snake fruit peel biochar used influences nutrient availability in the soil (Hossain et al., 2020). Further studies are needed to determine the optimal biochar content, because biochar contributes significant amounts of macro- and micronutrients, allowing it to function effectively as an SRF (Gwenzi et al., 2018; Marcińczyk & Oleszczuk, 2022).

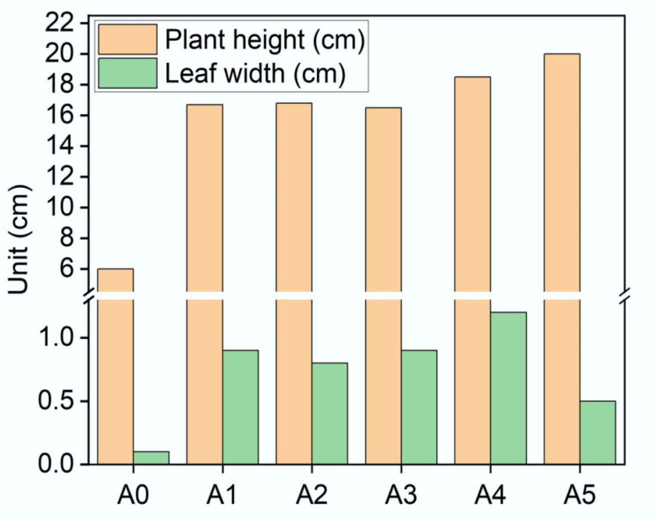

Figure 4. Average Results of Growth Observation Variables of Water Spinach

Table 5. Soil Analysis Results

Sample	N (ppm)	P (ppm)	K (me%)
Without fertilizer	435.56	575.48	8.99
Commercial Phonska fertilizer	2390.09	2063.63	10.51
NPK-Biochar SRF	1084.26	3388.66	11.47
NPK-Zeolite SRF	4004.28	5155.26	11.54
NPK-Biochar-Zeolite SRF	1786.40	3151.67	15.06

Zeolite is a hydrated aluminosilicate mineral with a porous structure that contains alkali cations, which can directly influence the availability of nutrients in the soil, such as nitrogen (N) and phosphorus (P). Therefore, the amount of activated natural zeolite applied affects the levels of N and P available in the soil. The application of activated natural zeolite combined with snake fruit peel biochar has a significant effect on the availability of N and P nutrients in the soil (Legese et al., 2024; Villada et al., 2024).

5. CONCLUSION

In conclusion, this study underscores the significant potential of snake fruit peel as a sustainable alternative to KCl in the production of SRF. The high potassium content, with values of 7.175 mg g^{-1} in 100 mL and 358.785 mg g^{-1} in 500 mL, along with a substantial K_2O content, positions snake fruit peel as a valuable source of potassium for fertilizer production. Energy Dispersive X-ray (EDX) analysis of the snake fruit peel biochar showed a diverse elemental composition, including carbon (32.83 %), nitrogen (12.92 %), oxygen (33.70 %), magnesium (1 %), silica (0.76 %), and potassium (9.33 %). When combined with activated natural zeolite, the biochar significantly improved the morphology of NPK slow SRF, resulting in a more porous surface structure. This feature enhances the fertilizer ability to absorb and temporarily store essential nutrients, enabling a slower and more controlled release, thereby improving overall efficiency. In terms of plant growth, the use of commercial Phonska fertilizer led to a more balanced nutrient content in water spinach plants, with nitrogen at 2390.09 ppm, phosphorus at 2063.63 ppm, and potassium at 10.51 me%, yielding superior results compared to soils without synthetic or commercial fertilizer. Among the treatments, NPK-Biochar-Zeolite SRF (A4) was the most effective, increasing plant height by 2.2 % and leaf width by 0.3 % compared to the other treatments (A1, A2, and A3). More importantly, the NPK SRF Zeolite–Biochar treatment also showed superior potassium retention, while the NPK SRF Biochar had better phosphorus and potassium retention. These results suggest that incorporating biochar from snake fruit peel and zeolite into SRF formulations can significantly improve fertilizer efficiency and support optimal plant growth, making it a promising strategy for sustainable agriculture.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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