

## Recycling agricultural waste into controlled-release fertilizer: Integrating rice husk biochar with NPK fertilizer for efficient okra growth

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### ABSTRACT

The development of sustainable and efficient fertilizers is crucial for improving agricultural productivity while minimizing environmental impact. In this study, we introduce an efficient impregnation method for producing rice husk biochar (RHB)-based NPK fertilizers, aimed at enhancing nutrient use efficiency (NUE) and plant growth of okra at the small scale. Physicochemical characterization confirmed successful NPK impregnation into the biochar matrix, as evidenced by X-ray diffraction (XRD) analysis, nitrogen sorption analysis, and Energy Dispersive X-ray Spectroscopy (EDX). XRD results revealed distinct crystalline phases of NPK compounds within the biochar structure, while nitrogen sorption analysis indicated a significant reduction in surface area from 88.512 m<sup>2</sup>/g (RHB) to 0.485 m<sup>2</sup>/g (NPK-impregnated RHB; NPK-*i*RHB), confirming nutrient occupation within biochar pores. Elution studies confirmed a more controlled and sustained nutrient release in NPK-*i*RHB, leading to superior NUE (38%), compared to RHB (0%;  $p=0.000$ ), NPK fertilizer (19%;  $p=0.048$ ) and physically mixed NPK-RHB (24%;  $p=0.999$ ) towards the final stage. Additionally, NPK-*i*RHB reduced fertilizer input by 50% compared to NPK fertilizer ( $p=0.004$ ), demonstrating significant cost savings. The enhanced performance of NPK-*i*RHB was attributed to stronger nutrient binding and controlled release properties, which were absent in the physically mixed NPK-RHB (*pm*-NPK-RHB). These findings underscore the importance of biochar impregnation over simple mixing, providing a more effective and environmentally friendly fertilizer alternative. The proposed impregnation technique is not only simpler, requiring fewer processing steps, and more cost-effective but also offers a promising solution for sustainable nutrient management in agriculture while repurposing agricultural waste into high-value fertilizers.

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## 1. INTRODUCTION

Biochar is a type of charcoal derived from the thermochemical conversion of animal or plant biomass using various burning methods. It has multiple applications, including use as biofuels, fertilizer adsorbents, catalysts, soil conditioners, and hydrogen storage (Qian et al., 2015). The production of biochar can utilize various feedstocks, and its application enhances both the physical (porosity, structure, and texture) and chemical (pH, cation exchange capacity [CEC], and functional groups) properties of the soil (Sohi et al., 2010). Common biochar production methods include flash carbonization, hydrothermal carbonization, gasification, and hydrolysis (Amalina et al., 2022). The chemical and physical properties of biochar vary depending on the production method and temperature. While carbon (C) is the primary element, biochar also contains hydrogen (H), oxygen (O), and trace amounts of sulphur (S) and nitrogen (N). Due to its carbon sequestration capabilities and greenhouse gas (GHG) reduction properties, biochar is considered environmentally

friendly. Additionally, different types of biochar serve specialized roles as soil amendments (Guo et al., 2020).

Biochar's low nutrient concentration, coupled with its favourable properties for further treatment, has increased its potential for integration with fertilizers to form biochar-based fertilizers (Castejón-del Pino et al., 2023). Research has shown that biochar loaded with nutrients exhibits superior nutrient retention and prolonged nutrient availability compared to other organic materials (Bakshi et al., 2021). Cations such as ammonium (NH<sub>4</sub><sup>+</sup>) and potassium (K<sup>+</sup>) electrostatically bind to negatively charged oxygen-containing functional groups on biochar's surface, forming amines and amides with acidic functional groups, which further enhance nitrate (NO<sub>3</sub><sup>-</sup>) adsorption. The adsorption of NH<sub>4</sub><sup>+</sup> increases with biochar's CEC (Cai et al., 2016). Conversely, NO<sub>3</sub><sup>-</sup> binds with positively charged functional groups on acidified biochar surfaces. Meanwhile, phosphate (PO<sub>4</sub><sup>3-</sup>) adsorbs to negatively charged surface functional groups, such as hydroxyls, carbonyls, and phenols. However, due to biochar's typically low anion

exchange capacity, its ability to adsorb  $\text{PO}_4^{3-}$  is limited. Treating biochar with metal ions has been shown to enhance its  $\text{PO}_4^{3-}$  adsorption capacity (Zhang et al., 2020).

Nitrogen-Phosphorus-Potassium (NPK) fertilizer is a widely used plant nutrient source containing essential elements for plant growth (Fatima et al., 2024). Its water solubility allows for practical application in various agricultural settings, including poly bag plantations, fertigation, and aerial application (Falls & Siegel, 2005). By supplying N, P, and K in a single compound, NPK fertilizer enhances soil chemical properties, optimizing plant growth and crop productivity. However, NPK fertilizers are prone to nutrient leaching and volatilization, leading to reduced nutrient use efficiency and environmental concerns such as soil degradation, air pollution, and water contamination (Wang et al., 2024). Nutrient losses due to leaching, volatilization, or nitrification decrease nutrient availability for plant uptake, ultimately causing soil infertility and lower crop yields (Wang et al., 2024).

To mitigate these issues, controlled-release fertilizers (CRFs) offer an alternative that minimizes environmental pollution while improving nutrient use efficiency. CRFs delay nutrient availability to plants, reducing leaching and nutrient loss (Rajan et al., 2021). Research into CRF production has explored various methods and ingredients, including biochar, to manipulate the controlled release of nutrients (Marciniarczyk and Oleszczuk, 2022). The central argument of this study is that biochar impregnation offers a superior mechanism for nutrient retention and controlled release, thereby improving NUE and crop performance while reducing fertilizer input. This work aims to (i) develop an efficient impregnation technique for producing NPK-impregnated RHB (NPK-*i*RHB), (ii) characterize its physicochemical properties, (iii) evaluate its nutrient release behaviour, and (iv) assess its agronomic performance using okra (*Abelmoschus esculentus* L.) as a model crop.

Rice husk biochar (RHB) is particularly promising due to its high silica content, which enhances nutrient retention and adsorption capacity, further improving soil fertility and fertilizer efficiency (Nguyen, 2021). RHB contains approximately 50% cellulose, 25-30% lignin, and 15-20% silica. The high silica content provides enhanced nutrient retention, plant turgidity, and structural support when combined with fertilizers (Bu et al., 2017). The combustion of lignin and cellulose during carbonization creates a porous carbon structure that enhances soil nutrient retention and serves as a slow-release agent for fertilizers (Asadi et al., 2021). Previous research has demonstrated the potential of RHB as a heterogeneous catalyst support in sugar valorisation (Al-Amsyar, 2022; Al-Amsyar et al., 2017, 2018).

To evaluate its effectiveness, a comparative study

was conducted on okra growth, assessing the nutrient efficiency of NPK-*i*RHB against conventional NPK fertilizer, RHB, and physically mixed NPK-RHB (*pm*-NPK-RHB). Okra was chosen as the test crop due to its wide cultivation, economic importance, high nutrient requirements, fast growth cycle, and sensitivity to nutrient stress, making it an ideal model for evaluating the efficiency of controlled-release fertilizers, as shown by Suhaimi et al., (2022).

## 2. MATERIALS AND METHODS

### 2.1 Crops Preparation

This experiment utilized okra (*Abelmoschus esculentus* L.) plants. A first-generation hybrid variety resistant to cucumber mosaic virus and Phytophthora blight was selected to minimize external factors affecting crop yield. To mitigate the risk of poor or erratic germination, okra seeds were pre-germinated in peat moss. From these, the 12 highest-quality seedlings were selected and transplanted into poly bags containing cocopeat (Toh et al., 2024).

Standard crop management practices were followed throughout the experiment. The plants were maintained at an average temperature of  $28 \pm 2$  °C, with a relative humidity of  $70 \pm 5\%$  under natural daylight conditions (12 h light/12 h dark). Each polybag was watered for ten minutes in the morning and evening using a water sprinkler. Pesticides and herbicides were applied to plants showing symptoms of disease, while weeding was performed to remove moss growth. Pruning was conducted to promote vegetative growth.

The experiment was designed with four treatments; each replicated three times. Yield data were recorded for each replicate within every treatment group. The treatments included three control fertilizers: NPK (15:15:15), rice husk biochar (RHB), and a combination of *pm*-NPK-RHB, as well as one experimental fertilizer, NPK-*i*RHB. The physicochemical properties of these fertilizers were analysed using X-ray diffraction (XRD), scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDX), and Brunauer-Emmett-Teller (BET) analysis to determine surface area, total pore volume, and average pore size (Al-Amsyar, 2022).

A randomized complete block design (RCBD) was implemented, with treatments randomly assigned to plants (Adewole & Ilesanmi, 2011). Thirty okra seeds were germinated over 14 days, after which the 12 best seedlings were selected and transplanted into poly bags. One week after transplanting, 13 g of RHB and 26 g of NPK, *pm*-NPK-RHB, or NPK-*i*RHB were incorporated into the soil at a depth of 2 cm.

Plant height was measured weekly, while harvested fruits were counted and weighed at the same interval. All yield

parameters were subjected to statistical analysis. At the end of the harvesting period, yield improvement percentages and nutrient use efficiency were calculated.

## 2.2 Preparation of Rice Husk Biochar (RHB)

Rice husk biochar was produced by burning rice husk in a furnace at 300 °C for 30 minutes (Al-Amsyar et al., 2017). After cooling, the biochar was ground using a pestle and mortar to achieve a fine, powder-like texture. This powdered rice husk biochar was then used in the synthesis of *pm*-NPK-RHB and NPK-*i*RHB.

### 2.2.1 Physical Mixture of NPK Fertilizer and Rice Husk Biochar (*pm*-NPK-RHB)

Granular 15-15-15 NPK fertilizer was ground into a fine powder. It was then physically mixed with rice husk biochar in a 1:1 ratio. For each replicate plant in that group, 13 g of powdered NPK fertilizer was combined with 13 g of rice husk biochar to produce 26 g of *pm*-NPK-RHB.

### 2.2.2 NPK Fertilizer-Impregnated Rice Husk Biochar (NPK-*i*RHB)

A 1:1 ratio of NPK fertilizer and RHB was used in the impregnation method (C. Wang et al., 2022). Each replicate plant in the group received 26 g of NPK-*i*RHB. To produce 26 g of the treatment, granular 15-15-15 NPK fertilizer was ground into a fine powder, and 13 g of it was dissolved in 13 mL of distilled water. Subsequently, 13 g of RHB was immersed in the NPK solution. An additional 24 mL of distilled water was added, and the mixture was thoroughly stirred before being oven-dried overnight.

## 2.3 Soil Elution Analysis

The effect of NPK fertilizer, RHB, *pm*-NPK-RHB, and NPK-*i*RHB on outflow conductivity was studied using soil elution analysis with some modifications (Mann et al., 2019). A compact 2.5 kg block of cocopeat was soaked in 15 L of water for 15 minutes. After soaking, 2.5 L of water was passed through the cocopeat, and the outflow conductivity was measured until it consistently fell below 100 µS. If the conductivity remained above 100 µS, additional washing was performed until the threshold was reached. The prepared cocopeat was used for both column elution studies and yield performance evaluations. Fifteen measuring cylinders were each filled with 150 g of washed cocopeat. A plastic mesh was secured at one end of each tube to hold the cocopeat in place. To pack and wet the soil, 100 mL of deionized water was added to each column.

For the experimental setup, a control column was prepared, and 10 g of NPK fertilizer, 5 g of RHB, and 10 g of *pm*-NPK-RHB were buried at a depth of 5 cm in their respective columns. Similarly, 10 g of NPK-*i*RHB was buried at a depth of 5 cm in the cocopeat. To elute the NPK salts, the columns were secured to a retort stand, and 50 mL portions of water were sequentially added. The outflow was collected for three minutes before measuring its conductivity. This elution process continued in 50 mL increments until the outflow conductivity dropped below 100 µS. The study was conducted over six days.

## 2.4 Yield Parameters

The measured parameters included the time taken to enter the flowering stage, plant height, fruit number, fruit weight, and yield percentage. These parameters were recorded throughout the harvesting period. Plant size was determined by measuring the plant height using a measuring tape. The first measurement was taken one week after transplanting the seedlings.

As the plants entered the fruiting stage, the number and weight of harvested fruits were recorded weekly until the end of the plant's life cycle. The harvested fruits were weighed using a digital scale, and the weekly accumulated fruit weight was recorded as the total yield for each group. The increase in yield percentage for each treatment compared to the control was calculated using the following equation:

$$\text{Increase yield percentage (\%)} = \frac{Y_i - Y_o}{Y_o} \times 100$$

Where:

$Y_i$  = Yield of the treated group

$Y_o$  = Yield of the control group

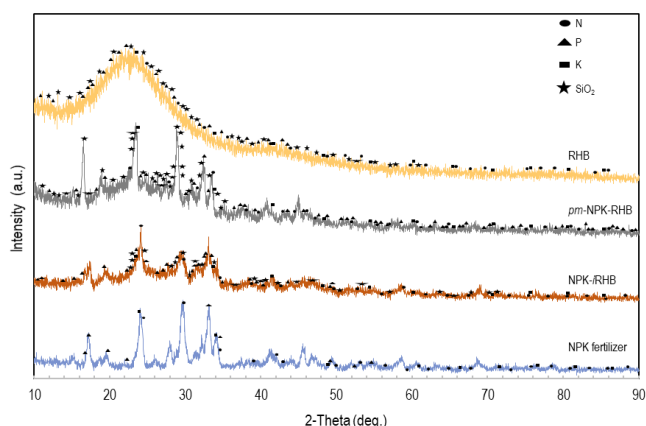
The nutrient use efficiency was calculated by comparing the fruit weight over NPK utilization for NPK fertilizer, RHB, *pm*-NPK-RHB, and NPK-*i*RHB. NPK utilization is the amount of NPK fertilizer used for each fertilizer (Liu et al., 2024).

## 2.5 Statistical Analysis

All yield parameter data were analysed using a one-way Analysis of Variance (ANOVA) with SPSS software. The treatment means were compared using Tukey's Honestly Significant Difference (HSD) test to determine significant differences between the control and treatment groups (Consentino et al., 2022).

### 3. RESULT AND DISCUSSION

The successful impregnation of NPK nutrients into rice husk biochar (RHB) was confirmed by XRD analysis, which revealed distinct peaks corresponding to nitrogen-, phosphorus-, and potassium-bearing crystalline phases (Figure 1). The presence of these peaks, absent in raw RHB, indicates the formation of nutrient–biochar complexes or mineral precipitates within the carbon framework. Such structural integration suggests that the impregnation process promoted chemical stabilization of nutrients through ion exchange and surface complexation rather than simple physical adsorption. The incorporation of phosphate and potassium ions into the siliceous and carbonaceous matrix of RHB likely occurred via capillary-driven infiltration during drying, followed by precipitation within pore channels.



**Figure 1:** The diffractogram of NPK fertilizer, RHB, *pm*-NPK-RHB, and NPK-*i*RHB

The nitrogen sorption analysis revealed significant differences in the surface area, total pore volume, and average pore size among the tested samples (Table 1). The RHB exhibited the highest surface area (88.512 m<sup>2</sup>/g), attributed to its highly porous structure. In contrast, the *pm*-NPK-RHB sample showed a drastic reduction in surface area (7.091 m<sup>2</sup>/g), suggesting partial blockage of pores by NPK particles. The NPK-*i*RHB sample exhibited the lowest surface area (0.485 m<sup>2</sup>/g), indicating substantial pore filling by NPK nutrients, leading to a highly compacted structure.

The total pore volume followed a similar trend, decreasing from 0.06849 cm<sup>3</sup>/g (RHB) to 0.01459 cm<sup>3</sup>/g (*pm*-NPK-RHB) and further to 0.0044 cm<sup>3</sup>/g in the NPK-*i*RHB. This reduction suggests that nutrient particles were primarily deposited within the biochar pores rather than merely coating the external surface. Both surface area and total pore volume correlate with findings by Cheng and Wang (2017) where RHB impregnated with boric acid had decreased the surface area and total pore volume of the RHB. The low surface area and total pore volume of NPK-*i*RHB signify the successful impregnation of NPK solution into the RHB.

Interestingly, the average pore size of the NPK-*i*RHB (1051.92 Å) was larger than that of RHB (575.95 Å) and *pm*-

NPK-RHB (551.96 Å). This increase indicates that during the impregnation process, smaller micropores were occupied by nutrients, leaving predominantly larger mesopores available (Montes & Hill, 2018). Xiang et al., (2020) examined biochar-based urea fertilizers and found that molten urea infiltration into biochar pores led to structural modifications. The study indicated that urea occupied finer pores and changed the biochar’s textural properties.

**Table 1:** The textural properties from N<sub>2</sub> sorption analysis

Sample	Surface Area (m <sup>2</sup> /g)	Total Pore Volume (cm <sup>3</sup> /g)	Average Pore Size (Å)
NPK- <i>i</i> RHB	0.485	0.0044	1051.92
RHB	88.512	0.06849	575.95
<i>pm</i> -NPK-RHB	7.091	0.01459	551.96

The EDX spectra (Table 2) reinforce the textural evidence by showing clear compositional shifts after impregnation. The NPK-*i*RHB sample exhibited elevated nitrogen (N) and phosphorus (P) contents compared to the *pm*-NPK-RHB, indicating improved nutrient retention and distribution. The uniformity of elemental mapping implies homogeneous nutrient deposition throughout the biochar surface and internal pores, a key factor for consistent release performance. In contrast, *pm*-NPK-RHB showed localized nutrient accumulation, consistent with the external coating mechanism typical of physical mixing. The observed reduction in surface silicon (Si) content in NPK-*i*RHB suggests partial masking or modification of silica-dominated ash surfaces due to nutrient binding. This may reflect the substitution of Si–OH groups by phosphate or nitrate ions, which alters surface chemistry and potentially influences adsorption capacity (Bi et al., 2023).

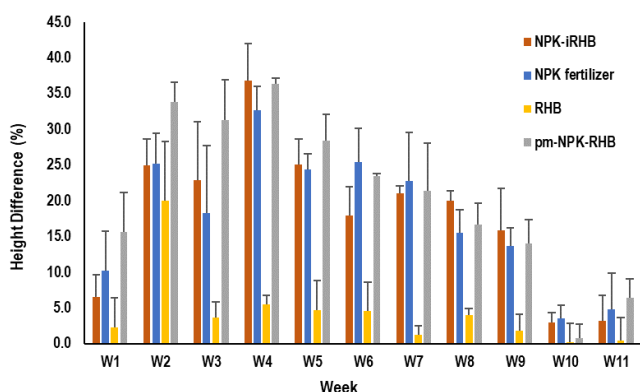
**Table 2:** Elemental compositions of NPK fertilizer, RHB, *pm*-NPK-RHB, and NPK-*i*RHB by using EDX analysis.

Element	Weight (%)			
	NPK- <i>i</i> RHB	NPK fertilizer	RHB	<i>pm</i> -NPK-RHB
C	0.41	0.07	0.51	0.34
O	30.02	20.45	36.19	34.09
Si	25.03	0.74	38.40	19.75
N	0.44	0.70	0.05	0.39
P	7.53	12.89	0.38	3.53
K	11.35	15.37	0.87	16.14
Ca	14.58	-	16.03	14.09
Zn	10.08	-	7.35	11.67

Such structural modifications improve electrostatic interactions between biochar and nutrient ions, enhancing immobilization and reducing nutrient losses through

volatilization or leaching. Collectively, these results indicate that chemical impregnation establishes a stable nutrient–biochar interface capable of providing controlled nutrient availability over time compared to conventional NPK fertilizer and *pm*-NPK-RHB. Further investigations, including okra growth trials and elution studies are studied to assess its long-term agronomic benefits.

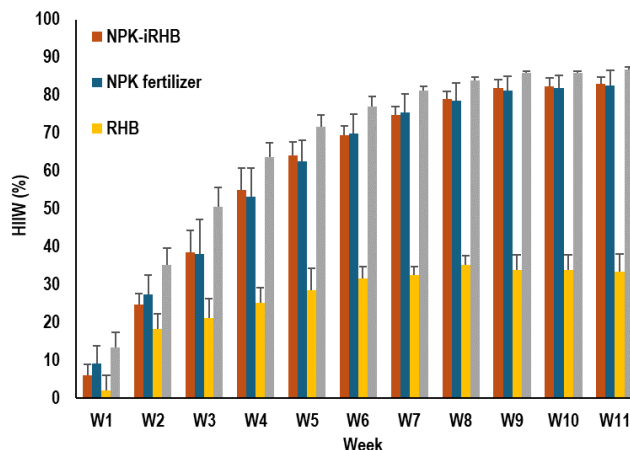
Figure 2 illustrates the weekly height difference (%) of okra plants subjected to different treatments to give a better clarity on the differences. The results indicate that RHB exhibited consistently lower height increments throughout the experimental period, reinforcing its limited agronomic benefit when applied without NPK. In contrast, NPK fertilizer, *pm*-NPK-RHB, and NPK-*i*RHB demonstrated higher growth rates, with peaks observed around weeks 3–5, after which a gradual decline was noted. Notably, NPK-*i*RHB exhibited comparable performance to NPK fertilizer ( $p=1.000$ ) and *pm*-NPK-RHB ( $p=0.895$ ), suggesting that biochar impregnation does not significantly enhance NPK efficacy in promoting plant height (Table 3). These findings indicate that while biochar alone has minimal impact on plant growth, its combination with NPK, either through impregnation or physical mixing, is effective in promoting height increments similar to conventional NPK application.



**Figure 2:** The height difference by week (HDW) of okra for NPK fertilizer, RHB, *pm*-NPK-RHB, and NPK-*i*RHB.

Figure 3 presents the Height Increment from Initial Week (HIIW) over an 11-week period for NPK fertilizer, RHB, *pm*-NPK-RHB, and NPK-*i*RHB. Throughout the experimental period, NPK-*i*RHB (82.92%) and conventional NPK fertilizer (82.65%) exhibited a consistently higher HIIW compared to RHB alone (33.4%), indicating their superior efficacy in promoting plant height growth. Notably, NPK-*i*RHB demonstrated a more sustained growth trend, with a comparable but slightly improved performance over conventional NPK fertilizer in the later weeks. In contrast, the *pm*-NPK-RHB treatment initially showed a rapid increase in HIIW but plateaued towards the later weeks, suggesting that simple physical mixing of biochar and NPK fertilizer may not

sustain prolonged nutrient availability. The RHB displayed the lowest HIIW throughout the study, highlighting its limited role in direct nutrient supply. These findings suggest that the impregnation of biochar with NPK enhances nutrient retention and slow-release properties, leading to improved and sustained plant growth compared to conventional fertilizers and physically mixed alternatives.



**Figure 3:** The height increment from the initial week (HIIW) of okra for NPK fertilizer, RHB, *pm*-NPK-RHB, and NPK-*i*RHB.

In order to explain the efficiency of NPK-*i*RHB in okra growth compared to others, the conductivity of outflow ( $\mu\text{S}$ ) over six days as a function of elution volume (mL) was performed (Figure 4). The elution study provides insight into the nutrient release dynamics of each fertilizer treatment throughout the testing period. On Day 1, all treatments except RHB showed a noticeable increase in conductivity, indicating the initial dissolution of surface-available nutrients. NPK-*i*RHB recorded the highest initial conductivity at approximately 1100  $\mu\text{S}$ , followed by *pm*-NPK-RHB (900  $\mu\text{S}$ ) and NPK fertilizer (500  $\mu\text{S}$ ), while RHB maintained a very low conductivity ( $\sim 50 \mu\text{S}$ ), confirming its minimal contribution to nutrient release. The higher initial conductivity of NPK-*i*RHB and *pm*-NPK-RHB reflects the early-stage release of loosely bound nutrients on the biochar surface. Specifically, NPK-*i*RHB recorded the highest peak conductivity of approximately 4200  $\mu\text{S}$  on Day 2, followed by *pm*-NPK-RHB (3900  $\mu\text{S}$ ) and NPK fertilizer (3600  $\mu\text{S}$ ), while RHB maintained a nearly constant conductivity below 100  $\mu\text{S}$  throughout the study. For NPK fertilizer, the steep drop after Day 2 ( $\sim 500 \mu\text{S}$ ) shows that most nutrients had already leached out, implying poor nutrient retention. The slightly higher peak in NPK-*i*RHB compared to the other treatments suggests that the impregnation method enhanced nutrient accessibility while still moderating the release rate through diffusion from internal pores.

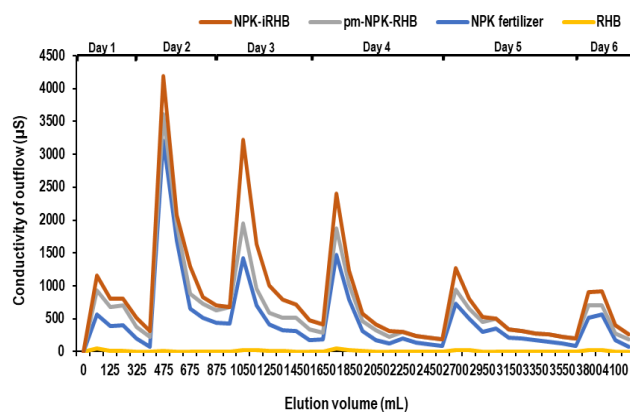
**Table 3:** The height difference by week (HDW) and height increment from the initial week (HIW) of okra (*Abelmoschus esculentus* L.) for NPK-*i*RHB (T1), NPK fertilizer (C1), RHB (C2), and *pm*-NPK-RHB (C3).

Parameter	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	p-value
Height difference by week (%)												
T1	6.50	24.99	22.87	36.83	25.07	17.94	21.02	19.99	15.91	3.02	3.19	<.001
C1	10.23	25.19	18.31	32.68	24.37	25.37	22.81	15.49	13.66	3.55	4.80	
C2	2.26	20.04	3.64	5.55	4.63	4.62	1.22	4.04	1.81	0.18	0.46	
C3	15.58	33.82	31.30	36.32	28.47	23.48	21.44	16.67	14.04	0.77	6.43	
%Difference												
T1/C1	-36.44	-0.78	24.91	12.71	2.89	-29.28	-7.86	29.08	16.44	-15.14	-33.65	1.000
T1/C2	187.62	24.74	528.40	563.73	441.29	288.23	1626.63	394.71	780.56	1617.00	597.86	.008
T1/C3	-58.26	-26.09	-26.92	1.42	-11.92	-23.59	-1.97	19.92	13.31	291.91	-50.45	.895
Height increment from initial week (%)												
T1	6.05	24.80	38.55	54.94	64.05	69.55	74.83	79.01	81.82	82.37	82.92	<.001
C1	9.12	27.35	38.09	53.25	62.45	69.99	75.42	78.67	81.27	81.93	82.65	
C2	2.10	18.29	21.10	25.28	28.45	31.69	32.53	35.14	33.89	33.75	33.40	
C3	13.34	35.18	50.49	63.68	71.71	77.09	81.17	83.86	85.85	85.96	86.80	
%Difference												
T1/C1	-33.70	-9.34	1.20	3.19	2.55	-0.63	-0.78	0.44	0.69	0.54	0.33	1.000
T1/C2	187.71	35.61	82.67	117.34	125.09	119.47	130.05	124.87	141.43	144.07	148.24	.007
T1/C3	-54.67	-29.52	-23.66	-13.73	-10.69	-9.78	-7.81	-5.78	-4.69	-4.18	-4.47	.886

In order to explain the efficiency of NPK-*i*RHB in okra growth compared to others, the conductivity of outflow ( $\mu\text{S}$ ) over six days as a function of elution volume (mL) was performed (Figure 4). The elution study provides insight into the nutrient release dynamics of each fertilizer treatment throughout the testing period. On Day 1, all treatments except RHB showed a noticeable increase in conductivity, indicating the initial dissolution of surface-available nutrients. NPK-*i*RHB recorded the highest initial conductivity at approximately 1100  $\mu\text{S}$ , followed by *pm*-NPK-RHB (900  $\mu\text{S}$ ) and NPK fertilizer (500  $\mu\text{S}$ ), while RHB maintained a very low conductivity ( $\sim 50 \mu\text{S}$ ), confirming its minimal contribution to nutrient release. The higher initial conductivity of NPK-*i*RHB and *pm*-NPK-RHB reflects the early-stage release of loosely bound nutrients on the biochar surface. Specifically, NPK-*i*RHB recorded the highest peak conductivity of approximately 4200  $\mu\text{S}$  on Day 2, followed by *pm*-NPK-RHB (3900  $\mu\text{S}$ ) and NPK fertilizer (3600  $\mu\text{S}$ ), while RHB maintained a nearly constant conductivity below 100  $\mu\text{S}$  throughout the study. For NPK fertilizer, the steep drop after Day 2 ( $\sim 500 \mu\text{S}$ ) shows that most nutrients had already leached out, implying poor nutrient retention. The slightly higher peak in NPK-*i*RHB compared to the other treatments suggests that the impregnation method enhanced nutrient accessibility while still moderating the release rate through diffusion from internal pores.

From Day 3 to Day 6, the conductivity of all treatments declined progressively, indicating the depletion of easily soluble nutrients and a transition toward slower diffusion-controlled release from inner pores. *pm*-NPK-RHB

exhibited a gentler decline ( $\sim 750 - 2000 \mu\text{S}$ ), reflecting moderate nutrient adsorption on the biochar surface but still limited sustained release capacity. In contrast, NPK-*i*RHB maintained moderate conductivity values ( $\sim 1000 - 3200 \mu\text{S}$ ), demonstrating its ability to retain and gradually release nutrients over time through diffusion from internal pores and chemical bonding within the biochar matrix. RHB, throughout the experiment, maintained conductivity values near baseline ( $< 100 \mu\text{S}$ ), reaffirming its inert behaviour and lack of nutrient contribution. The prolonged, moderate conductivity response in NPK-*i*RHB suggests that nutrients were gradually released from internal pores through a diffusion-controlled mechanism. Mann et al., (2019) found a similar observation when employing NPK sulphur polymer composites as controlled-release fertilizers.



**Figure 4:** The conductivity of outflow for NPK fertilizer, RHB, *pm*-NPK-RHB, and NPK-*i*RHB.

When correlated with the weekly height difference (%) and height increment from the initial week (HIIW) of okra plants, the enhanced nutrient availability in NPK fertilizer, *pm*-NPK-RHB, and NPK-*i*RHB aligns with their superior plant growth performance. The peak conductivity on specific days coincides with periods of rapid plant height increments (notably between weeks 3 to 7), further emphasizing the impact of controlled nutrient release on plant development. The comparative effectiveness of NPK-*i*RHB and *pm*-NPK-RHB in sustaining nutrient availability supports their similar plant height growth trends, as seen in the height difference and increment data (Table 3). Meanwhile, the limited conductivity in RHB corresponds with its consistently lower growth performance, reaffirming that biochar alone is insufficient for optimal plant height development.

Table 4 presents the fruit weight and fruit number of okras under different fertilizer treatments. The total fruit weight was highest in *pm*-NPK-RHB (318.00 g), followed by NPK-*i*RHB (311.00 g) and NPK fertilizer (292.00 g), whereas RHB produced no fruits throughout the study. The mean fruit weight followed a similar trend, with NPK-*i*RHB (103.67 g) and *pm*-NPK-RHB (106.00 g) showing comparable values, while NPK fertilizer lagged slightly behind (97.34 g), and RHB remained at 0.00 g. The statistical analysis revealed a highly significant difference ( $p < 0.001$ ) for both fruit weight and fruit number, confirming the substantial impact of different fertilizer treatments on okra productivity. The results suggest that NPK-*i*RHB and *pm*-NPK-RHB provided superior nutrient availability, leading to improved fruit yield, while the absence of nutrient supplementation in RHB resulted in no fruit

production.

Table 5 presents NPK utilization and fertilizer cost under different treatments. The results indicate that NPK-*i*RHB and *pm*-NPK-RHB required significantly lower NPK input (140 g) compared to NPK fertilizer (280 g), while RHB did not utilize any NPK. Similarly, the overall fertilizer cost was lowest in RHB (RM 0.43), followed by NPK-*i*RHB and *pm*-NPK-RHB (RM 2.52), whereas NPK fertilizer exhibited the highest cost (RM 4.63). Based on the post-mortem analysis run by Turkey Post-Hoc, there is a significant difference in NPK fertilizer utilization and fertilizer cost between NPK-*i*RHB and NPK fertilizer at  $p=0.004$  and  $p=0.007$ , respectively, where it shares the same  $p$ -value with RHB. In contrast, there is no significant difference between NPK-*i*RHB and *pm*-NPK-RHB in NPK fertilizer utilization ( $p=1.00$ ) and fertilizer cost ( $p=1.00$ ).

To assess the periodical nutrient use efficiency (NUE) trends across different fertilizer treatments, the average NUE was analysed at three distinct phases: weeks 6–7, weeks 8–9, and weeks 10–11 (Figure 5). The results indicate that NPK-*i*RHB exhibited a progressive increase in NUE, starting at 20% (weeks 6–7), slightly increasing to 22% (weeks 8–9), and significantly peaking at 38% (weeks 10–11), demonstrating its superior controlled-release capability. In contrast, conventional NPK fertilizer displayed a relatively low initial NUE of 6%, followed by a gradual rise to 12% (weeks 8–9) and 19% (weeks 10–11), indicating a less efficient nutrient release pattern. *pm*-NPK-RHB exhibited an initial NUE of 23%, which increased to 34% during weeks 8–9 but declined to 24% in the final stage, suggesting that physical

**Table 4:** The fruit weight and fruit number of okra (*Abelmoschus esculentus* L.) for NPK-*i*RHB (T1), NPK fertilizer (C1), RHB (C2), and *pm*-NPK-RHB (C3).

Parameters		Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Overall	P-value		
Fruit weight (g)	T1	Total	63.00	14.00	54.00	31.00	74.00	75.00	311.00	<.001	
		Mean	21.00	4.67	18.00	10.33	24.67	25.00	103.67		
	C1	Total	14.00	33.00	49.00	48.00	86.00	62.00	292.00		
		Mean	4.67	11.00	16.33	16.00	28.67	20.67	97.34		
	C2	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
		Mean	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
	C3	Total	68.00	22.00	54.00	79.00	51.00	44.00	318.00		
		Mean	22.67	7.33	18.00	26.33	17.00	14.67	106.00		
	Yield increase (%)	T1/C1	350.00	-57.58	10.20	-35.42	-13.95	20.97			0.993
		T1/C2	Nil	Nil	Nil	Nil	Nil	Nil			0.001
T1/C3		-7.37	-36.29	0.00	-60.77	45.12	70.42		1.000		
Fruit number	T1	Total	4.00	1.00	4.00	2.00	5.00	4.00	20.00	<.001	
		Mean	1.33	0.33	1.33	0.67	1.67	1.33	6.66		
	C1	Total	1.00	3.00	4.00	3.00	3.00	3.00	17.00		
		Mean	0.33	1.00	1.33	1.00	1.00	1.50	6.16		
	C2	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
		Mean	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
	C3	Total	4.00	1.00	3.00	4.00	3.00	2.00	17.00		
		Mean	1.33	0.33	1.00	1.33	1.00	0.67	5.66		
	Yield increase (%)	T1/C1	300.00	-66.67	0.00	-33.33	66.67	-11.11			0.980
		T1/C2	Nil	Nil	Nil	Nil	Nil	Nil			<.001
T1/C3		0.00	0.00	33.00	-49.62	67.00	98.51		0.867		

mixing does not provide sustained nutrient release comparable to the impregnation method. Meanwhile, RHB consistently showed an NUE of 0%, confirming its lack of direct nutrient contribution.

**Table 5:** NPK utilization and fertilizer cost for NPK fertilizer, RHB, *pm*-NPK-RHB, and NPK-*r*RHB

Parameters	NPK- <i>r</i> RHB	NPK fertilizer	RHB	<i>pm</i> -NPK-RHB	p-value
<b>NPK utilization (g)</b>					
a	65.00	130.00	0.00	65.00	<.001
b	75.00	150.00	0.00	75.00	
Overall	140.00	280.00	0.00	140.00	
<b>Fertilizer cost (RM)*</b>					
a	1.17	2.15	0.20	1.17	<.001
b	1.35	2.48	0.23	1.35	
Overall	2.52	4.63	0.43	2.52	

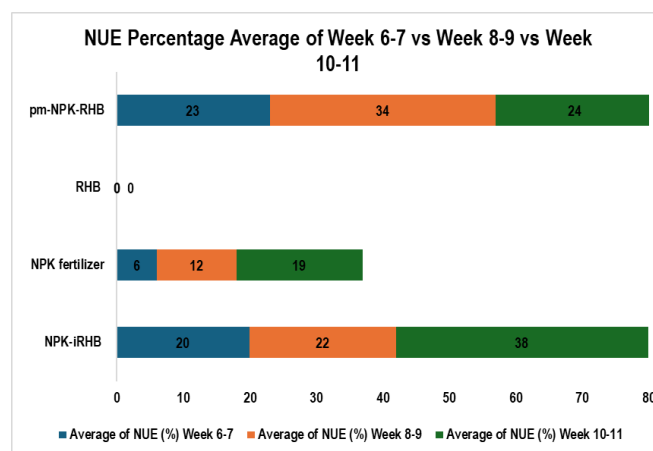
\*USD1 = RM4.40

These findings highlight the effectiveness of NPK-*r*RHB in enhancing nutrient retention and availability over time, reinforcing its potential as a sustainable controlled-release fertilizer alternative to conventional NPK. The findings of this study are consistent with several previous reports on biochar-based and controlled-release fertilizers. Similar to the present results, Xiang et al. (2020) observed that molten urea infiltration into biochar pores resulted in a slower and more controlled nutrient release pattern compared to conventional urea, attributed to diffusion through the biochar matrix. Likewise, Bi et al. (2023) demonstrated that biochar composites enhanced nutrient retention and minimized leaching losses, leading to improved nutrient use efficiency (NUE) in crop production systems. The gradual decline in conductivity and sustained nutrient availability observed in NPK-*r*RHB also aligns with Mann et al. (2019), who reported that polymer-based NPK composites exhibited similar diffusion-controlled release kinetics. Furthermore, Tan et al. (2024) found that high-pressure impregnation techniques improved nutrient retention and promoted stable crop growth over extended periods. These comparisons reinforce that the impregnation approach used in this study effectively integrates the advantages of both biochar and controlled-release fertilizers, resulting in improved nutrient efficiency and long-term plant performance.

#### 4. CONCLUSION

The findings of this study demonstrate that NPK-*r*RHB significantly enhances nutrient use efficiency, reduces fertilizer consumption, and improves okra production compared to conventional NPK fertilizer, RHB, and *pm*-NPK-RHB. The superiority of NPK-*r*RHB is attributed to the impregnation process, which ensures controlled nutrient release, minimizes losses, and enhances nutrient uptake

efficiency, as evidenced by its consistently higher NUE values and stable fruit production across weeks. In contrast, *pm*-NPK-RHB exhibited declining efficiency, highlighting the limitations of physical mixing in nutrient retention and availability. This observation can be directly correlated with the findings from the elution studies, which demonstrated a more controlled and sustained nutrient release in NPK-*r*RHB compared to other treatments. Overall, the results justify the necessity of impregnation over physical mixing as an effective approach for optimizing fertilizer efficiency, promoting sustainable agricultural practices, and improving crop productivity. Furthermore, this work provides an effective solution for repurposing agricultural waste while reducing environmental impacts associated with synthetic fertilizers.



**Figure 5:** The percentage of nutrient use efficiency of Week 6-7, Week 8-9 and Week 10-11 of NPK fertilizer, RHB, *pm*-NPK-RHB, and NPK-*r*RHB.

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