



Corn Starch/Soybean Wax Double Coated Biochar-based Controlled-release Nitrogen Fertilizer: Water Retention, Release Kinetics and Okra Growth

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Abstract Water-soluble fertilizers, although widely used to enhance crop productivity, often lead to environmental pollution due to their rapid nutrient loss. To address this issue, coated biochar-based fertilizers have gained attention for improving nutrient use efficiency and reducing environmental impacts, with their performance greatly depends on the formulation of the encapsulating materials. Biopolymers such as starch offer a biodegradable alternative to synthetic polymers, while soybean wax provides an environmentally-friendly and highly hydrophobic coating capable of enhancing the controlled-release behaviour. Together, these materials present a promising strategy for developing more sustainable controlled-release fertilizer formulations. In this study, a double-layered coated biochar-based fertilizer was synthesized using corn starch as the inner coating and soybean wax as the outer layer to enhance the nutrient release performance and support sustainable agriculture. The double-coated formulation improved the water retention and slowed the nitrogen release

as compared with the uncoated fertilizer, following a zero-order kinetic mechanism. These controlled-release characteristics enhanced the plant performance as evidenced by the increased okra height. Overall, the corn starch/soybean wax coating demonstrated a strong potential for reducing the nutrient loss while promoting crop growth.

Keywords Biochar-based fertilizer · Soybean wax · Corn starch · Water retention · Release mechanism

1 Introduction

As world population increases, the food demand among humans also increases. The improvement of crop yield is necessary to provide sufficient and quality food to humans. Fertilizers have been used in farming and planting for decades to maintain the fertility of soil and provide sufficient nutrients to the crops, thus improving the quality and quantity of crops (Chen et al., 2018). Nitrogen, phosphorus and potassium are essential macronutrients for plant growth, yet conventional fertilizers are not fully absorbed by plants due to their high solubility which leads to nutrient loss through leaching, volatilization or surface runoff (Sim et al., 2021). Controlled-release fertilizers address this problem by releasing nutrients more efficiently and sustaining their availability in the soil for a longer period. By controlling the nutrient release rate, these fertilizers improve

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nutrient use efficiency, reduce environmental pollution and minimize nutrient loss from heavy rainfall or excessive irrigation (Lawrencía et al., 2021). As a result, controlled-release fertilizers help to ensure that nutrients are better absorbed by crops while protecting the environment.

Biochar is a carbon-rich material produced during pyrolysis process using biomass as the feedstock (Manyà et al., 2018). Biochar is commonly used in reducing greenhouse gas emissions, adsorption, waste management, catalyst, energy storage and carbon sequestration (Ndoung et al., 2021). In agriculture, biochar is also used in amending the soil texture and properties by absorbing heavy metals contained in the soil (Kwapinski et al., 2010). Besides, biochar is also used to improve soil properties such as cation exchange capacity, soil acidity, water retention and plant growth (Xiang et al., 2020). Biochar-based fertilizers are recently invented by researchers to reduce nutrient leaching and improve nutrient use efficiency. Despite biochar-based fertilizers slow down the release of nutrients, the release property of the nutrients still needs to be improved due to the weak bonding between the biochar and nutrients (An et al., 2021; Sim et al., 2025). To enhance the prolonged release mechanism, coating technology and biochar-based fertilizer have been combined as a potential option. Zhang et al. (2023) developed a sodium alginate coated urea-impregnated biochar-based fertilizer and studied its effect on maize growth, which showed excellent slow-release property and enhanced maize growth performance. The nutrient release rate of the coated biochar-based fertilizers greatly depended on the encapsulating materials.

Synthetic polymers have been commonly used as encapsulating materials to synthesize controlled-release fertilizers. Most of the synthetic polymers are costly and non-biodegradable which cause environmental pollution (Lawrencía et al., 2021). The non-biodegradable polymers accumulate in soil, thus reducing the soil quality and crop production. In recent years, bio-based polymers such as starch have gained interests as green encapsulating materials to replace synthetic polymers as they are biodegradable and cheaper. The main drawback of using starch as an encapsulating material is the high hydrophilicity, thereby the release rate of nutrients would be fast. The modification of starch or the use of crosslinker have been introduced to overcome this limitation.

Double coating layer is an innovative method to alleviate the performance of the nutrient release rate of the coated biochar-based fertilizers. Kareem et al. (2021) claimed that the double coating layer of fertilizer extended the release performance as compared with single coating layer. Apart from polymer-based encapsulating material, waxes such as paraffin wax, microcrystalline wax (Wang et al., 2017), carunaba wax, beeswax and candedila wax (Baird et al., 2023) have been investigated as encapsulating materials to reduce the release of nutrients due to their hydrophobic characteristics. Soybean wax is another natural wax commonly used in food coating (Shen et al., 2020). The application of soybean wax as an encapsulating material to synthesize controlled-release fertilizers has not been explored in the literature. Various formulations of double coated fertilizers such as polyacrylate and carnauba wax (Ge et al., 2022), chitosan and microcrystalline wax (Wang et al., 2017), ethyl cellulose and cellulose superabsorbent (Zhang & Yang, 2021), hydroxy propyl methyl cellulose/polyvinyl alcohol/glycerol and blended paper (Kareem et al., 2021), polyvinyl alcohol/silica (Ghosh et al., 2024) and biopolyurethane/ceresin wax (Su et al., 2024) had been utilized as encapsulating materials to synthesize double coated slow/controlled-release fertilizers. To date, the use of corn starch/soybean wax combination to develop new formulation of double coated slow/controlled-release fertilizer has not been found in the literature. Therefore, this study investigated the potential of an environmentally-friendly double coated biochar-based controlled-release fertilizer synthesized using corn starch as inner coating and soybean wax as outer coating. This study evaluated the performance of the double coated biochar-based fertilizer in terms of the thermal stability, water retention in soil, nitrogen release behaviour, release kinetics and okra plant growth.

2 Materials and Methods

2.1 Synthesis of Uncoated and Corn Starch/Soybean Wax Double Coated Biochar-based Fertilizers

Rice husk ash biochar fertilizer supplied by BioChar Organik was used in this study. The biochar fertilizer was first grinded to powder form and 25% (w/w) of hydroxypropyl methyl cellulose was mixed with the

biochar fertilizer powder with a ratio of 1:10 (w/w). The mixture was placed in a pellet press machine to form pellets and dried in an oven overnight at 70 °C. This sample was labelled as uncoated biochar-based fertilizer. To synthesize corn starch/soybean wax coated biochar-based fertilizer, 2% (w/w) of corn starch was prepared by mixing 2 g of corn starch with 100 mL of distilled water (Himmah et al., 2018). 1 g of glycerol was then added into the corn starch. The solution was stirred and heated using a magnetic stirrer hot plate until the solution turned homogenous. The solution was cooled to room temperature (25 ± 2 °C). The granulated biochar fertilizer was dipped into the solution and dried in an oven for 2 h at 70 °C. This step was repeated four times to make sure that the granulated biochar fertilizer was evenly coated with corn starch. After coating with corn starch, 5 g of soybean wax was heated using a magnetic stirrer hot plate until the soybean wax turned into liquid form. The biochar fertilizer coated with corn starch was then dipped into the soybean wax solution and naturally dried at room temperature (25 ± 2 °C). The schematic diagram of the synthesis of corn starch/soybean wax coated biochar-based fertilizer is shown in Fig. 1. The coating content was calculated using Eq. (1) (Su et al., 2024).

$$\text{Coating content (\%)} = \frac{m_2 - m_1}{m_2} \times 100 \quad (1)$$

where m_2 represents the weight of the coated biochar-based fertilizer while m_1 represents the weight of the uncoated biochar-based fertilizer.

2.2 Characterization of Uncoated and Corn Starch/Soybean Wax Double Coated Biochar-based Fertilizers

The nitrogen contents of the uncoated and corn starch/soybean wax coated biochar-based fertilizers were determined using Kjeldahl method (Liu et al., 2019). The surface morphology and elemental composition of the fertilizers were determined using scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDS) (Model TM4000Plus, Hitachi, Japan) with accelerating voltage of 15 kV (Adeniyi et al., 2019). The surface chemistry of the fertilizers was analyzed using Fourier transform infrared spectroscopy (FTIR) (Model IRAffinity 1S, Shimadzu, Japan) under $400\text{--}4000\text{ cm}^{-1}$ (Sarkar et al., 2021) while the thermal stability of the fertilizers was determined using a thermal analyzer (Model DTG-60, Shimadzu, Japan).

2.3 Cumulative Nitrogen Release Behaviour

About 400 g of soil was weighed and placed in a bottle with holes on the cap. Two pieces of filter papers were cut into small round shape and lined the cap. 0.73 g of uncoated biochar-based fertilizer and 0.78 g of corn starch/soybean wax coated biochar-based fertilizer was respectively placed into 400 g of the soil. The fertilizers were buried in the middle section of the soil and 50 mL of distilled water was added into the soil. The soil was watered once every two days, and the water collected under the bottle was tested for the nitrogen

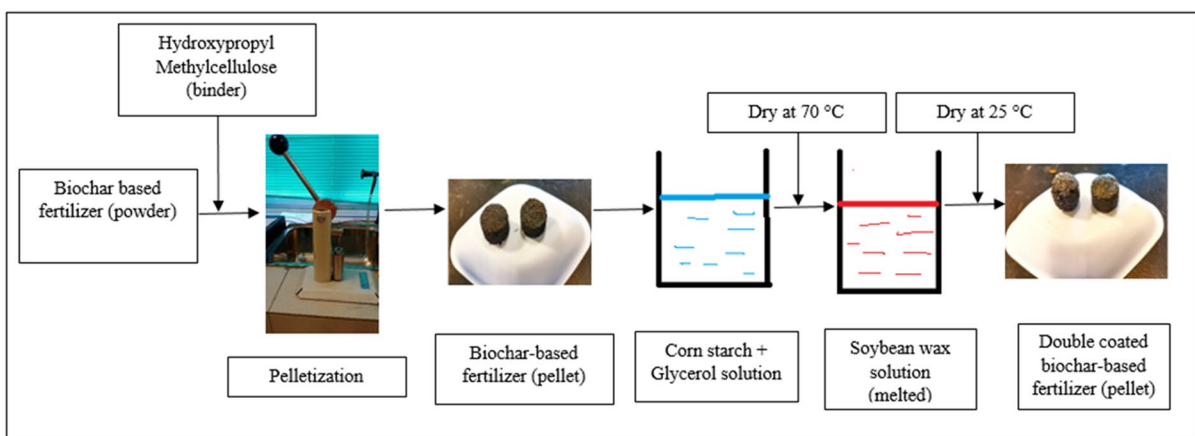


Fig. 1 Schematic diagram of the synthesis of corn starch/soybean wax coated biochar-based fertilizer

content using Kjeldahl method (Liu et al., 2019). The nitrogen content was determined using Eq. (2).

$$\text{Nitrogen(\%)} = \frac{(\text{Titrantvolume} - \text{titrantblank}) \times \text{normality of acid} \times 14 \times 1000}{\text{Sampleweight(mL)}} \quad (2)$$

2.4 Release Kinetic Modelling

The nutrient release kinetic models used to study the release mechanism of the uncoated and corn starch/soybean wax coated biochar-based fertilizers were zero-order release kinetic model, first-order release kinetic model, Higuchi model and Korsmeyer-Peppas model (Maghsoodi et al., 2020; Sim et al., 2024), as shown in Eqs. (3)–(6), respectively:

$$Q = Q_0 + k_0 \quad (3)$$

$$\text{Log } C_t = \text{Log } C_0 - \frac{k_t}{2.303} \quad (4)$$

$$\frac{M_t}{M_0} = k_{Ht} \frac{1}{2} \quad (5)$$

$$\frac{M_t}{M_0} = k_{kp} t^n \quad (6)$$

where Q is the amount of nitrogen release (mg), Q_0 is the initial amount of nitrogen leach in the beaker (mg), C_0 is the initial amount of nitrogen in the fertilizer (mg) and C_t is the amount of nitrogen leach in the beaker, t is the time (day), $\frac{M_t}{M_0}$ represents the release of nitrogen from uncoated and corn starch/soybean wax coated fertilizer at time t , n indicates the exponent (transport mechanism) whereas k_p , k_0 , k_H and k_{kp} are the release constants.

2.5 Water Retention in Soil

About 400 g of soil was weighed and placed in a bottle. Then, 0.73 g of the uncoated biochar-based fertilizer and 0.78 g of the corn starch/soybean wax double coated biochar-based fertilizer was added into the 400 g of the soil separately. The fertilizers were buried in the middle of the soil and 150 mL of distilled water was added into the soil, and the bottles with the soil and distilled water were weighed again. The bottles were weighed every two days

until constant readings were obtained. The water retention capacity of both the uncoated and corn

starch/soybean wax coated biochar-based fertilizers was calculated using Eq. (7) (Olad et al., 2018):

$$\text{WR(\%)} = \frac{W_t - W}{W_o - W} \quad (7)$$

where WR (%) is the water retention of the fertilizer, W_t (g) is the weight of sample bottle measured daily, W_o (g) is the initial weight of bottle containing soil, fertilizer and distilled water, W (g) is the weight of bottle containing soil and distilled water (control experiment).

2.6 Plant Growth

Okra (lady fingers) seedlings were first wetted in a container and kept in a dark and cool place. After two days, the seeds were transplanted to the pots prepared with normal topsoil. The texture of the soil was clayey-textural type, while the pH of the soil was 6.48. The nitrogen content of the soil was about 0.2%. The plant growth experiments were conducted for a short-term period of 25 days. The application rate of nitrogen was supplied at 200 kg/ha (Jallow et al., 2021). The plants were left to grow for another few days before the uncoated and corn starch/soybean wax coated biochar-based fertilizers were respectively added to the plants. The uncoated and corn starch/soybean wax coated biochar-based fertilizers were then buried around the roots of the plants in the pots (about 5 cm deep in the soil). The initial height of the plants and number of leaves were measured. The pots were placed under the sun and watered every day. The height of the plants and number of leaves were recorded every five days.

3 Results and Discussion

3.1 Surface Morphology and Elemental Analysis

Figure 2 shows the surface morphology of the (a) uncoated biochar-based fertilizer and (b) corn starch/

soybean wax coated biochar-based fertilizer under 200 \times magnification. From Fig. 2(a), the surface of the uncoated biochar-based fertilizer was rough, uneven and had more pores. The contact area between the membrane shell of the biochar-based fertilizer and water molecules was increased by the surface roughness and porousness. As a result, a lot of water quickly permeated the fertilizer membrane, accelerating the nutrient decomposition and release (Tian et al., 2021). Besides, the surface of the uncoated biochar-based fertilizer was loose and did not hold tightly together. The biochar-based fertilizer pellets would then scatter easily when water was added to them, thus increasing the nutrient release rate. This caused the scattered biochar-based fertilizer to have a direct contact with the water as more surface area was exposed to water, thereby increasing the nutrient release rate. Wang et al. (2023) found that the biochar-based fertilizer

without granulation had a higher nutrient release rate than the biochar-based fertilizer with granulation. In contrast, the surface of the corn starch/soybean wax coated biochar-based fertilizer (Fig. 2(b)) was smoother, more even and had less pores on the surface. This was possibly due to the presence of the coating layers which had sealed the pores of the biochar-based fertilizer. The findings were consistent with Su et al. (2024) which reported that the addition of a layer of ceresin wax sealed the micropores of the biopolyurethane coated fertilizer. The diffusion of water molecules into the core and release of nutrients from the core could be stopped by the uniform and dense coating layers (Jia et al., 2020). This helped to prevent the fertilizer to release nutrients too quickly and being washed away by heavy rainfall. The surface of the biochar-based fertilizer was covered by a dual thin coating layer, reducing particle scattering during watering. If the fertilizer were scattered, the surface area for nutrient leaching would also increase. Therefore, the presence of coating layers was important to prevent the biochar-based fertilizer from scattering during handling or watering (Alemi et al., 2010). The coating content of the corn starch/soybean wax coated biochar-based fertilizer was 10%.

The nitrogen content of the uncoated biochar-based fertilizer was found to be 1.33%, whereas the nitrogen content of the corn starch/soybean wax coated biochar-based fertilizer was 1.26%. The insignificant difference was possibly caused by the loss of nitrogen during the encapsulating process, as part of the soluble nitrogen might dissolve and diffuse from the fertilizer. Similar observation was reported by Sim et al. (2024) that the tapioca starch/palm oil coated biochar-based fertilizer had a lower nitrogen content (9.50%) than the uncoated biochar-based fertilizer (15.50%) due to the loss of nitrogen during the encapsulating process. Different nitrogen content could also be due to the different synthesis methods, conditions and materials used such as the type of biochar and nutrient. The different porous structure and functional groups of biochar varied with the biochar type and synthesis conditions, thereby the ability of nutrient retention varied greatly. It is important to optimize the nutrient loading capacity of the biochar in order to ensure more nutrient can be supplied to the plants (Sim et al., 2025). Himmah et al. (2018) conducted a study to compare the nitrogen content of starch coated and uncoated NPK fertilizer,



Fig. 2 Surface morphology of (a) uncoated and (b) corn starch/soybean wax coated biochar-based fertilizers (200 \times magnification)

and found that the nitrogen content of starch coated NPK fertilizer was 11.91% whereas the nitrogen content of uncoated NPK fertilizer was 14.04%. It was stated that the reduction of the nitrogen content was probably due to the effect of dilution and volatilization that occurred during the coating process (Himmah et al., 2018). It was concluded that the nitrogen content of starch coated NPK fertilizer was slightly lower than the uncoated NPK fertilizer. Although the nitrogen content was slightly reduced, the controlled-release profile was enhanced, allowing nutrients to be supplied to the plants over a longer period rather than being rapidly released and lost through leaching into groundwater or surface runoff. This not only mitigates environmental pollution but also improves nutrient use efficiency by plants.

Table 1 compares the total mass percentage and atom percentage of other elements contained in the uncoated and corn starch/soybean wax coated biochar-based fertilizers. There were five elements namely carbon, oxygen, potassium, phosphorus and silicon detected in both the uncoated and corn starch/soybean wax coated biochar-based fertilizers. According to Asadi et al. (2021), rice husk biochar contained carbon, oxygen, phosphorus, potassium and silicon. The total mass percentage of carbon and oxygen of the rice husk biochar was higher than other elements. The uncoated and corn starch/soybean wax coated biochar-based fertilizers synthesized in this study contained higher carbon and oxygen as compared to other elements. However, the carbon and oxygen mass percentage of the corn starch/soybean wax coated biochar-based fertilizer was higher than the uncoated biochar-based fertilizer. This was possibly due to the nutrient analysis of the coated fertilizer had been impacted by the inclusion of starch as the

coating (Himmah et al., 2018). The silicon element was reduced for soybean wax coated biochar-based fertilizer due to the diffusion of water-soluble silicon from the biochar-based fertilizer during the coating process. The phosphorus and potassium contents of both the uncoated and corn starch/soybean wax coated biochar-based fertilizers showed no significant difference. The phosphorus, potassium and silicon contents of the uncoated and corn starch/soybean wax coated biochar-based fertilizers could act as nutrient sources to alleviate the soil fertility. Sim et al. (2024) also claimed that the other elements found in the tapioca starch/palm oil biochar-based fertilizer could be used as macronutrient and micronutrient for plant growth.

3.2 Chemical and Thermal Properties

Figure 3 shows the FTIR spectrum of the (a) uncoated biochar-based fertilizer and (b) corn starch/soybean wax coated biochar-based fertilizer. Referring to Fig. 3(a), OH stretching vibration was found at 3800 cm^{-1} (Lingegowda et al., 2013). The aromatic primary amine, N–H strength was found in the range of wavelength $3510\text{--}3460\text{ cm}^{-1}$. Another broad absorption between $3100\text{--}3500\text{ cm}^{-1}$ indicated the presence of hydroxyl group. The sharp peaks found at 2033.33 cm^{-1} and 2164.13 cm^{-1} indicated that the sample contained isothiocyanate (-NCS) and thiocyanate (-SCN). The $\text{C}=\text{C}$ aromatic ring stretching and secondary amine $>\text{N}-\text{H}$ bend was detected at 1580 cm^{-1} . At 1062.78 cm^{-1} , inorganic compounds such as silicate ion, phosphate ion and sulphate ion were detected. Primary amine, CN stretch and alkyl substituted ether, and C–O stretch was found at 1062.78 cm^{-1} . The presence of ether and oxy

Table 1 Comparison of elements contained in uncoated and corn starch/soybean wax coated biochar-based fertilizers

Elements	Mass (%)		Atom (%)	
	Uncoated biochar-based fertilizer	Corn starch/soybean wax coated biochar-based fertilizer	Uncoated biochar-based fertilizer	Corn starch/soybean wax coated biochar-based fertilizer
Carbon (C)	57.1211	60.5847	52.3714	69.3563
Oxygen (O)	56.4057	31.0474	38.8236	26.6823
Potassium (K)	0.8187	0.8396	0.2306	0.2953
Phosphorus (P)	0.4445	0.6930	0.1580	0.3076
Silicon (Si)	21.4650	6.2296	8.4164	3.0499

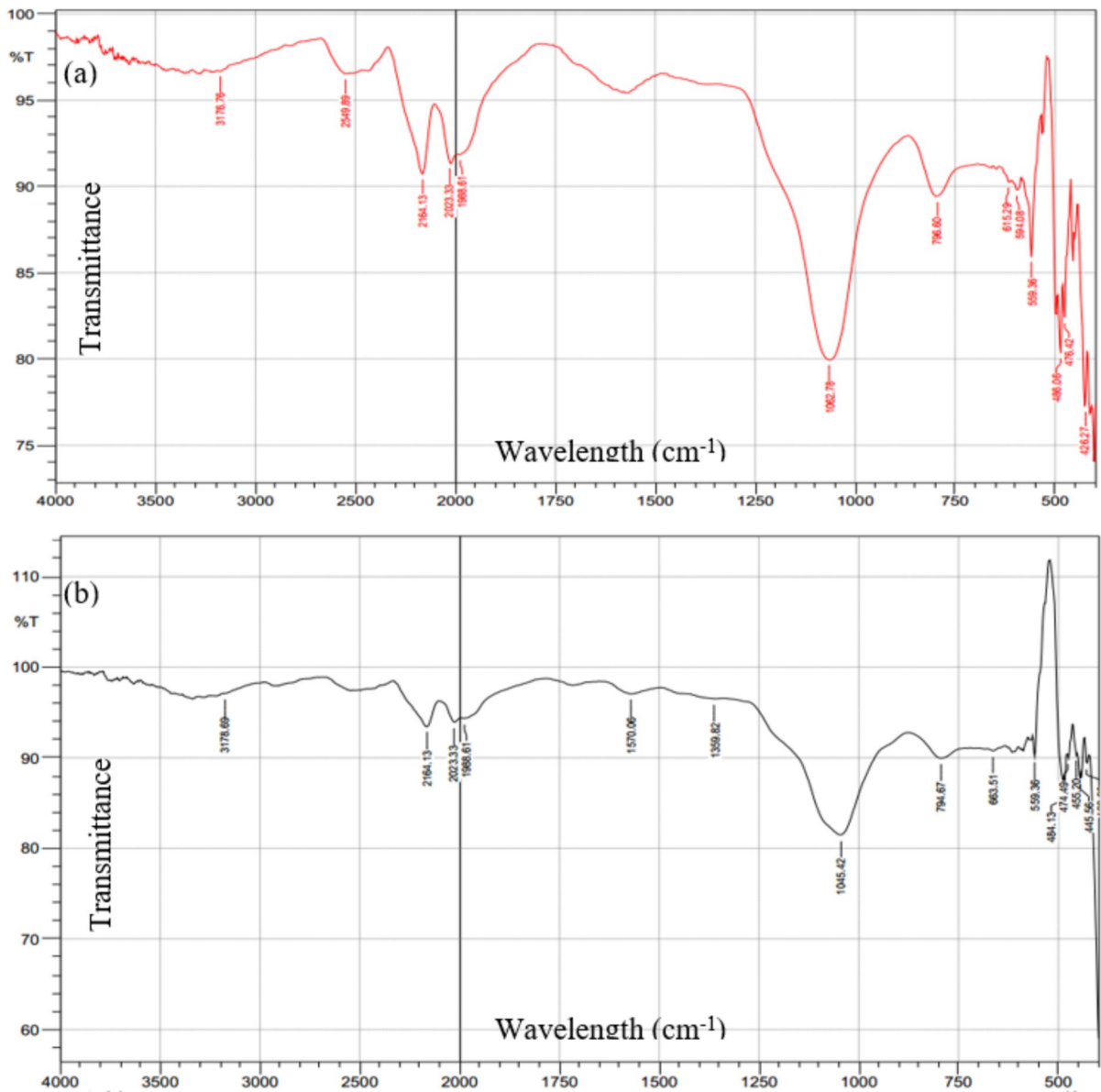


Fig. 3 Surface chemistry of (a) uncoated and (b) corn starch/soybean wax coated biochar-based fertilizers

compounds in the sample was due to the addition of hydroxypropyl methylcellulose (Akinosho et al., 2013). In the range of 400–700 cm^{-1} thiols and thio-substitute compounds were observed.

The FTIR spectrum of the corn starch/soybean wax coated biochar-based fertilizer was quite similar to the uncoated biochar-based fertilizer. Due to the corn starch/soybean wax coating layers, the peaks observed at the fingerprint region were slightly shifted. Zafar

et al. (2021) stated that with the addition of a coating layer, the wavelength present in FTIR would have a slight difference from the uncoated biochar-based fertilizer. At 1045.42 cm^{-1} , aliphatic phosphate, P-O-C stretch was detected. Primary amine, CN stretch and phosphate ion were also detected. The presence of aliphatic phosphate was due to the soybean wax coating layer having hydrophobic properties, and the aliphatic group was generally hydrophobic (Ge et al., 2022).

Hence, aliphatic group was not found in the FTIR spectrum of the uncoated biochar-based fertilizer. Ge et al. (2022) reported similar findings in which the water-borne polymer coated with carnauba wax urea fertilizer showed different functional groups than the uncoated fertilizer. Due to the hydrophobic property of carnauba wax, aliphatic group was present only in the coated urea fertilizer.

Figure 4(a) and Fig. 4(b) respectively shows the thermal behaviour of the uncoated and corn starch/soybean wax coated biochar-based fertilizers. Referring to Fig. 4(a), at the range of 32 °C to 280 °C, 8.37 % of the uncoated biochar-based fertilizer sample was lost, as compared to 1.66 % of the corn starch/soybean wax coated biochar-based fertilizer sample was lost. At the range of 310 to 355 °C, another 3.18 % of the uncoated biochar-based fertilizer was lost due to the decomposition of the cellulose and lignin contents of the sample. According to Ramesh and Raghavan (2024), the decomposition of cellulose and lignin contents in the urea impregnated biochar-based fertilizer was observed at 200 °C to 500 °C. For corn starch/soybean wax coated biochar-based fertilizer,

the decomposition process occurred at the range of 280 °C to 405 °C where only 0.15 % of the sample was lost. At 355 °C, the weight of the uncoated biochar-based fertilizer was further reduced by 10.03 %, whereas the weight of the corn starch/soybean wax coated biochar-based fertilizer was reduced by only 3.33 % at 405 °C. Referring to Fig. 4(b), two sharp peaks were found on the uncoated biochar-based fertilizer sample. The first sharp peak was at the range of 32 °C to 146 °C, where at this stage the evaporation and degradation of the sample occurred. The second peak was observed at the range of 270 °C to 400 °C, where the degradation of the sample residual continued. For the corn starch/soybean wax coated biochar-based fertilizer, an obvious sharp peak was found at the range of 230 °C to 470 °C due to degradation of the sample. The TGA data of the uncoated and corn starch/soybean wax coated biochar-based fertilizers are shown in Table 2. Based on the DTG and TGA results, the thermal stability of the corn starch/soybean wax coated biochar-based fertilizer was better than the uncoated biochar-based fertilizer. This indicated that the use of corn starch as an inner coating

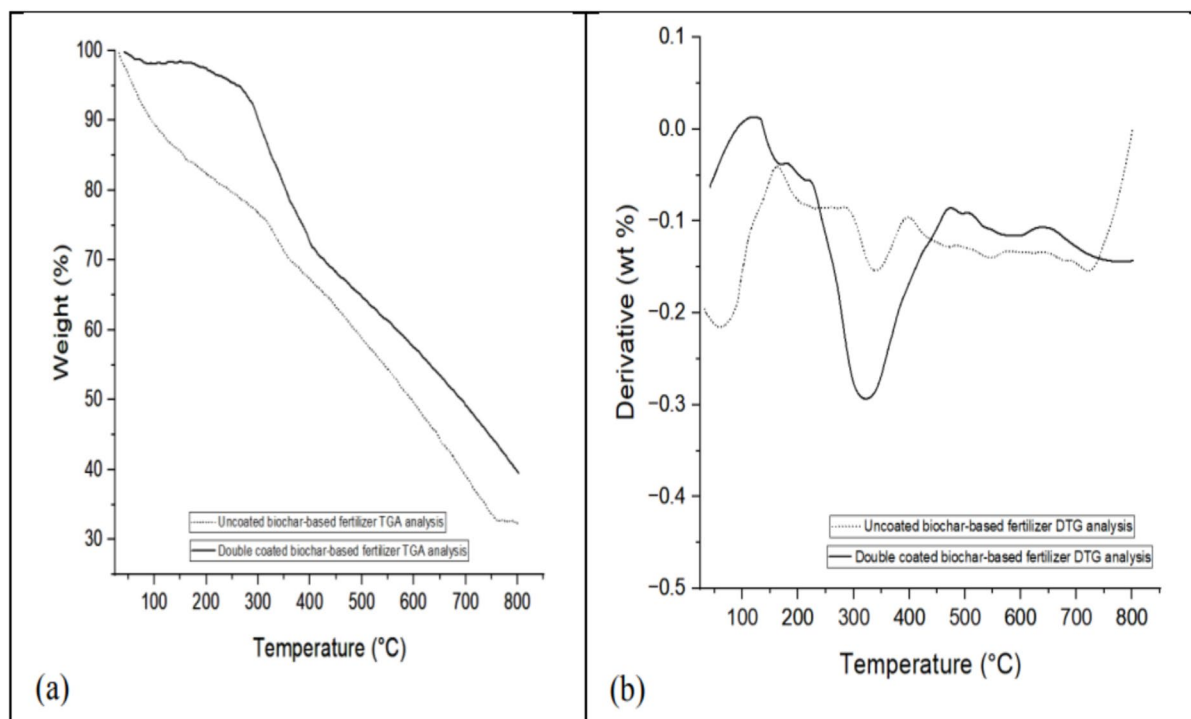


Fig. 4 (a) TGA and (b) DTG graphs of uncoated and corn starch/soybean wax coated biochar-based fertilizers

Table 2 TGA data of uncoated and corn starch/soybean wax coated biochar-based fertilizers

Sample	T ₅ (°C)	T ₅₀ (°C)	Residual weight (%)
Uncoated biochar-based fertilizer	59.78	595.82	32.24
Corn starch/soybean wax coated fertilizer	254.31	681.42	39.57

material and soybean wax as an outer coating material had successfully improved the thermal stability of the coated biochar-based fertilizer. In contrast, An et al. (2021) observed that biopolymers coated biochar-based fertilizer had a poorer thermal stability than the uncoated biochar-based fertilizer. It could be concluded that the thermal stability of the coated fertilizer depended on the formulation of the encapsulating methods and materials used.

3.3 Water Retention Capacity

Figure 5 shows the water retention capacity of (a) uncoated and (b) corn starch/soybean wax coated biochar-based fertilizers in soil. The uncoated biochar-based fertilizer had a lower water retention capacity of 58.11% as compared to the corn starch/soybean wax coated biochar-based fertilizer (65.54%) achieved on day 23. This was because the corn starch coating material assisted in retaining the water molecules due to its high hydrophilicity which allowed water

molecules to interact with the corn starch (Fertahi et al., 2021). The tapioca starch/palm oil encapsulated biochar-based fertilizer synthesized by Sim et al. (2024) also improved the water retention of sandy soil. Gungula et al. (2021) also reported that the water retention capacity of the fertilizer coated with *Borassus aethiopum* starch and *Maesopsis eminii* hydrogels was higher than the uncoated fertilizer, which reduced the frequency of irrigation. The ability to retain water is important to a fertilizer as it could supply water during dry periods. Additionally, it promotes optimal plant growth, improves water efficiency and shortens watering cycles (Gungula et al., 2021).

3.4 Cumulative Nitrogen Release Behaviour

Figure 6 shows the cumulative nitrogen release of (a) uncoated and (b) corn starch/soybean wax coated biochar-based fertilizers in 23 days. The cumulative nitrogen release of the uncoated biochar-based fertilizer was 1.096 mg, whereas the cumulative nitrogen release of the corn starch/soybean wax coated biochar-based fertilizer was only 0.474 mg after 23 days. The slow-release rate of corn starch/soybean wax coated biochar-based fertilizer was caused by the dual coating layers which acted as water barrier to prevent the water to enter or have a direct contact with the fertilizer core. The soybean wax as outer layer coating was hydrophobic which further reduced the uptake of water molecules. From day 1 to 15, the corn starch/soybean wax coated biochar-based fertilizer released very little nitrogen which was 0.205 mg (2.23%) and

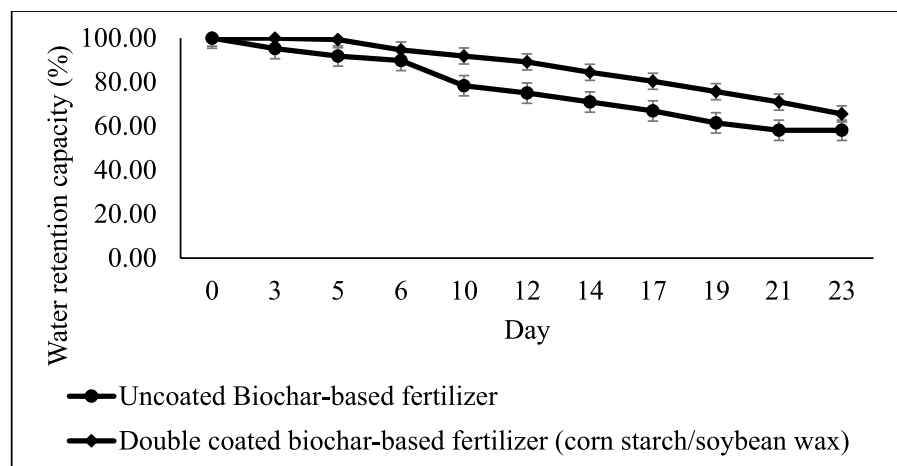
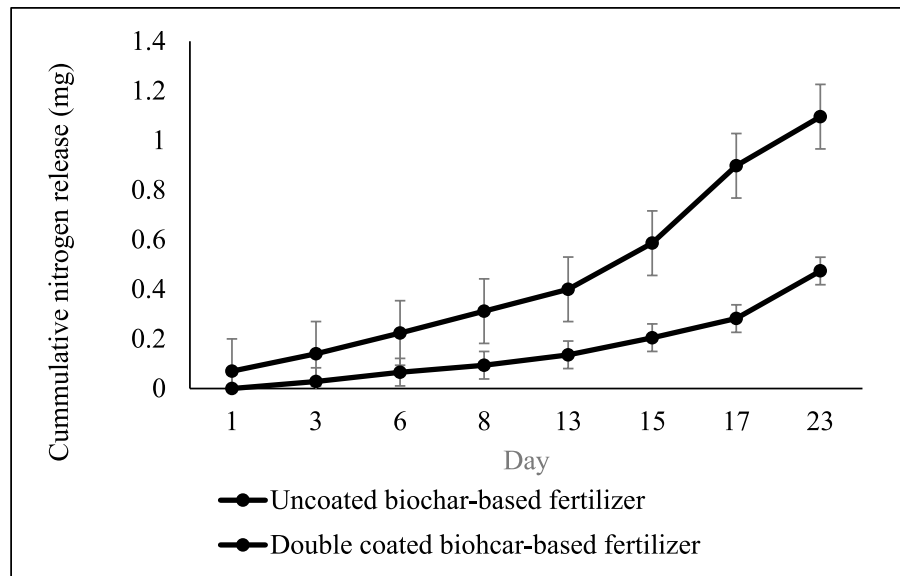
Fig. 5 Water retention capacity of (a) uncoated and (b) corn starch/soybean wax coated biochar-based fertilizers in soil

Fig. 6 Cumulative nitrogen release behaviour of (a) uncoated and (b) corn starch/soybean wax coated biochar-based fertilizers in soil



started to release more nitrogen after 17 days. This was because the coating layers started to degrade as microorganisms in the soil engulfed the coating layers. According to Himmah et al. (2018), the starch that was not mixed with chemicals was easier to be degraded by microorganisms, hence the fertilizer coated with starch only would release nutrients faster than the fertilizer coated with other polymers or waxes. Therefore, with soybean wax acting as a protective layer, the microorganism would take a longer time to degrade the soybean wax layer before degrading the corn starch coating layer.

Although the uncoated biochar-based fertilizer released more nitrogen content than the coated biochar-based fertilizer, the nitrogen release rate of the uncoated biochar-based fertilizer was considered slow. As shown in Fig. 6, after 23 days, only 11% of the total nitrogen content in the uncoated biochar-based fertilizer had been released. This was because the nutrient was bound to the surface functional group and pores of the biochar which caused the biochar-based fertilizer to possess slow-release property (Piash et al., 2022). As demonstrated by Ndoung et al. (2021), the release rate of nutrient from the uncoated biochar-based fertilizer was slower than the conventional fertilizers such as urea, ammonium nitrate, potassium dibasic phosphate and single super phosphate. On day 23, only 5.15% of the nitrogen was released from the corn starch/soybean wax coated biochar-based fertilizer. This proved that the corn starch/soybean wax

coating layers were more efficient as the coating layers would slow down the nitrogen release, thus preventing nitrogen from evaporating into the air or being washed due to heavy rainfall or irrigation.

3.5 Nitrogen Release Kinetic Modelling

The release kinetic rate constant (k), release exponent (n) and R^2 of the uncoated and corn starch/soybean wax coated fertilizers obtained from zero-order release kinetic model, first-order release kinetic model, Higuchi model and Korsmeyer-Peppas model are summarized in Table 3. The first-order release kinetic model, Higuchi model and Korsmeyer-Peppas model were not suitable for explaining the nitrogen release mechanism of both the uncoated and corn starch/soybean wax coated biochar-based fertilizers as the R^2 values were relatively low. The R^2 values obtained for the zero-order release kinetic model were the highest (close to 1), which indicated that this kinetic model best described the nitrogen release mechanism of both the uncoated and corn starch/soybean wax coated biochar-based fertilizers. The release of nitrogen was found to be independent of the concentration. The nitrogen release rate of the corn starch/soybean wax coated biochar-based fertilizer was slower than the uncoated biochar-based fertilizer. This proved that the corn starch/soybean wax encapsulating layers were effective in slowing down the nutrient release of the fertilizer synthesized in this study. Sim et al. (2024) in the other

Table 3 Parameters of different kinetic models for uncoated and corn starch/soybean wax coated biochar-based fertilizers

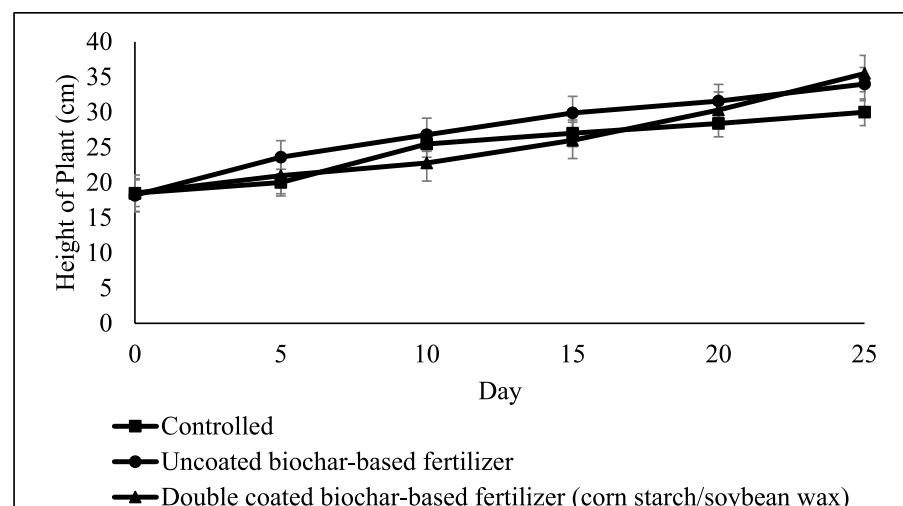
Kinetic model	Parameter	Uncoated biochar-based fertilizer	Corn starch/soybean wax coated biochar-based fertilizer
Zero order kinetic model	k (day^{-1})	0.4525	0.1798
	R^2	0.9746	0.9483
First order kinetic model	k (day^{-1})	-0.1509	-0.2634
	R^2	0.4768	0.4180
Higuchi model	k (day^{-1})	2.8714	1.1878
	R^2	0.9004	0.8339
Korsmeyer-Peppas model	k (day^{-1})	0.5852	0.0927
	N	0.6549	0.2411
	R^2	0.9588	0.2117

hand observed that the Korsmeyer-Peppas model was the best in describing the nutrient release of tapioca starch/palm oil encapsulated biochar-based fertilizer which involved multiple release mechanisms. Kareem et al. (2021) found that the first-order release kinetic model was best in describing the hydroxyl methyl propyl cellulose/polyvinyl alcohol/glycerol and blend paper double coated fertilizer. The different release mechanism occurred for different type of controlled-release fertilizers could be due to the different conditions and encapsulation formulations used to synthesize the fertilizers.

3.6 Okra Growth Performance

Figure 7 shows the height of the okra plants in 25 days. From day 5 to day 20, the okra plant added with the

uncoated biochar-based fertilizer was taller than the other samples. The plant added with the corn starch/soybean wax coated biochar-based fertilizer had lower growth initially. On day 10, the controlled plant and the plant with the uncoated biochar-based fertilizer grew higher. The controlled plant grew 7 cm higher than the plant with the corn starch/soybean wax coated biochar-based fertilizer, whereas the plant with the uncoated biochar-based fertilizer was 8.6 cm higher. This was because the nutrients in the corn starch/soybean wax coated biochar-based fertilizer released more slowly. On day 25, more nutrients were being released hence the plant added with the corn starch/soybean wax coated biochar-based fertilizer started to grow higher than the other two samples, achieving the highest height of 35.5 cm. The number of leaves of the plant added with corn starch/soybean

Fig. 7 Height of okra plants for control, added with uncoated and corn starch/soybean wax coated biochar-based fertilizers

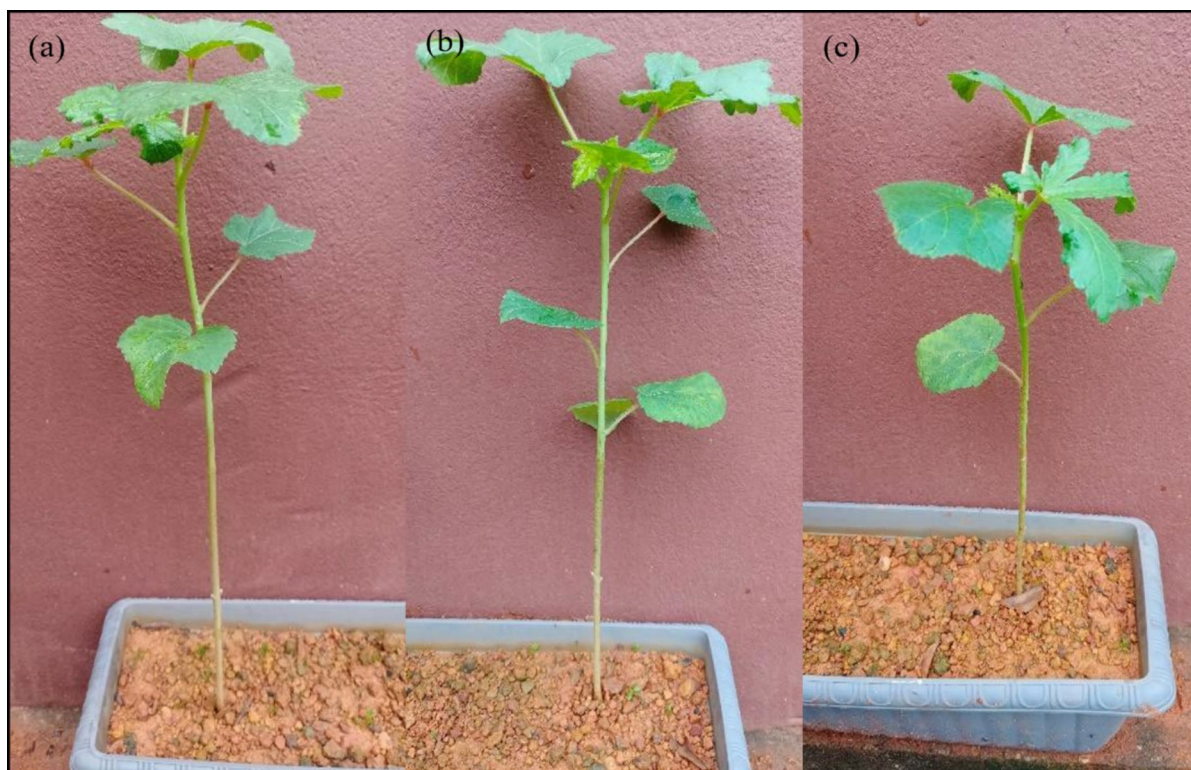


Fig. 8 Leaves of okra plants (a) control, (b) added with uncoated biochar-based fertilizer and (c) added with corn starch/soybean wax coated biochar-based fertilizer

wax coated biochar-based fertilizer increased from 3 to 6 (Fig. 8(a)) whereas the number of leaves of the plant added with uncoated biochar-based fertilizer increased from 3 to 7 (Fig. 8(b)). This was possibly due to the nutrients released by the corn starch/soybean wax coated biochar-based fertilizer was slower, hence longer time was required for the plant to absorb more nutrients at the early stage, thus causing a slower growth. This however benefits in the long-term by providing more consistent nutrients throughout the growth cycle of the plant. As the plant growth performance was conducted in a short duration in this study, it was believed that the number of leaves of the plant added with corn starch/soybean wax coated biochar-based fertilizer would eventually increase and outperform the plant with uncoated biochar-based fertilizer as more nutrients for the uncoated biochar-based fertilizer would be leached without being utilized by the plant due to the fast nutrient release rate. The findings were supported by Sun et al. (2023) which found that the controlled-release fertilizer was not able to meet the rapid demand in the early rice seedlings growth stage.

4 Conclusions

Corn starch/soybean wax double coated biochar-based controlled-release nitrogen fertilizer was synthesized. The corn starch/soybean wax coated fertilizer enhanced the water retention capacity in soil (65.54%) as compared to the uncoated biochar-based fertilizer (58.11%) after 23 days. The nutrient release rate of the corn starch/soybean wax coated biochar-based fertilizer was slower than the uncoated biochar-based fertilizer, with the zero-order kinetic model best described the release kinetics of both the uncoated and coated fertilizers. The thermal stability of the corn starch/soybean wax coated biochar-based fertilizer was better than the uncoated biochar-based fertilizer. The height of okra plant added with corn starch/soybean wax coated fertilizer treatment was the highest as compared to the control and uncoated biochar-based fertilizer samples after 25 days. This study demonstrated that the corn starch/soybean wax formulation is a promising and sustainable coating for controlled-release

systems, thereby contributing to the advancement of modern agricultural technologies. Overall, the dual-layer corn starch/soybean wax coated biochar-based fertilizer functions as a green controlled-release fertilizer that improves nutrient use efficiency and minimizes environmental impact. In future studies, the long-term effect and techno-economic analysis of the formulated corn starch/soybean wax coated biochar-based fertilizer on other plants can be investigated to evaluate its feasibility for large-scale production and field application.

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Data Availability Data will be made available on request.

Declarations

Ethics approval and consent to participate Not applicable.

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Competing interests The authors declare no competing interests.

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