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Synthesis and characterization of slow release fertilizer nitrogen and slow release fertilizer potassium based on biochar with nanotechnology and alginate

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ABSTRACT

Conventional nitrogen (N) and potassium (K) based fertilizers on agricultural soils face efficiency constraints due to high leaching rates and rapid nutrient release. This study aims to synthesize and characterize slow-release fertilizers (SRF-N and SRF-K) based on nano biochar and impregnation using alginate as a binder. Nano biochar was synthesized through ball milling, while impregnation was carried out through a cross-linking process, each method using 0% and 2% alginate. Characterization of the treatment was carried out using Fourier Transform Infrared Spectroscopy (FTIR) for functional group analysis, Scanning Electron Microscopy (SEM) and Image-J for morphology and particle size, and X-ray diffraction (XRD) for mineral crystal structures. The results showed that SRF-Nn and SRF-Kn based on nano biochar had more diverse functional groups, including hydroxyl (-OH), carbonyl (C=O), and carboxyl (-COOH), which could increase cation exchange capacity and nutrient adsorption capacity. Ball milling produced nano biochar with an average size of 40.42 nm, where 92.37% of particles were 1–100 nm. The morphology of nano biochar showed a smoother surface, more even pore distribution, and a larger surface area than conventional biochar and impregnated biochar. SRF-Nn and SRF-Kn with 2% alginate formed a more stable and homogeneous structure. XRD analysis showed that nano biochar had a higher crystallinity level with a dominance of quartz (SiO_2) and calcite ($CaCO_3$). This content increased the adsorption capacity and stability of the nanostructure, thus potentially increasing the efficiency of nutrient release gradually.

Keywords: slow-release fertilizer (SRF), nano biochar, Alginate, functional groups, surface morphology, mineral structure.

INTRODUCTION

The demand for sustainable agricultural systems continues to increase along with global challenges, including climate change, land degradation, and increasing food needs (Saleem *et al*., 2024). One of the main obstacles to developing sustainable agriculture is the low efficiency of fertilizer use, especially for essential nutrients such as nitrogen (N) and potassium (K). Loss of nutrients through leaching, denitrification, and fixation reduces crop yields and contributes to environmental pollution, such as water eutrophication and greenhouse gas emissions (Yahaya *et al*., 2023). Therefore, an innovative approach is needed in fertilizer formulation that can increase nutrient use efficiency and minimize negative environmental impacts.

SRF (slow-release fertilizer) is a type of fertilizer designed to slow the release of nutrients into the soil so plants can absorb them more efficiently (Rashid *et al.*, 2021). Unlike conventional fertilizers that release nutrients quickly, SRF provides a longer supply of nutrients, reducing the frequency of application and the potential for losses due to leaching or evaporation (Yamamoto *et al.*, 2016). In addition, using SRF (slow-release fertilizer) can reduce negative environmental impacts because it can minimize the accumulation of nutrients in groundwater and surrounding waters (Giroto *et al*., 2017). One of the innovative materials that has the potential to be used in the formulation of SRF (slow-release fertilizer) is biochar (Ramesh and Raghavan, 2024).

Biochar is a carbon-rich solid material produced through pyrolysis or combustion with limited oxygen (Zhang *et al.*, 2023). Biochar can increase soil fertility, increase water retention capacity, and has high porosity that can absorb and retain nutrients, such as nitrogen (N), phosphorus (P), and potassium (K), which can then be released gradually (Yadav *et al*., 2023). Biochar can also increase soil organic carbon, increase cation exchange capacity (CEC), improve soil microbial communities, and reduce the negative impacts of pollutants (Manikandan *et al*., 2023) However, conventional biochar has several limitations, especially its performance efficiency in formulating SRF (slow-release fertilizer). Thus, innovation is needed in the use of biochar to increase its release efficiency. The two main approaches in the development of innovative and sustainable biochar-based SRF (slow-release fertilizer) fertilizers are nanotechnology and biochar-based impregnation (Zhang *et al*., 2023).

Nanotechnology is a technology related to objects measuring 1 to 100 nm, having different properties from the original material, and having the ability to control or manipulate on an atomic scale (Tundisi *et al*., 2023). The results of research by Kumalasari *et al*. (2022) reported that fertilizers with nanotechnology using zeolite raw materials and crab shells with N-K coating could release nutrients gradually and increase shallot yields. Several other studies have also shown significant results from developing SRF fertilizers with different technologies. Meanwhile, impregnation is a technology to modify or enrich nutrients by permeating the porous structure of biochar, thus producing biochar material with certain properties in releasing nutrients (Zakaria *et al.*, 2021).

The potential of biochar-based slow-release fertilizer is influenced by various factors, including biochar raw materials, pyrolysis temperature, particle size, morphological structure, fertilizer method or modification, and soil type (Golezani & Rahimzadeh, 2022). Yuan *et al.* (2016) stated that biochar has a negative charge and affects the retention of anions such as NO3- in the soil, but not as good as the retention of cations (NH^{4+}) and K+, which are positively charged. Therefore, biochar modification with ball milling or nano biochar and biochar impregnated with nutrients can increase its retention capacity (Zhao *et al.*, 2021). However, the biochar produced from this modification is still possible to move with surface flow and soil infiltration, so a potential binder is needed to improve the characteristics of the resulting fertilizer *(*Wang *et al*., 2018).

Alginate is a natural polymer rich in carboxyl and hydroxyl groups and has the potential to improve biochar performance, especially its mechanical properties (Wang *et al.*, 2018). The application of alginate together with biochar not only stabilizes biochar in the soil but also increases nutrient retention from biochar. Several studies on biochar and alginate have focused more on the removal of heavy metals, phosphates, and organic pollutants from water (Feng *et al.,* 2022), while there has been no research on the synthesis and characterization of SRF-N and SRF-K fertilizers based on nano biochar and alginate.

This study aims to synthesize and characterize SRF-N and SRF-K fertilizers based on nano biochar with alginate to improve fertilization efficiency. The results of this study are expected to contribute to the development of more efficient, environmentally friendly SRF fertilizers and support the sustainability of agricultural systems, thus playing a role in meeting global food needs in the future.

RESEARCH METHODS

This research was conducted at the Soil Laboratory, Faculty of Agriculture, Universitas Gadjah Mada (UGM) from March to July 2024. Biochar production was carried out in Gunung Kidul, while nano biochar synthesis was done at the Production Laboratory, Universitas Muhammadiyah Yogyakarta (UMY). The biochar impregnation process was carried out at the Soil Laboratory, Faculty of Agriculture, UGM, while characterization using SEM, XRD, and FTIR was carried out at the Integrated Research and Testing Laboratory (LPPT UGM).

The materials used include rice husk biochar, urea fertilizer, KCl, alginate, and standard SRF-N and SRF-K. The equipment includes a pyrolysis drum, biochar grinding machine, ball milling, sieve, and granule-making tool. Nano biochar was synthesized by ball milling, using a ratio of steel balls, rice husk biochar, and water of 500 g: 100 g: 60 ml, then ground for 6 hours (Hartatik *et al*., 2020). Nano biochar is considered successful if

50% or more of its particles are 1–100 nm in size (Khan *et al*., 2017). The formulation of SRF nano biochar fertilizer is carried out by mixing urea and KCl with rice husk nano biochar in a ratio of 6:1 (Kottegoda *et al*., 2017) using a centrifugal mixing method until completely coated (Amusat *et al*., 2021). A 2% alginate solution ($g \cdot g^{-1}$) is used as an adhesive by spraying 30 ml of solution per 100 g of NK fertilizer (Himmah *et al*., 2018). The synthesis of impregnation-based SRF fertilizer is carried out by absorbing N-K nutrient solution into 100 mesh biochar for 72 hours at 25 ± 0.5 °C (Bakshi et al., 2021). The impregnation process was carried out by stirring for 20 minutes using a stirrer (Cen *et al*., 2021). Cross-linking was carried out with 2% alginate solution ($g \cdot g^{-1}$) and 0.1 M $CaCl_2$ solution, forming a spherical hydrogel which was dried at 55 °C for 12 hours ((Wang *et al.*, 2018).

Characterization of SRF nano biochar fertilizer and biochar impregnation was carried out using FTIR for functional group analysis and SEM to observe the surface morphology of biochar, which was analyzed using Image-J software for the size of nano biochar particles (Sivasubramanian *et al.*, 2023), and XRD for mineral structure analysis at LPPT UGM.

RESULTS AND DISCUSSION

Functional groups with FTIR

Fourier transform infrared spectroscopy (FTIR) analysis was used to identify functional groups in biochar, nano biochar, and SRF fertilizer, which play a role in physicochemical properties and interactions with soil (Gong *et al.*, 2024). Functional groups such as carboxyl (-COOH), hydroxyl (-OH), and carbonyl (C=O) affect nutrient adsorption and cation exchange capacity. The FTIR spectrum of biochar and nano biochar shows a wave range of 1042.70–1094.21 cm^{-1} related to the aromatic structure and Si-O stretching due to the high silica content in rice husks. Hidayat *et al*. (2022) reported that rice husk biochar has SiO_2 with a concentration reaching 85.35% to 89.47%. In addition, there are peaks at 498.84 cm^{-1} (Si-O bending), 949.84 cm^{-1} (C-H bending), and 2924.13–3404.87 cm^{-1} from the hydroxyl functional group (-OH). The presence of these groups indicates the complex chemical properties of biochar and its potential for soil improvement applications (Yang *et al*., 2022).

The results of the FTIR analysis (Fig. 1) show that the functional groups of nano biochar are more diverse than conventional biochar. This is in line with the statement of Gadore *et al.* (2023), which states that nano-sized biochar has more diverse surface functional groups, increased cation exchange capacity, andand increased porosity compared to conventional biochar. This is influenced by nano biochar's particle size, surface area, and physicochemical properties (Hussein *et al*., 2022).

The analysis shows that in nano biochar, a distinctive peak was identified at 2012.74 cm^{-1}, which was not found in biochar. Chen *et al*. (2024) stated that the peak in the range of 2012–2013 cm^{-1} indicates the presence of olefin (C=C) or carbonyl (C=O) structures that play a role in interactions with nutrients. This carbonyl group appears due to the ball milling process, which can change the crystal structure, increase the surface area, and add functional groups to nano biochar (Gao *et al*., 2024). Ramanayaka *et al*. (2020) also reported that nanobiochar has more

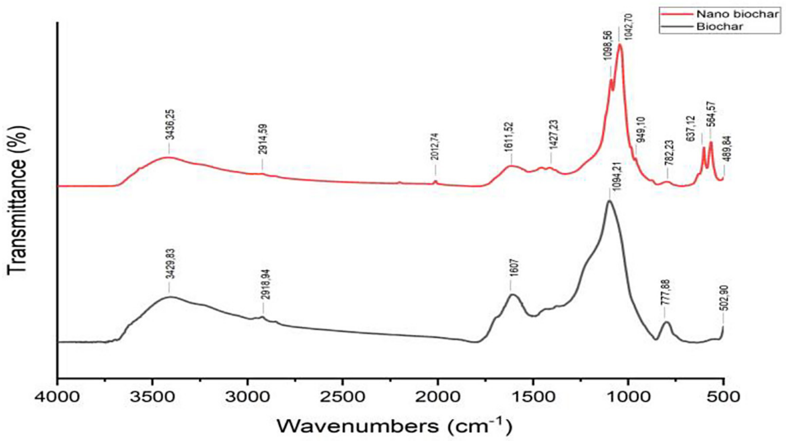

Figure 1. FTIR analysis of biochar and nano biochar

evenly distributed pores, creating new reactive sites that strengthen interactions with oxygen and other compounds. In addition, biochar and nano biochar showed peaks at 2914.59–2918.94 cm^{-1} related to the stretching vibration of methyl groups ($-CH_3$) in aliphatic compounds, which have lower reactivity than hydroxyl or carbonyl groups (Yang *et al.*, 2022). The hydroxyl (-OH) peak at 3436.25–3439.83 cm^{-1} is related to lignocellulose and carboxyl (-COOH) residues, which contribute to increased nutrient adsorption and improved soil properties (Fan *et al.*, 2021). Zhang *et al*. (2024) added that the pyrolysis process at temperatures < 500 °C allows carboxyl groups to form that increase biochar and nanobiochar reactivity in the soil environment.

Functional groups in SRF-Nn and SRF-Ni fertilizers with 0% and 2% alginate in Figure 2 detected a wave peak of 3214.24–3447.86 cm^{-1}, indicating hydroxyl vibrations (-OH), which helps increase interactions with polymers and nutrients and strengthens the attachment of active materials to the biochar surface, increasing the release of nutrients gradually Rashid *et al.* (2023). Meanwhile, the wave peak of 2803.58–2807.93 cm^{-1} found in SRF-Nn + alginate 0%, 2% shows C-H stretching (aliphatic), indicating that nano biochar has a large surface area and non-aromatic hydrocarbon chains that interact with urea, KCl, and alginate fertilizers. Rashid *et al.* (2023) stated that aliphatic groups (-CH) increase stability against microbial degradation and slow down the release of nutrients, while alginate as a natural polysaccharide helps form three-dimensional networks and increases the detection of aliphatic groups (-CH) (Zakaria *et al*., 2022).

Based on the results of the FTRI analysis in Figure 2, SRF-Ni + alginate 0% and 2% fertilizers cause urea and alginate to enter the pores of the biochar so that the aliphatic groups interact with other functional groups in the biochar, such as carbonyl (C=O), hydroxyl (O-H), and carboxyl groups (-COOH). The aliphatic group can form new bonds or different structures so that the original vibrations are not found. He et al. (2024) stated that biochar modification can affect the presence and number of functional groups. In SRF-Nn + alginate 0% and alginate 2% fertilizers, as well as SRF-Ni + alginate 0% and alginate 2% fertilizers, the detected wave peaks were almost the same, namely in the range of 519.58 cm^{-1} to 1685.53 cm^{-1}. The wave peak around 519.58 cm^{-1} is included in the mineral bond related to the silica compound (SiO2). In this range, Si-O-Si vibrations are usually associated with silica minerals' crystalline or amorphous structure. Meanwhile, 1685.53 cm^{-1} belongs to the carboxyl functional group (-COOH). This wave peak reflects the C=O vibration in the carboxyl group in compounds derived from the pyrolysis process (Volkov *et al.*, 2021).

The results of FTIR analysis on SRF-Kn + alginate 0% and 2% in Figure 3 show a wave peak of 3436.25–3429.72 cm^{-1}, indicating the hydroxyl group (-OH) of biochar and alginate. The wave peaks of 2921.84 cm^{-1} and 2919.67 cm^{-1} indicate the aliphatic C-H group, especially $-CH_2$ and $-CH_3$, which are characteristics of aliphatic compounds. The 500.72 cm^{-1}–1109.45 cm^{-1} peaks are related to C-O-C vibrations (Han *et al.*, 2021). SRF nano biochar fertilizer has more diverse functional groups than SRF-impregnated biochar because nano biochar has a larger surface area and higher porosity, allowing for more complex interactions. SRF nano

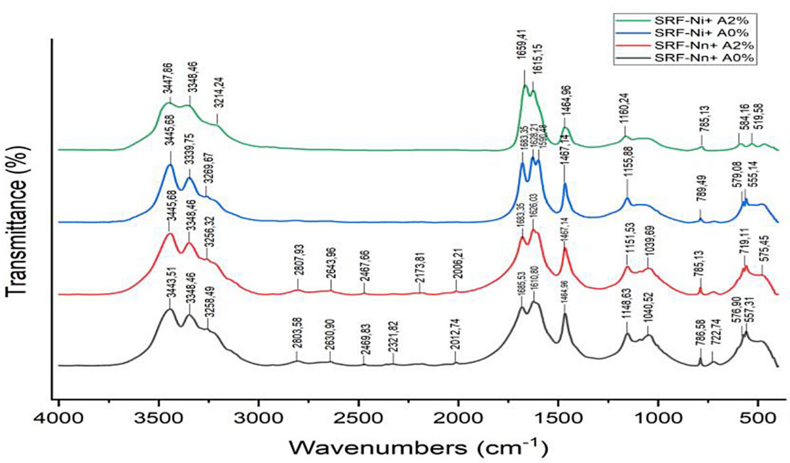

Figure 2. FTIR analysis of SRF-Nn and SRF-Ni with 0% and 2% alginate

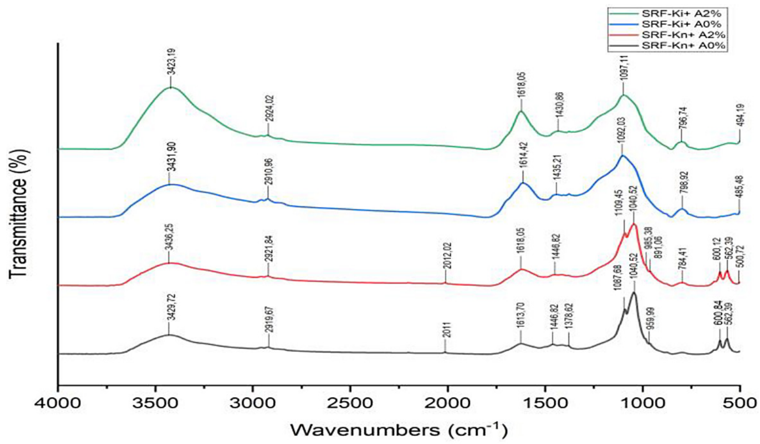

Figure 3. FTIR analysis of SRF-Kn and SRF-Ki with 0% and 2% alginate

biochar absorbs more nutrients. The development of SRF nano biochar urea produces more varied functional groups compared to KCl because urea contains amine (-NH_2) and carbonyl (-C=O) groups that can form hydrogen bonds (Mingke *et al.*, 2023). The highest wave peak in SRF-Kn is 1040.52 cm^{-1}, related to the C-O-C vibration in ether and C-O in the –OH group (Chandra *et al*., 2020).

Nanoparticle size analysis and SEM

Nanoparticle size analysis was performed using a scanning electron microscope (SEM), which produces visual images of surface morphology and particle size (Khan *et al.*, 2019). Classification of nanoparticle size is important because it affects the material's chemical, physical, and reactivity properties and increases the adsorption capacity and efficiency of molecular transport (Mekuye & Abera, 2023). The classification of nanoparticle sizes can be seen in Table 1.

The SEM analysis results were processed using Image-J software to measure particle size accurately through calibration, segmentation, and particle size distribution analysis. Image-J is a digital image processing program developed by researchers at the Research Services Branch, National Institute of Mental Health, Bethesda, Maryland, USA. The results of the analysis of the size of rice husk biochar nanoparticles can be seen in Table 2.

The results of the analysis of the size of biochar nanoparticles using Image-J showed an average particle size of 40.42 nm with the following distribution: 5.22% (0–10 nm), 28.49% (10–20 nm), 58.66% (20–100 nm), 6.20% (100–250 nm), 1.87% (250–1000 nm), and 0.10% (> 1000 nm). The total particles measuring 1–100 nm reached 92.37%, which is the criteria for the success of making nanomaterials (Khan *et al.*, 2017). The grinding process with steel balls and grinding time affect the size of nanoparticles, which have also been shown to increase biochar's adsorption capacity and chemical reactivity (Mekuye and Abera, 2023). Raczkiewicz *et al.* (2024) who also observed an increase in the surface area of milled biochar for 6 hours, were able to break down the macrostructure of biochar into nano and reduce the particle size, which in turn increased the adsorption capacity and chemical reactivity of biochar. Based on the results of SEM morphological analysis of rice husk biochar and nano biochar can be seen in Figures 4, 5, and 6.

Table 1. Classification of nanoparticle size

No	Particle diameter (nm)	Information
1	1–10	Nanocrystal particles
2	10–20	Nanopowder particles
3	20–100	Ultrafine particles
4	100–2500	Fine particles
5	2500–10.000	Coarse particles

Table 2. Size of rice husk biochar nano particles.

Diameter (nm)	Nano biochar Sekam Padi	
	Amount	Percentage (%)
0–10	106	5.19
10–20	579	28.34
20–100	1193	58.39
100–250	126	6.17
250–1000	37	1.81
>1000	2	0.10
Mean: 40.42 (nm)		

Note: Further test results using Image-J software.

Figures 4 a and b show the differences in the surface morphology of biochar and nano biochar at a magnification of 300x. Biochar has a rough surface with irregular particles, while nano biochar is smoother and more even, indicating the success of the ball milling process. Nano biochar has a larger surface area and more diverse pore volume than conventional biochar, thus providing more active sites for adsorption and potential chemical reactions (He *et al*., 2022).The results of SEM analysis show that conventional biochar has an irregular pore distribution, while nano biochar is more even and defined, increasing the specific surface area and adsorption capacity. This makes nano biochar superior for applications such as SRF fertilizer and nutrient retention. Khan *et al.* (2021) reported that nano biochar fertilizer from wheat straw releases nutrients gradually in the long term. Nano modification and impregnation affect the morphology of SRF fertilizer, as seen in the SEM results comparing SRF-Nn and SRF-Ni with various alginate concentrations.

The results of the SEM analysis in Figure 5 show the differences in the surface morphology of SRF-Nn and SRF-Ni fertilizers with various alginate concentrations. SRF-Nn fertilizers with

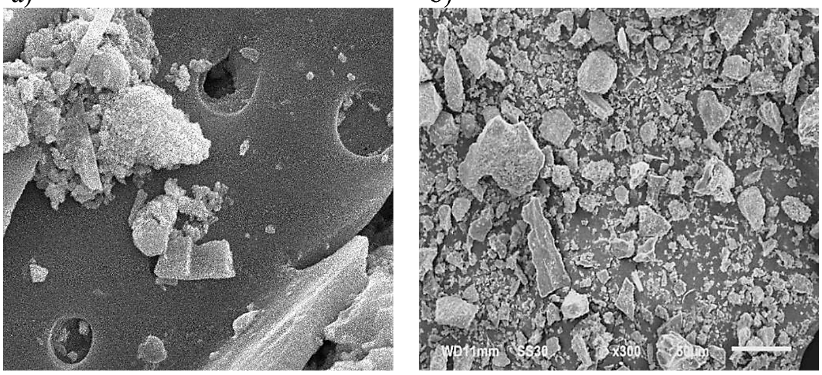

Figure 4. SEM analysis results of: (a) biochar, (b) nano biochar

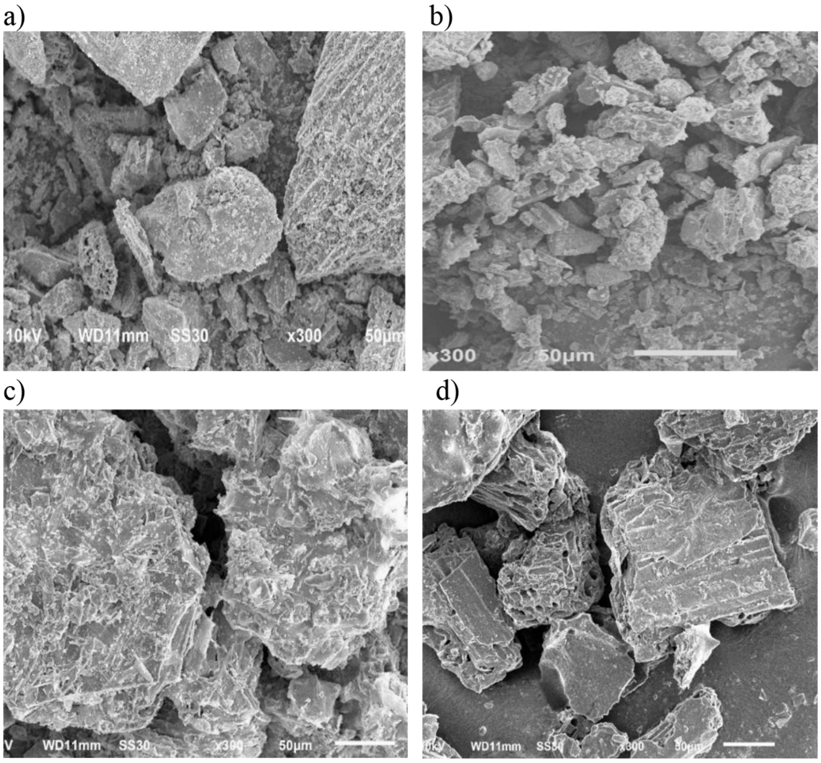

Figure 5. SEM analysis of: (a) SRF-Nn+ alginate 0%, (b) SRF-Nn + alginate 2%, (c) SRF-Ni+ alginate 0%, (d) SRF-Ni+ alginate 2%

0% and 2% alginate have a smooth surface and homogeneous distribution compared to SRF-Ni. The 2% alginate layer on nano biochar forms a physical barrier that slows down the diffusion of urea, resulting in a stronger, denser, and more uniform structure. In contrast, without alginate, the nano biochar layer is less stable. This finding is in line with Feng *et al.* (2024), who reported that alginate can increase the mechanical stability of biochar in soil, improving its performance. Meanwhile, Figures 5c and d show the differences in the surface morphology of SRF-Ni fertilizers with 0% and 2% alginate. SRF-Ni + 0% alginate has a rough surface and closed pores due to urea impregnation, which reduces the specific surface area. In contrast, SRF-Ni + 2% alginate has a smoother surface, indicating alginate's effect in maintaining biochar's pore structure. Impregnation of urea biochar with 0% alginate can cause pore blockage by urea crystals, reducing biochar's specific surface area and adsorption capacity *(He et al.*, 2024). In contrast, impregnation with 2% alginate forms a protective layer that prevents blockage, keeping the pores open. Alginate, as a natural polysaccharide, forms a permeable layer that maintains water flow and enhances nutrient retention (Wang *et al*., 2023).

The surface morphology of SRF-Kn + alginate 0% fertilizer shows a sharp and unstructured shape, while SRF-Kn + 2% is more uniform with a compact nano biochar structure and strong interactions (Fig. 6). Nano biochar is evenly distributed and well bound by alginate, thus creating more active areas for nutrient absorption. Meanwhile, the surface morphology of SRF-Ki + alginate 0% fertilizer appears rough and non-uniform, with biochar and KCl particles separated and easily detached due to the absence of a binder. This risks accelerating the release of nutrients and increasing losses due to leaching. In contrast, SRF-Ki + alginate 2% shows a more homogeneous surface with strong bonds between biochar, KCl, and alginate and larger and blunt particles due to alginate impregnation. Using alginate in SRF fertilizer increases structural uniformity and integration between particles, while without alginate, the structure is rougher and less stable, potentially reducing the efficiency of nutrient release. Gürkan & İlyas, (2022) reported that alginate impregnation produces biochar with a fine texture and high adsorption capacity, increasing the interaction with metal ions and the adsorption efficiency of contaminants, thanks to the functional groups of alginate, which are selective towards metal ions.

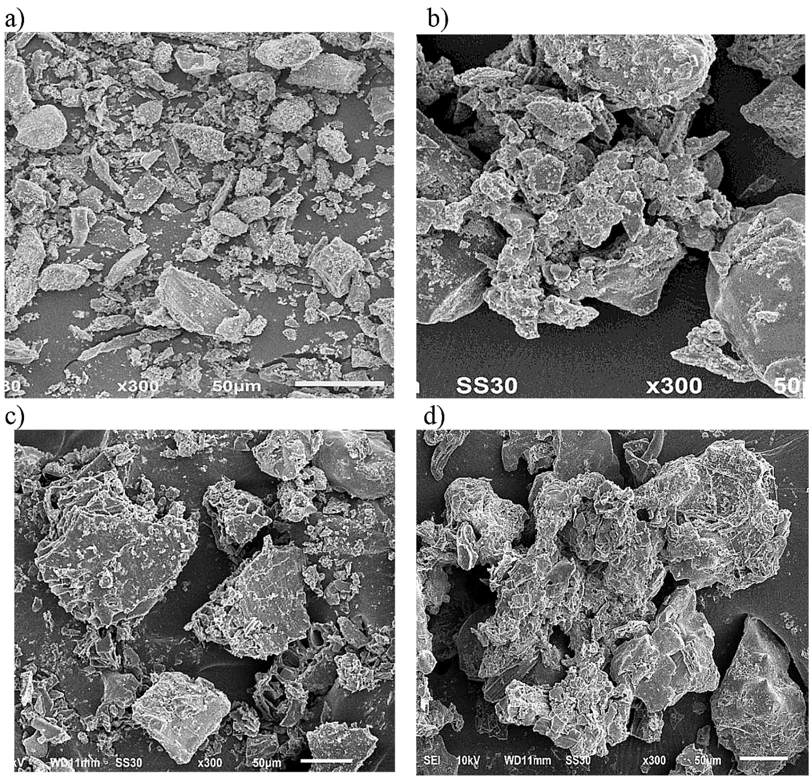

Figure 6. SEM analysis results of: (a) SRF-Kn + 0% alginate, (b) SRF-Kn + 2% alginate, (c) SRF-Ki+ alginate 0%, (d) SRF-Ki+ alginate 2%

Mineral structure analysis with XRD

XRD is a material characterization method used to analyze mineral composition and determine crystallinity properties, including biochar, nano biochar, and SRF (Slow-Release Fertilizer). The XRD pattern consists of a crystal structure with a short-range order indicated by a wide diffraction band, reflecting the material's irregularity or lack of crystalline composition. Meanwhile, the long-range order, with sharp and narrow diffraction peaks, indicates a highly regular crystalline structure (Neelancherry *et al*., 2024).

Based on the results of XRD analysis of biochar and nano biochar, there is the presence of SiO_2. However, the biochar diffraction pattern shows a material dominated by an amorphous structure and little crystalline regularity, with a weak diffraction peak around the 2θ or 2-theta angle of 22–25° which reflects the presence of amorphous silica (SiO_2), this amorphous structure mostly comes from irregular carbon components (Fig. 7). Thompson *et al.* (2021) stated that the characteristics of amorphous minerals are that they show a diffraction pattern in the form of a broad hump without sharp peaks. These amorphous minerals can help increase the slow-release capacity of nutrients through physical and chemical adsorption, such as nitrogen (N) and potassium (K). However, the instability of the atomic structure allows for faster release than crystalline minerals (Salimi *et al*., 2023). Biochar shows an XRD pattern with a reflection peak at 2θ = 26.59°, while in nano biochar, 2θ = 28.89° and 27.98° associated with irregular micro-graphite stacks, indicating a semi-crystalline structure and irregular layer stacks (Liu *et al*., 2019). In nano biochar, sharp peaks were also found around 2θ or 2-theta 25.90°, 31.75°, 32.87°, and 49.35° indicating the presence of crystalline quartz minerals (crystalline SiO_2) and calcite ($CaCO_3$). These crystalline minerals have a regular atomic structure and repeat periodically in three dimensions. Crystalline minerals have characteristics that show sharp and specific peaks (Potnuri and Rao, 2024). Zhang *et al.* (2024) stated that a more stable structure in crystalline minerals can increase their adsorption capacity and chemical reactivity.

XRD analysis shows that biochar has an amorphous nature that reflects the initial characteristics of its organic matter because pyrolysis at a certain temperature does not completely crystallize the organic structure. In contrast, nano biochar synthesized through ball milling experiences an increase in kinetic energy and mechanical energy, which changes the amorphous structure to crystalline through two mechanisms; the first is recrystallization, where additional energy allows atoms in the amorphous structure to move towards a more regular configuration and second, the removal of organic residues. This removes amorphous material and increases the dominance of crystalline minerals such as silica (Jafter *et al*., 2024). Based on XRD analysis of SRF-Nn + alginate 0%, SRF-Nn + alginate 2%, and SRF-Ni + alginate 0% fertilizers, as well as

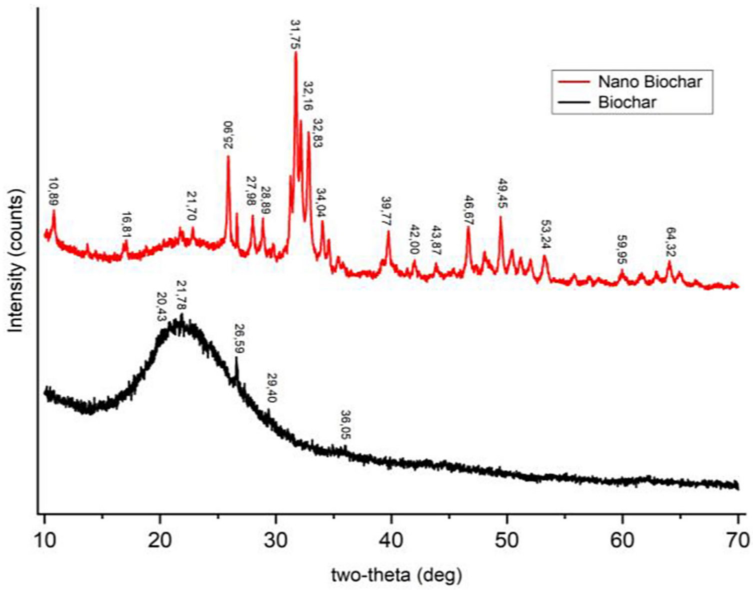

Figure 7. XRD analysis of biochar and nano biochar

SRF-Ni + alginate 2%, it was also carried out to identify possible changes in structure or the formation of new compounds that affect the mechanism of gradual release of nitrogen nutrients (Figure 8). The XRD (X-ray diffraction) analysis showed that SRF-Nn (nano biochar) had sharper diffraction peaks and higher intensity than SRF-Ni (using conventional biochar), indicating higher crystallinity of SRF-Nn, possibly due to the smaller and more homogeneous particle size of nano biochar. In contrast, SRF-Ni showed a more amorphous structure with less sharp diffraction peaks due to the larger particle size and structural heterogeneity that caused weaker and less defined diffraction peaks. This is by the findings of, (Zouari *et al*., 2024) who reported that biochar from bark with smaller particles tends to increase the adsorption capacity of the material due to the larger surface area and pore volume. In contrast, larger particles show a more heterogeneous structure and weaker diffraction peaks because amorphous minerals dominate them.

The XRD peak intensity of SRF-Nn + 2% alginate and SRF-Ni + 2% alginate showed an increase compared to 0% alginate; this occurred because of the role of alginate as a binder that affects the crystallization and structure of biochar. Hao *et al*. (2025) reported that adding alginate to biochar increased crystal orientation, as higher XRD diffraction intensity indicated. This is due to the ability of alginate to rearrange the biochar structure to be more organized, strengthen the bonds between particles, and create a more regular crystal pattern, especially in small biochar particles, such as nano biochar. The XRD diffraction peak of SRF-Nn with 2% alginate is the highest because the carboxylate group in alginate can interact with the active groups of nano biochar such as hydroxyl and carbonyl, thus forming stable ionic or covalent bonds. The stable bond can promote a more regular redistribution of atoms, creating a larger crystal area and more intense XRD diffraction. Wang *et al*. (2023) reported that the addition of alginate polymer to biochar-based materials can improve the crystal structure and adsorption, resulting in significant changes in the XRD diffraction pattern.

Identification of diffraction peaks in SRF-Kn fertilizer + 0% and 2% alginate and SRF-Ki alginate 0% and 2% in Figure 9 shows that all SRF-K fertilizer samples show a typical diffraction pattern, namely a sharp peak at the 2θ position around 28.33° to 28.99°, indicating the high crystallinity of biochar and nano biochar with KCl. However, in SRF-Kn with 2% alginate, there is an increase in the intensity of the diffraction peaks at a higher 2θ position, indicating an increase in crystallinity. This is due to the interaction of carboxyl groups in alginate with active groups in nano biochar, which promotes the redistribution of atoms and the formation of more stable bonds, increasing the crystal order in the KCl structure. (Wang *et al*., 2018) reported that the interaction of carboxyl functional groups in alginate with the surface of nano biochar, through ion exchange or hydrogen bond formation, significantly affects the order and increase in crystals.

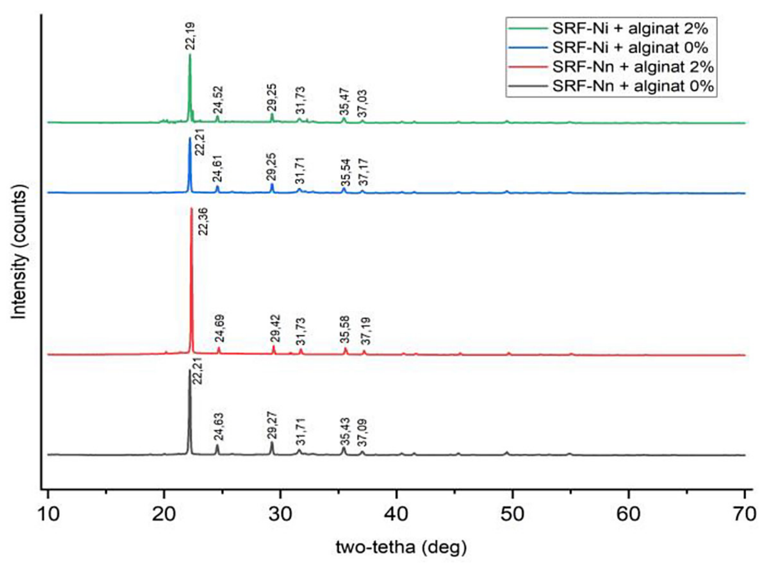

Figure 8. XRD analysis of SRF-Nn and SRF-Ni fertilizers with 0% and 2% alginate

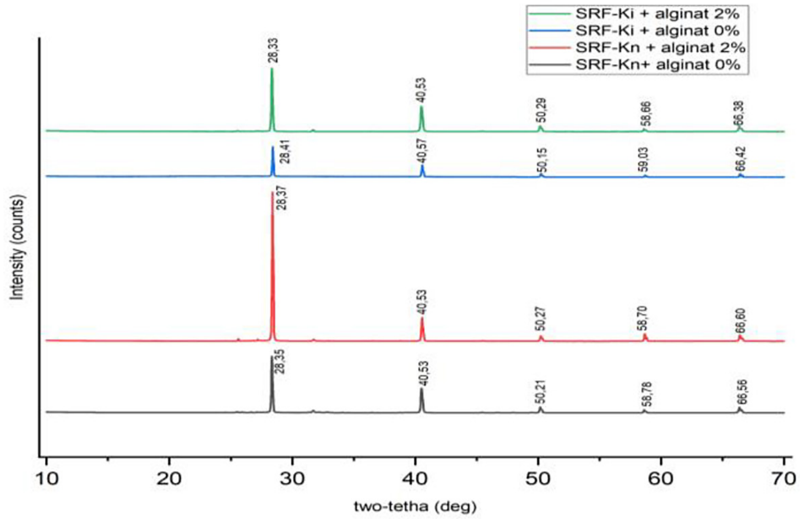

Figure 9. XRD analysis of SRF-Kn and SRF-Ki fertilizers with 0% and 2% alginate

The diffraction analysis (XRD) results show diffraction peaks that provide important information about the material components. The peak at 2θ or 2thetha 26–28° indicates the presence of quartz (SiO_2), whose intensity reflects the purity and concentration of this mineral in the sample. At 40.53°, the peak shows an organized carbon structure such as graphite, which is formed due to the transformation of amorphous carbon during pyrolysis. Meanwhile, the peak at 50.21° reflects the crystal structure of KCl, which does not experience significant changes, indicating that the interaction with biochar is more physical, such as adsorption or electrostatic forces, rather than chemical reactions that can change the crystal structure of KCl. This shows that biochar does not cause changes in the crystal lattice, which maintains its shape and arrangement despite the presence of carbon. Nkoh *et al.* (2021) also stated that biochar is an adsorbent that can attract ions or molecules through Van der Waals forces or electrostatic interactions without significantly changing the crystal structure of the adsorbed material, such as KCl.

CONCLUSIONS

SRF-Nn and SRF-Kn (based on nano biochar) have an average particle size of 40.42 nm with a finer morphology, evenly distributed pores, and a larger surface area. The diversity of functional groups in nanobiochar increases the cation exchange and nutrient adsorption capacity, contributing to nutrient release efficiency. The even pore structure creates new reactive sites, strengthening the interaction with oxygen and other compounds in the soil. Adding 2% alginate produces a more stable and homogeneous structure, increasing the durability of SRF fertilizer. SRF-Nn and SRF-Kn (based on nano biochar) have high crystallinity with a dominance of quartz (SiO_2) and calcite ($CaCO_3$) minerals, which play a role in increasing the adsorption capacity and structure stability. Overall, these characteristics make SRF-Nn and SRF-Kn have the potential to gradually improve nutrient release efficiency compared to impregnated biochar, thus supporting increased fertilizer efficiency and agricultural sustainability.

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