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Enhancing Ultisol fertility index, nutrient uptake and agronomic yield of cucumber (*Cucumis sativus*) through biochar types and incubation periods

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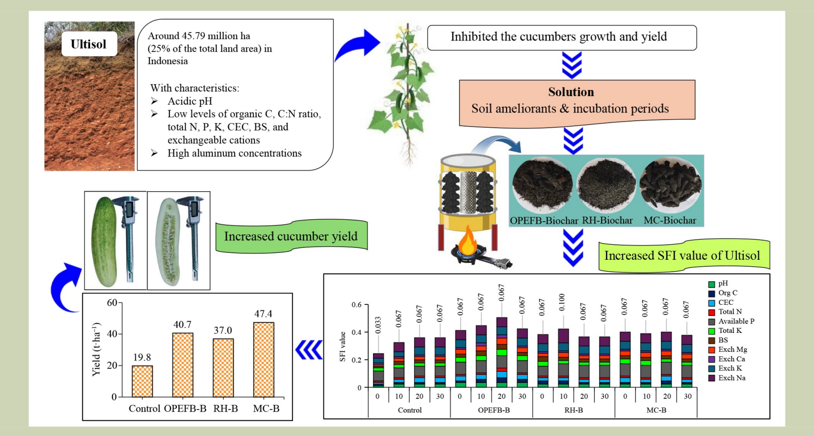
KEYWORDS

Aacidic soil, incubation periods, MC-B, OPEFB-B, soil fertility

HIGHLIGHTS

- Maize cob biochar was identified as the superior amendment for directly enhancing cucumber productivity, yielding 47.4 t·ha^{-1} and significantly boosting the uptake of N, P and K by about 125%.
- A 20-d incubation period was found to be optimal, maximizing cucumber yield was 38.2 t·ha^{-1}.
- Oil palm empty fruit bunches biochar proved most effective for improving overall soil fertility, achieving the highest Ultisol fertility index of 0.447, particularly when combined with a 10 to 20-d incubation period.
- Cucumber yield was strongly correlated with key soil fertility indicators, including organic C, cation exchange capacity, base saturation, and exchangeable Ca and K, underscoring their role as critical drivers of agronomic performance.

GRAPHICAL ABSTRACT



ABSTRACT

Ultisol, characterized by acidic pH and low fertility index, present significant challenges for crop productivity. This study investigated the efficacy of three biochar types, oil palm empty fruit bunches (OPEFB-B), rice husk and maize cob (MC-B) applied at 10 t·ha^{-1}, with varying incubation periods (0, 10, 20 and 30-d) with three replicates, to enhance Ultisol fertility index and cucumber performance. A factorial randomized complete block design was used, which was conducted in farmer fields in Medan, Indonesia from June to October 2023. This investigation used the cucumber hybrid Metavy F1, cultivated in a

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composite sample of randomly collected Ultisol. Following analysis of variance, significant means were separated by Duncan’s multiple range test at a 5% level, and correlations among the variables were evaluated. Soil fertility index (SFI) of Ultisol was established and classified. Results demonstrated that MC-B was superior in boosting cucumber yield to 47.4 $t\cdot ha^{-1}$. This increase is attributed to a significant elevated in the uptake of nitrogen, phosphorus and potassium by about 125%. In contrast, OPEFB-B was most effective at improving Ultisol SFI by 0.447 (a 38.8% increase). An incubation period of 20-d was identified as optimal for maximizing yield and nutrient uptake. The interaction between biochar type and incubation periods were significant effect on plant height and leaf area. Specifically, the combination of OPEFB-B with 10- or 20-d incubation enhanced soil fertility and increased the N and K content in plant shoots. Correlation analysis revealed significant positive associations between cucumber productivity and key soil properties: organic C, cation exchange capacity, base saturation, and exchangeable Ca and K with values of 0.321, 0.342, 0.420, 0.392 and 0.487, respectively. Synergistic improvements in soil fertility and crop yield require the extended incubation period of MC-B and OPEFB-B, applied separately or in combination.

1 Introduction

Cucumbers (*Cucumis sativus*) are a high-value horticultural crop with significant health benefits. The fruit consists of over 90% water, making it an excellent hydration source, while being exceptionally low in calories[1]. Additionally, cucumber possesses bioactive compounds with antimicrobial properties and has been shown to exhibit hypoglycemic effects[2]. Other components contain various antioxidants, including flavonoids, tannins and polyphenols, which help prevent oxidative stress and reduce the risk of chronic diseases[3]. Also, cucumber is widely used as a complementary ingredient in dishes, vegetables, the food industry (pickles and salads) and beauty products, resulting in increased demand for cucumber increasing annually. This growing demand is clearly reflected in the data from the Ministry of Agriculture[4], cucumber consumption in Indonesia increased from 2.06 kg per capita per year in 2018 to 2.21 kg per capita per year in 2023. This high consumption rate should be balanced with cucumber productivity. However, data from the BPS-Statistics Indonesia[5] indicated a decline in productivity by 0.7% from 2020 to 2024.

In general, cucumber cultivation is often constrained by marginal land conditions, specifically on acidic soils such as Ultisol. In Indonesia, Ultisol dominate about 25% of the total land area, covering around 45.8 million ha (Mha)[6]. The largest distribution of Ultisol is found in Kalimantan (21.9 Mha), followed by Sumatra (9.47 Mha), Maluku and Papua (8.86 Mha), Sulawesi (4.30 Mha), Java (1.17 Mha), and Nusa Tenggara (53 kha). As a dominant soil order in tropical regions of Indonesia, Ultisol exhibit limiting characteristics such as acidic pH and low levels of organic C, C:N ratio, total N, cation exchange capacity (CEC), base saturation (BS), and exchangeable cations[7]. Additionally, Ultisol is reported to have low phosphorus and high aluminum concentrations[8]. Naibaho et al.[9] reported that Al stress significantly inhibited plant biomass. Ultisol condition highly affects nutrient availability, potentially restricting plant growth and negatively impacting cucumber productivity.

Cucumber cultivation on acidic soils such as Ultisol has strategic potential to optimize the use of marginal lands. However, the inherent constraints of acidic soils necessitate soil improvement strategies, including the application of biochar to enhance acidic soil productivity. The selection of biochar raw materials greatly affects the ability to increase soil fertility and crop productivity. Aller[10] found that biochar produced from plant residues exhibits higher nutrient content and pH compared to wood-derived biochar. Other alternative potential plant residues for increasing the fertility of acidic soils include oil palm empty fruit bunches (OPEFB), rice husks (RH) and maize cobs (MC). Rabileh et al.[11] reported that OPEFB-biochar significantly increased soil pH, exchangeable cations, CEC, organic C and total N in Ultisol along with increasing biochar doses from 5 to 20 t·ha^{-1} compared to the control. Radin et al.[12] demonstrated that OPEFB biochar significantly increased pH, organic C, total N, C:N ratio, CEC, Mg and Ca, but significantly reduced ammonium N leaching by 21% to 46% in Ultisol. Ngui et al.[13] reported that RH-biochar doses of 35 and 70 g·pot^{-1} significantly increased organic matter, available P, K, Ca, Mg, Cu and Zn in acidic soil compared to the control. Mensah and Frimpong[14] also found that MC-biochar at 2% rate significantly increased soil pH, organic C, available P, total N and CEC of acidic soil compared to the control.

Therefore, the development of biochar-based technology requires not only the selection of appropriate raw materials but also consideration of the incubation period to optimize the enhancement of Ultisol productivity. An adequate incubation period allows for optimal decomposition and activation of biochar, thereby improving its effectiveness in enhancing Ultisol fertility and nutrient availability for plants. Previous studies have reported varying incubation periods for different biochars in improving Ultisol fertility: 16 weeks for OPEFB-biochar[15], 8 weeks for RH-biochar[16] and 4 weeks for MC-biochar[17]. These incubation periods were determined through testing with indicator plants other than cucumber. Thus, validating the specific incubation periods of these three biochar materials is necessary for cucumber cultivation in Ultisol. Cucumber plant was selected for this study due to its sensitivity to soil pH, which has a well-defined optimum range of 5.5 to 6.5[18]. This study was designed with the following objectives: (1) to determine the suitable biochar types (OPEFB, RH and MC) and incubation periods for improving Ultisol fertility, nutrient availability, and cucumber agronomic yield, and (2) to assess the correlation between Ultisol chemical characteristics (pH, organic C, CEC, total N, available P, total K, BS, exchangeable Mg, Ca, K, Na, and nutrient uptake with cucumber productivity).

2 Materials and methods

2.1 Collection of Ultisol and biochar materials

Ultisol, as a planting medium were taken at a depth of 20 cm from Kwala Bekala Village (98°37.8′ E; 3°29.6′ N), Medan Johor Subdistrict, Medan City, North Sumatra, Indonesia. Ultisol was collected randomly from multiple points and combined to form a composite sample. The collection of biochar materials is detailed in Table 1. Each biochar material was burned anaerobically with a modified drum and a stainless steel cylinder with a hole in the middle (Fig. 1). The temperature was measured up to 350 °C and after complete combustion, the material was removed to a storage container at room temperature. Biochar products from OPEFB, RH and MC are shown in Fig. 1. Ultisol sample of 250 g and biochar samples of 100 g each were taken for the analysis of the chemical characteristics in the laboratory (Tables 2–3). The analysis results showed that Ultisol had chemical characteristics ranging from very low to low. The chemical characteristics of OPEFB-B and MC-B were higher than RH-B.

2.2 Study site and selection of cucumber cultivar

This study was conducted in farmer fields in Medan Selayang I, Padang Bulan, Medan City (98°38.8′ E; 3°33.7′ N) from June to October 2023. Ultisol samples were placed into 30 kg polybags (33 cm high by 32 cm diameter). The planting distance between polybags was 50 cm × 40 cm. Cucumber cultivar used was the Metavy F1 with a potential yield of 60–70 t·ha^{-1} (East West Seed Indonesia Ltd. Campaka, Purwakarta, West Java, Indonesia).

Table 1 Sites of biochar materials collection in this study

Biochar material	Coordinate	Location	Altitude (m A.S.L.)
Oil palm empty fruit bunches	99°33.4′ E; 3°08.9′ N	Palm Oil Mill-Tanah Datar, Asian Agri, Sei Suka Village, Talawi Subdistrict, Batu Bara District, Indonesia	548
Rice husk	98°35.6′ E; 3°32.3′ N	Tanjung Selamat Village, Sunggal Subdistrict, Deli Serdang District, Indonesia	24
Maize cob	98°38.8′ E; 3°33.7′ N	Farmland in Medan Selayang I, Padang Bulan, Medan City, Indonesia	14

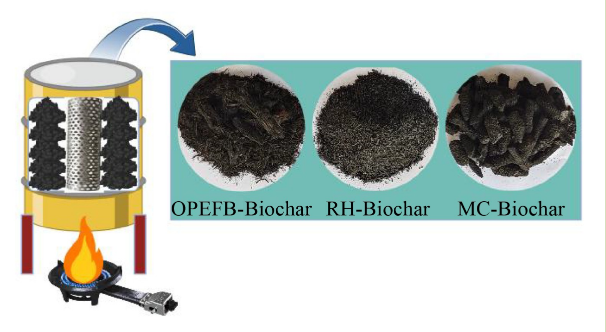

Fig. 1 Customized steel drum for biochar production and biochar products in this study.

2.3 Study design and determination of biochar requirement

This study used a factorial randomized complete block design with the first factor being the biochar types (control; OPEFB-B, oil palm empty fruit bunches-biochar; RH-B, rice husk biochar; and MC-B, maize cob biochar) and the second being the incubation periods (0, 10, 20 and 30-d). Each treatment combination was replicated three times. Biochar was applied at a dose of 10 t·ha^{-1} (equivalent to 150 g per polybag), ground homogeneously, and mixed evenly at a 10 cm depth. The incubation periods were staggered, with the first incubation period initiated at 30-d, followed by subsequent at 20- and 10-d before planting.

2.4 Cucumber growth

A total of 2 cucumber seeds were planted in a polybag and separated 4-d after planting, followed by the installation of vertical stakes. Subsequently, the stakes were made of bamboo 1.5 m high and stuck at a distance of 10 cm from the plant stem which was tied with plastic rope until the end of the generative phase. Watering was performed daily at a rate of 200 mL per polybag by applying water uniformly around the plant base. Base fertilizer was applied as NPK compound fertilizer at dose of 4.5 g per polybag was calculated by converting the recommended application rate of 300 kg·ha^{-1} to a soil-based equivalent (0.15 g·kg^{-1} of soil) and multiplying by the polybag soil weight (30 kg). This total dose was split into three equal applications of 1.5 g per polybag with applied at 2-week interval. The fertilizer was dissolved in 100 mL of water and applied through circular irrigation around the plant stem. Insecticide (deltamethrin) and fungicides (e.g., propineb and mancozeb) were sprayed depending on pest and disease attacks. Pruning of lateral bud was performed from 3 weeks after planting (WAP) until the end of the vegetative phase.

2.5 Variables recorded

Agronomic parameters of cucumber plants in this study included plant height, number of leaves, leaf area and thickness, stem diameter, SPAD total chlorophyll, fresh and dry weight, water content, harvest age, number of fruits, fruit length and diameter, total fruit weight, and yield.

Table 2 Analysis of chemical characteristics of Ultisol in this study

Ultisol chemical characteristic	Method	Value	Category*
H_2O pH	Potentiometry	4.23	Strongly acidic
Org C (%)	Walkley & Black	0.74	Very low
CEC (meq per 100 g)	Ammonium acetate pH 7	17.1	Moderate
Total N (%)	Kjehldahl	0.18	Low
Available P (mg·kg^{-1})	Bray-II	214	Moderate
Total K (mg·kg^{-1})	HNO_3 with AAS	168	Low
BS (%)	Calculation	10.5	Very low
Exchangeable K (meq per 100 g)	Ammonium acetate pH 7	0.28	Low
Exchangeable Mg (meq per 100 g)	Ammonium acetate pH 7	0.72	Low
Exchangeable Ca (meq per 100 g)	Ammonium acetate pH 7	0.62	Very low
Exchangeable Na (meq per 100 g)	Ammonium acetate pH 7	0.17	Low

Note: *Soil chemical characteristic categories refer to the Ministry of Agriculture[19]. CEC, cation exchange capacity; BS, base saturation.

Table 3 Analysis of biochar chemical characteristics in this study

Chemical characteristic	Method	OPEFB-B	RH-B	MC-B
H_2O pH	Electrometry	10.1	8.35	10.1
Org C (%)	Gravimetry	5.26	3.35	10.0
C:N ratio	–	9.15	5.47	8.36
Moisture (%)	Oven with gravimetry	23.3	6.17	14.9
CEC (meq per 100 g)	Ammonium acetate pH 7	27.8	24.8	56.2
BS (%)	Calculation	404	56.0	208
N (%)	Kjehldahl	0.57	0.61	1.20
P (%)	Dry ashing–HNO with AAS	0.45	0.14	0.34
K (%)	Dry ashing–HCl with AAS	5.79	0.52	5.82
Mg (%)	Dry ashing–HCl with AAS	0.36	0.07	0.52
Ca (%)	Dry ashing–HCl with AAS	0.44	0.25	0.86

Note: OPEFB-B, oil palm empty fruit bunches biochar; RH-B, rice husk biochar; MC-B, maize cob biochar; CEC, cation exchange capacity; BS, base saturation.

Measurements of plant height, number of leaves, leaf area and thickness, stem diameter, and SPAD total chlorophyll were measured weekly until the end of the vegetative phase (5 WAP). Leaf length (l) and width (w) were measured using a digital caliper, then the leaf area (LA) was calculated based on the formula by Cho et al.[20] as $-210.62 + (13.358 \times w) + (0.5356 \times l \times w)$. Leaf thickness was measured using a portable plant leaf blade thickness gauge and stem diameter measurements were taken from the base using a digital caliper. Also, SPAD total chlorophyll measurements were performed on the second leaf from the shoot apex using a Konica Minolta Chlorophyll Meter SPAD-502Plus. Harvests were made every 4-d with fruit length and diameter measured using digital caliper. At the end of this study, the fresh and dry weight were determined by cleaning the roots from the soil then weighing them with an analytical scale and putting the samples in a brown envelope. The samples were oven dried at 80 °C for 24 h and weighed. Yield ($t \cdot ha^{-1}$) was calculated by multiplying the number of plants per hectare by the total fruit weight.

Measurements of the cucumber fruit structural characteristics, including length and width of the fruit neck, exocarp and mesocarp thickness, and seed cavity, were made with digital caliper. In addition, 50 g of leaf samples were taken to analyze the nutrient content of N, P and K using Kjeldahl-Titrimetry, Spectrophotometry and Flamephotometry methods. Nutrient uptake was calculated using the formula: nutrient content × dry weight. At the end of the study, soil samples of 250 g were taken using a soil sampler tube and analyzed for soil chemical characteristics such as pH (Potentiometry), organic C (Walkley & Black), total N (Kjehldahl), available P (Bray-II), total K (HNO_3 digestion with AAS), BS (calculation) and CEC along with exchangeable cations (Mg^{2+}, Ca^{2+}, K^+ and Na^+) via the ammonium acetate pH 7 method. Also, the soil fertility index (*SFI*) was calculated using principal component analysis (PCA). PCA is used to identify data to be used as the main components. Data with the highest PCA value was selected as the minimum data set representing all indicators. The weighting index (*Wi*) for each selected indicator was calculated by multiplying the proportion with the cumulative value. The *SFI* was calculated follows Bagherzadeh et al.[21] using equations 1–4, and the *SFI* classification including very low (0.00–0.25), low (0.25–0.50), moderate (0.50–0.75), high (0.75–0.90), and very high (0.90–1.00).

$$SFI = \frac{\sum_{i=1}^{n} Sci}{N} \times 10 \tag{1}$$

$$Sci = Cj \times Pc \tag{2}$$

$$Cj = Si \times Wi \tag{3}$$

$$Pc = \frac{1}{Nc} \tag{4}$$

where, *SFI* is soil fertility index, *Sci* is score of each indicator, *N* is number of indicators, *Cj* is numbers of weighting indices, *Pc* is score of class, *Si* is scoring index, *Wi* is weighting index and *Nc* is the number of classes.

2.6 Statistical analysis

Statistical analysis was performed using an ANOVA with post-hoc Duncan's multiple range test at $\alpha = 0.05$. Pearson correlation analysis was used to examine relationships between soil chemical properties, nutrient uptake, and cucumber agronomic yield using IBM SPSS software for versions 20.

3 Results

3.1 Agronomic yield of cucumber

The application of biochar types significantly affected the agronomic and yield characteristics of cucumber, except for stem diameter (Tables 4–6 and Fig. 2). In general, MC-B

Table 4 Effect of biochar types, incubation periods, and their interactions on plant height, number of leaves and leaf area of cucumber plants

Treatment		Plant height (cm) at WAP					Number of leaves at WAP					Leaf area (cm^2) at WAP				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Biochar types (B)																
Control		1.64 b	4.67 b	11.1 c	31.2 c	50.3 b	2.00 ns	4.25 ns	7.08 b	10.8 b	14.3 c	1.65 b	15.9 c	43.4 c	58.2 c	65.0 c
OPEFB-B		2.08 ab	5.76 a	14.2 bc	45.6 bc	63.2 b	2.00 ns	4.50 ns	8.42 ab	11.6 b	15.2 bc	2.86 a	21.2 ab	57.5 b	88.1 b	95.2 b
RH-B		2.50 a	6.48 a	18.4 b	57.2 b	83.6 a	2.00 ns	4.50 ns	9.00 a	13.8 a	18.2 a	1.87 b	19.1 bc	59.4 b	92.3 ab	98.2 b
MC-B		2.25 a	6.61 a	24.2 a	72.6 a	87.8 a	2.00 ns	4.67 ns	9.92 a	14.8 a	17.0 ab	2.78 a	23.4 a	77.8 a	108 a	116 a
Incubation periods (T days)																
0		2.33 ab	5.58 ns	14.6 ns	42.3 b	59.3 b	2.00 ns	4.42 ns	8.00 ns	12.0 ns	15.0 b	2.60 ns	17.2 c	54.5 ns	83.9 ns	88.0 ns
10		2.52 a	6.07 ns	16.8 ns	56.0 a	72.6 ab	2.00 ns	4.42 ns	9.00 ns	12.7 ns	15.4 b	2.46 ns	22.6 a	64.3 ns	86.0 ns	95.0 ns
20		1.93 bc	6.11 ns	18.4 ns	60.4 a	82.9 a	2.00 ns	4.58 ns	9.33 ns	13.5 ns	17.8 a	2.21 ns	21.4 ab	59.7 ns	91.4 ns	97.9 ns
30		1.69 c	5.76 ns	18.0 ns	47.9 ab	70.1 ab	2.00 ns	4.50 ns	8.08 ns	12.8 ns	16.5 ab	1.88 ns	18.3 bc	59.6 ns	85.6 ns	93.5 ns
Interactions (B × T)																
Control	0	1.90 bcd	4.93 ns	11.6 ns	22.0 ns	39.8 ns	2.00 ns	4.33 ns	6.33 ns	8.33 ns	12.3 ns	1.93 ns	12.5 d	39.5 ns	46.8 ns	51.0 ns
	10	1.70 cd	4.83 ns	10.8 ns	27.7 ns	40.1 ns	2.00 ns	4.00 ns	7.00 ns	10.7 ns	12.0 ns	1.78 ns	16.7 cd	37.1 ns	50.2 ns	57.9 ns
	20	1.57 d	4.50 ns	13.3 ns	46.5 ns	72.9 ns	2.00 ns	4.67 ns	8.33 ns	13.3 ns	18.0 ns	1.44 ns	18.5 cd	55.7 ns	80.1 ns	91.2 ns
	30	1.40 d	4.40 ns	8.5 ns	28.5 ns	48.5 ns	2.00 ns	4.00 ns	6.67 ns	11.0 ns	15.0 ns	1.44 ns	15.7 cd	41.3 ns	55.5 ns	59.8 ns
OPEFB-B	0	1.93 bcd	4.97 ns	10.6 ns	38.7 ns	55.4 ns	2.00 ns	4.33 ns	7.33 ns	11.0 ns	15.0 ns	2.69 ns	16.5 cd	49.8 ns	82.0 ns	89.4 ns
	10	2.47 bcd	6.33 ns	14.1 ns	55.1 ns	60.3 ns	2.00 ns	4.67 ns	8.67 ns	13.0 ns	14.7 ns	3.60 ns	21.7 bc	71.0 ns	98.2 ns	106 ns
	20	2.27 bcd	7.30 ns	21.1 ns	54.1 ns	79.1 ns	2.00 ns	4.67ns	10.0 ns	12.0 ns	15.7 ns	3.18 ns	28.4 ab	55.8 ns	97.3 ns	98.9 ns
	30	1.67 cd	4.43 ns	10.8 ns	34.4 ns	58.0 ns	2.00 ns	4.33 ns	7.67 ns	10.3 ns	15.3 ns	1.96 ns	18.3 cd	53.5 ns	75.0 ns	86.7 ns
RH-B	0	2.80 b	6.97 ns	16.9 ns	45.9 ns	73.0 ns	2.00 ns	4.33 ns	9.33 ns	14.0 ns	17.7 ns	1.55 ns	20.4 cd	56.0 ns	97.1 ns	99.3 ns
	10	3.73 a	6.83 ns	22.4 ns	52.6 ns	95.9 ns	2.00 ns	4.33 ns	8.33 ns	13.0 ns	18.3 ns	2.23 ns	20.0 cd	58.0 ns	86.7 ns	101 ns
	20	1.63 cd	5.80 ns	13.9 ns	69.8 ns	76.1 ns	2.00 ns	4.67 ns	9.33 ns	14.0 ns	18.7 ns	1.66 ns	17.1 cd	50.3 ns	83.0 ns	87.7 ns
	30	1.83 bcd	6.33 ns	20.2 ns	60.3 ns	89.4 ns	2.00 ns	4.67 ns	9.00 ns	14.0 ns	18.0 ns	2.05 ns	18.9 cd	73.3 ns	102 ns	105 ns
MC-B	0	2.70 bc	5.47 ns	19.5 ns	62.6 ns	69.1 ns	2.00 ns	4.67 ns	9.00 ns	14.7 ns	15.0 ns	4.25 ns	19.6 cd	72.5 ns	110 ns	112 ns
	10	2.17 bcd	6.27 ns	19.8 ns	88.5 ns	94.1 ns	2.00 ns	4.67 ns	12.0 ns	14.0 ns	16.7 ns	2.21 ns	31.9 a	91.0 ns	109 ns	115 ns
	20	2.27 bcd	6.83 ns	25.2 ns	71.3 ns	104 ns	2.00 ns	4.33 ns	9.67 ns	14.7 ns	18.7 ns	2.57 ns	21.5 bc	77.1 ns	105 ns	114 ns
	30	1.87 bcd	7.87 ns	32.5 ns	68.2 ns	84.3 ns	2.00 ns	5.00 ns	9.00 ns	15.7 ns	17.7 ns	2.08 ns	20.3 cd	70.4 ns	110 ns	123 ns
CV (%)		25.8	21.4	37.6	30.9	26.8	–	13.1	20.6	16.7	15.1	34.7	21.8	22.6	24.2	17.3

Note: Means followed by the same letter with columns are not significantly different at $p = 0.05$. OPEFB-B, oil palm empty fruit bunches biochar; RH-B, rice husk biochar; MC-B, maize cob biochar; CV, coefficient of variation; WAP, weeks after planting; ns, not significant.

Table 5 Effect of biochar types, incubation periods, and their interactions on leaf thickness, stem diameter and SPAD total chlorophyll of cucumber plants

Treatment		Leaf thickness (mm) at WAP					Stem diameter (mm) at WAP					SPAD total chlorophyll at WAP				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Biochar types (B)																
Control		0.75 c	0.84 ns	0.87 b	0.89 b	0.97 b	1.54 b	3.40 ns	6.13 b	7.20 c	9.18 ns	30.5 c	36.3 c	40.1 c	43.6 b	44.9 b
OPEFB-B		0.83 a	0.86 ns	0.91 a	0.93 a	1.02 ab	1.93 a	3.84 ns	7.06 b	8.43 b	9.89 ns	41.7 a	44.8 a	45.3 a	46.5 a	48.7 a
RH-B		0.79 bc	0.84 ns	0.88 b	0.94 a	1.01 ab	1.73 ab	3.53 ns	6.99 b	8.88 ab	10.1 ns	37.0 b	40.5 b	42.7 b	45.1 ab	47.3 a
MC-B		0.82 ab	0.85 ns	0.90 a	0.94 a	1.04 a	1.76 ab	3.84 ns	8.20 a	9.55 a	10.7 ns	39.7 ab	42.5 ab	45.9 a	47.3 a	48.5 a
Incubation periods (T days)																
0		0.80 ns	0.84 ns	0.88 ns	0.91 b	0.96 b	1.82 ns	3.34 c	6.81 ns	8.09 ns	8.58 b	33.8 b	36.8 c	40.3 b	43.4 b	45.1 b
10		0.79 ns	0.85 ns	0.88 ns	0.92 ab	1.01 a	1.79 ns	3.99 a	7.08 ns	8.77 ns	10.5 a	35.9 a	39.8 bc	43.0 a	45.4 ab	47.4 a
20		0.81 ns	0.85 ns	0.88 ns	0.94 a	1.05 a	1.70 ns	3.77 ab	7.19 ns	8.45 ns	10.2 a	39.6 a	44.3 a	45.4 a	47.0 a	48.4 a
30		0.79 ns	0.85 ns	0.90 ns	0.94 a	1.03 a	1.65 ns	3.51 bc	7.29 ns	8.75 ns	10.6 a	39.5 a	43.1 ab	45.3 a	46.7 a	48.5 a
Interactions (B × T)																
Control	0	0.76 ns	0.83 ns	0.86 ns	0.87 ns	0.94 ns	1.65 ns	3.31 ns	5.61 ns	6.23 ns	6.91 ns	26.7 ns	31.3 ns	36.5 ns	40.9 ns	40.5 ns
	10	0.73 ns	0.83 ns	0.84 ns	0.87 ns	1.00 ns	1.45 ns	3.70 ns	6.17 ns	7.54 ns	9.52 ns	31.8 ns	34.9 ns	39.5 ns	43.5 ns	45.7 ns
	20	0.76 ns	0.84 ns	0.87 ns	0.93 ns	0.98 ns	1.49 ns	3.71 ns	6.85 ns	7.86 ns	10.3 ns	31.6 ns	41.7 ns	44.6 ns	47.2 ns	47.7 ns
	30	0.76 ns	0.84 ns	0.89 ns	0.91 ns	0.96 ns	1.55 ns	3.36 ns	5.90 ns	7.18 ns	10.0 ns	31.8 ns	37.2 ns	39.6 ns	42.7 ns	45.7 ns
OPEFB-B	0	0.84 ns	0.86 ns	0.90 ns	0.93 ns	0.95 ns	1.93 ns	3.12 ns	6.66 ns	7.74 ns	8.39 ns	37.3 ns	41.0 ns	42.5 ns	44.6 ns	47.9 ns
	10	0.84 ns	0.87 ns	0.91 ns	0.93 ns	1.01 ns	2.07 ns	4.17 ns	7.40 ns	9.75 ns	11.2 ns	44.0 ns	45.9 ns	46.8 ns	47.1 ns	48.9 ns
	20	0.85 ns	0.87 ns	0.89 ns	0.93 ns	1.07 ns	1.98 ns	4.46 ns	7.28 ns	7.82 ns	9.54 ns	42.3 ns	46.2 ns	44.7 ns	47.0 ns	49.0 ns
	30	0.80 ns	0.85 ns	0.92 ns	0.94 ns	1.05 ns	1.74 ns	3.61 ns	6.89 ns	8.39 ns	10.42 ns	43.0 ns	45.8 ns	47.0 ns	47.4 ns	48.9 ns
RH-B	0	0.75 ns	0.85 ns	0.86 ns	0.91 ns	0.96 ns	1.60 ns	3.62 ns	7.30 ns	9.09 ns	9.13 ns	34.3 ns	36.1 ns	38.2 ns	42.9 ns	45.5 ns
	10	0.79 ns	0.84 ns	0.88 ns	0.93 ns	0.99 ns	2.03 ns	3.32 ns	6.19 ns	8.78 ns	10.6 ns	29.7 ns	37.0 ns	40.4 ns	44.7 ns	47.0 ns
	20	0.81 ns	0.83 ns	0.89 ns	0.97 ns	1.04 ns	1.68 ns	3.24 ns	6.95 ns	8.76 ns	10.1 ns	40.9 ns	44.0 ns	45.8 ns	45.7 ns	47.5 ns
	30	0.79 ns	0.84 ns	0.87 ns	0.93 ns	1.04 ns	1.61 ns	3.44 ns	7.50 ns	8.89 ns	10.6 ns	43.2 ns	44.9 ns	46.3 ns	47.1 ns	49.2 ns
MC-B	0	0.84 ns	0.84 ns	0.90 ns	0.92 ns	0.97 ns	2.10 ns	3.29 ns	7.68 ns	9.30 ns	9.90 ns	37.0 ns	38.6 ns	43.9 ns	45.1 ns	46.5 ns
	10	0.79 ns	0.87 ns	0.90 ns	0.94 ns	1.04 ns	1.60 ns	4.78 ns	8.55 ns	9.03 ns	10.6 ns	38.3 ns	41.5 ns	45.3 ns	46.2 ns	48.0 ns
	20	0.82 ns	0.84 ns	0.88 ns	0.93 ns	1.11 ns	1.63 ns	3.64 ns	7.67 ns	9.34 ns	10.9 ns	43.6 ns	45.1 ns	46.4 ns	48.2 ns	49.5 ns
	30	0.82 ns	0.85 ns	0.92 ns	0.97 ns	1.05 ns	1.69 ns	3.63 ns	8.89 ns	10.5 ns	11.4 ns	39.9 ns	44.7 ns	48.1 ns	49.5 ns	50.0 ns
CV (%)		5.89	2.73	3.13	3.48	5.59	15.5	13.3	16.4	12.8	15.8	13.1	10.5	7.19	5.51	3.80

Note: Means followed by the same letter with columns are not significantly different at $p = 0.05$. OPEFB-B, oil palm empty fruit bunches biochar; RH-B, rice husk biochar; MC-B, maize cob biochar; CV, coefficient of variation; WAP, weeks after planting; ns, not significant.

dominantly increased the agronomic yield of cucumber followed by OPEFB-B and RH-B. The MC-B significantly increased plant height, leaf area and thickness, fresh and dry weight, water content, number of fruits, total fruit weight, and yield of cucumber by 74.4%, 78.7%, 7.30%, 223%, 111%, 14.6%, 125%, 139.1% and 139.2%, respectively, compared to the control. MC-B was shown to accelerate the harvesting period of cucumber fruit by 47.3-d. However, OPEFB-B significantly increased SPAD total chlorophyll, fruit length and cucumber fruit diameter by 8.39%, 22.7% and 9.81%, respectively, compared to the control. There was an increase in the number of cucumber leaves of 26.8% with RH-B.

Incubation periods also predominantly affected the agronomic

Table 6 Effect of biochar types, incubation periods, and their interactions on yield attributes of cucumber plants

Treatment		Fresh weight (g)	Dry weight (g)	Water content (%)	Harvest age (d)	Number of fruits	Fruit length (mm)	Fruit diameter (mm)	Total fruit weight (g)
Biochar types (B)									
Control		58.7 c	17.2 b	70.7 b	54.0 b	2.08 c	160 b	47.7 b	396 c
OPEFB-B		137 b	28.9 a	79.1 a	50.8 ab	3.50 b	197 a	52.4 a	813 ab
RH-B		138 b	29.3 a	77.8 a	48.4 a	3.75 b	182 a	51.0 a	740 b
MC-B		189 a	36.3 a	81.0 a	47.3 a	4.67 a	192 a	51.8 a	948 a
Incubation periods (T days)									
0		104 c	19.8 b	79.9 ns	50.6 ab	3.33 ns	163 b	46.8 b	642 ns
10		121 bc	26.6 ab	78.0 ns	52.7 b	3.58 ns	186 a	51.0 a	762 ns
20		158 a	32.8 a	76.0 ns	48.4 a	3.42 ns	198 a	53.7 a	764 ns
30		140 ab	32.6 a	74.6 ns	48.8 a	3.67 ns	185 a	51.5 a	730 ns
Interactions (B × T)									
Control	0	36.6 ns	6.91 ns	78.0 ns	58.7 ns	1.67 ns	130 ns	41.9 ns	253 ns
	10	51.5 ns	11.6 ns	77.5 ns	57.7 ns	1.67 ns	168 ns	48.7 ns	272 ns
	20	77.6 ns	26.7 ns	62.1 ns	48.3 ns	2.33 ns	188 ns	50.7 ns	492 ns
	30	69.1 ns	23.6 ns	65.1 ns	51.3 ns	2.67 ns	157 ns	49.5 ns	569 ns
OPEFB-B	0	117 ns	21.8 ns	82.0 ns	49.7 ns	3.00 ns	168 ns	49.3 ns	603 ns
	10	133 ns	26.4 ns	80.1 ns	56.3 ns	4.67 ns	187 ns	53.6 ns	1075 ns
	20	158 ns	28.2 ns	82.6 ns	47.7 ns	3.33 ns	228 ns	57.1 ns	918 ns
	30	138 ns	39.1 ns	71.7 ns	49.3 ns	3.00 ns	204 ns	49.6 ns	657 ns
RH-B	0	121 ns	28.0 ns	75.0 ns	48.0 ns	3.67 ns	171 ns	47.5 ns	724 ns
	10	124 ns	27.9 ns	76.6 ns	48.0 ns	3.67 ns	193 ns	49.6 ns	713 ns
	20	156 ns	30.0 ns	79.4 ns	51.0 ns	3.67 ns	169 ns	53.8 ns	752 ns
	30	153 ns	31.5 ns	80.2 ns	46.7 ns	4.00 ns	195 ns	53.2 ns	772 ns
MC-B	0	142 ns	22.4 ns	84.6 ns	46.0 ns	5.00 ns	182 ns	48.4 ns	986 ns
	10	175 ns	40.4 ns	77.8 ns	48.7 ns	4.33 ns	196 ns	52.1 ns	988 ns
	20	240 ns	46.2 ns	80.0 ns	46.7 ns	4.33 ns	206 ns	53.0 ns	893 ns
	30	200 ns	36.2 ns	81.5 ns	48.0 ns	5.00 ns	183 ns	53.7 ns	923 ns
CV (%)		29.4	22.7	10.4	7.82	26.7	12.7	6.28	30.0

Note: Followed by the same letter with columns are not significantly different at $p = 0.05$. OPEFB-B, oil palm empty fruit bunches biochar; RH-B, rice husk biochar; MC-B, maize cob biochar; CV, coefficient of variation; WAP, weeks after planting; ns, not significant.

and yield attributes of cucumber plants, except for leaf area, water content, number of fruits, total fruit weight and yield (Tables 4–6 and Fig. 2). There was an increase in plant height, number of leaves, leaf thickness, stem diameter, fresh weight, dry weight, fruit length and diameter along with the increasing incubation period up to 20-d were 39.7% 18.3%, 9.51%, 19.0%, 51.8%, 65.8% 21.6% and 14.7%, respectively, compared to non-incubated. The incubation period of 20-d also significantly accelerated the harvest period by around 48.4-d. However, there was an increase in SPAD total chlorophyll by 7.40% along with the increasing incubation period up to 30-d. Other results showed that the interaction between biochar types and incubation periods (B × T) had an insignificant impact on all agronomic yield characteristics of cucumber plants.

3.2 Cucumber fruit characteristics

All biochar types only significantly affected the fruit neck width

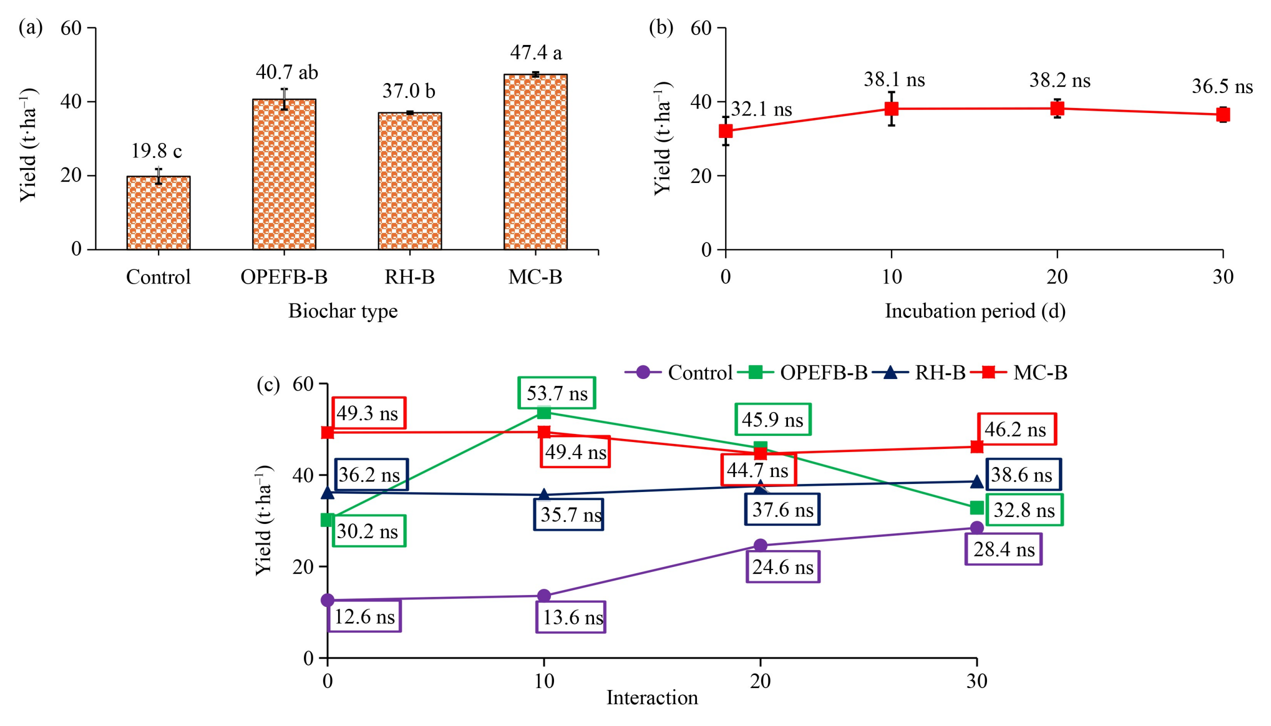

Fig. 2 Cucumber yield is affected by biochar types (a), incubation periods (b) and their interactions (c). OPEFB-B, oil palm empty fruit bunches biochar; RH-B, rice husk biochar; MC-B, maize cob biochar; ns, not significant; and the vertical line indicates the standard error.

of cucumber, but had insignificant effects on the fruit neck length, exocarp and mesocarp thickness and seed cavity (Table 7). The highest increase in the fruit neck width was found in OPEFB-B at 20.2% compared to the control. Incubation periods also significantly affected the fruit neck width and seed cavity but had an insignificant effect on the fruit neck length, exocarp and mesocarp thickness. The incubation period of 20-d produced the highest effect of widening the fruit neck (15.3% compared to the control) and the incubation period of 30-d significantly shortened the seed cavity. Other results showed that the interaction between the biochar types and incubation periods had an insignificant effect on all cross-section structures of cucumber fruit. Whole fruit and cross-sections based on the biochar types, incubation periods and interactions are shown in Fig. 3.

3.3 Changes in chemical characteristics and soil fertility index of Ultisol

The application of biochar types, incubation periods, and interactions significantly affected the chemical characteristics of Ultisol (Fig. 4 and Table 8). However, incubation periods showed only a slight impact on soil exchangeable K and the interactions also had an insignificant effect on soil exchangeable Na. The application of OPEFB-B produced the highest increase in soil pH, organic C, CEC, total N, total K, BS, and exchangeable Mg, Ca and K of 14.0%, 175%, 32.5%, 142%, 64.8%, 74.4%, 80.1%, 44.4% and 311%, respectively, compared to the control. In contrast, MC-B and RH-B showed the greatest potential to enhance available P and exchangeable Na by 34.9% and 26.2%, respectively. Also, extended incubation up to 20-d significantly improved soil pH, organic C, CEC, total N, total K, and exchangeable Mg and Ca in Ultisol by 2.35%, 62.5%, 22.6%, 20.4%, 19.2%, 11.2% and 28.7%, respectively, compared to non-incubated samples. Meanwhile, a 10-d incubation period significantly increased available P, BS and exchangeable Na by 12.1%, 19.9% and 51.0%, respectively. The interaction between OPEFB-B with incubation periods of 10 and 20-d significantly enhanced soil total K, exchangeable Mg, Ca and K, pH, organic C, CEC, and total N more than other treatments. However, available P and BS in Ultisol were most

Table 7 Effect of biochar types, incubation periods, and their interactions on cross-sectional structure of cucumber fruit

Treatment		Fruit neck length (mm)	Fruit neck width (mm)	Exocarp thickness (mm)	Mesocarp thickness (mm)	Seed cavity (mm)
Biochar types (B)						
Control		19.6 ns	30.8 b	0.68 ns	10.6 ns	13.8 ns
OPEFB-B		19.9 ns	37.1 a	0.87 ns	11.3 ns	14.1 ns
RH-B		17.9 ns	35.2 a	0.80 ns	11.4 ns	14.1 ns
MC-B		18.1 ns	34.9 a	0.87 ns	11.7 ns	13.9 ns
Incubation periods (T days)						
0		16.6 ns	32.1 b	0.67 ns	11.2 ns	14.3 b
10		20.5 ns	33.7 b	0.90 ns	10.6 ns	14.5 b
20		19.9 ns	37.0 a	0.90 ns	12.1 ns	14.1 b
30		18.5 ns	35.2 ab	0.76 ns	11.0 ns	12.8 a
Interactions (B × T)						
Control	0	12.4 ns	24.3 ns	0.57 ns	8.85 ns	14.7 ns
	10	26.6 ns	27.3 ns	0.80 ns	11.2 ns	14.3 ns
	20	20.2 ns	37.6 ns	0.79 ns	11.6 ns	13.1 ns
	30	19.1 ns	34.1 ns	0.56 ns	10.6 ns	13.0 ns
OPEFB-B	0	18.3 ns	34.1 ns	0.70 ns	12.6 ns	15.0 ns
	10	20.3 ns	37.6 ns	0.94 ns	8.91 ns	14.1 ns
	20	24.2 ns	40.6 ns	1.20 ns	12.9 ns	14.6 ns
	30	17.0 ns	36.1 ns	0.64 ns	10.8 ns	12.8 ns
RH-B	0	18.1 ns	34.0 ns	0.71 ns	12.0 ns	13.9 ns
	10	18.5 ns	35.4 ns	0.98 ns	10.8 ns	14.7 ns
	20	19.4 ns	35.7 ns	0.74 ns	12.2 ns	14.4 ns
	30	15.8 ns	35.5 ns	0.76 ns	10.6 ns	13.2 ns
MC-B	0	17.7 ns	36.1 ns	0.68 ns	11.5 ns	13.6 ns
	10	16.7 ns	34.4 ns	0.88 ns	11.5 ns	15.1 ns
	20	15.8 ns	34.2 ns	0.85 ns	11.7 ns	14.4 ns
	30	22.2 ns	35.0 ns	1.08 ns	12.0 ns	12.3 ns
CV (%)		16.6	10.7	17.7	16.4	11.0

Note: Means followed by the same letter with columns are not significantly different at $p = 0.05$. OPEFB-B, oil palm empty fruit bunches biochar; RH-B, rice husk biochar; MC-B, maize cob biochar; CV, coefficient of variation; ns, not significant.

effectively improved by MC-B with 10-d incubation and RH-B with non-incubated interactions.

The PCA results of the chemical characteristics of Ultisol as influenced by biochar types, incubation periods and their interactions are presented in Table 9. Three principal components (PC1–PC3) with eigenvalues > 1 were identified, cumulatively explaining 88.3% of the total variance in soil chemical properties. The eigenvalues decreased from PC4 to PC11 as shown in Fig. 5. PC1 accounted for 59.2% with significant contributions from pH, organic C, CEC, total N, total K, BS, and exchangeable Mg, Ca and K. PC2 explained 19.0% represented by exchangeable Na, while PC3 contributed 10.1% with available P. These components were subsequently used to determine the SFI. Based on Fig. 6, the SFI of Ultisol under different biochar treatments was classified as low, with the highest value observed in OPEFB-B (0.447), followed by MC-B (0.392) and RH-B (0.384). Similarly, the SFI of Ultisol

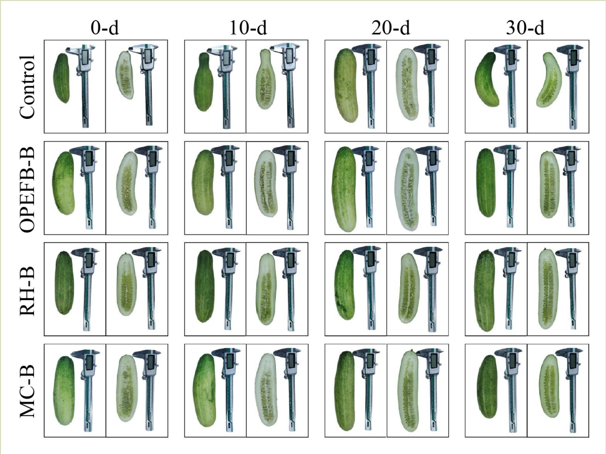

Fig. 3 Whole fruit (left) and cross-sectional (right) of cucumber fruits as affected by biochar type treatments (control; OPEFB-B, oil palm empty fruit bunches biochar; RH-B, rice husk biochar; and MC-B, maize cob biochar) and incubation periods (0, 10, 20 and 30-d).

under varying incubation periods was also categorized as low, with the highest value at 20-d (0.408), followed by 10-d (0.396) and 30-d (0.381). However, the interaction between biochar types and incubation period (B × T) showed a notable improvement in the SFI value of Ultisol, increasing from very low (0.245) to low and moderate levels (0.324–0.505). Notably, the interactions of OPEFB-B with a 20-d incubation period significantly enhanced the SFI value of Ultisol.

3.4 Macronutrient uptake and correlations

Biochar types and incubation periods significantly affected the content and uptake of macronutrients (N, P and K) in cucumber plant leaves (Table 10). OPEFB-B produced the highest contents of N and K nutrients by 13.9% and 17.6% compared to the control, while the highest increase in P nutrient content was found in MC-B by 9.88%. Similarly, the highest N, P and K nutrient uptake was recorded in MC-B with values of 125%, 123% and 122%, respectively, compared to the control. The 10-d incubation period resulted in the highest N content (14.7%), while the highest P and K contents were found in the 20-d incubation period by 15.1% and 14.7%, respectively. Also, the highest increases in N, P and K nutrient uptake due to the incubation period were found in 20-d, namely 100%, 106% and 103%, respectively, compared to non-incubated. The interaction of biochar types with incubation periods (B × T) was only significant for N, P and K contents, but had no significant effects on nutrient uptake. The interaction of OPEFB-B with 10-d incubation significantly enhanced N and K contents compared to other interactions. Meanwhile, the highest P content was found in the interaction of MC-B with 20-d incubation.

The correlation between soil chemical characteristics on the macronutrient uptake and agronomic yield of cucumber plants in response to biochar types, incubation periods and their interactions are presented in Table 11. Macronutrient uptake (N, P and K) was significant and positively correlated with soil organic C, available P, total K, and exchangeable Mg, K and Na. Also, the uptake of N, P and K had a significant positive correlation with cucumber dry weight with correlation coefficients of 0.622, 0.637 and 0.634, respectively. Additionally, cucumber yield per hectare was significantly and positively influenced by soil organic C, CEC, BS, and exchangeable Ca and K with values of 0.321, 0.342, 0.420, 0.392 and 0.487. These findings indicate that these soil characteristics are crucial for nutrient uptake, biomass formation and ultimately cucumber productivity.

4 Discussion

4.1 Effects of biochar types on Ultisol fertility and cucumber yield

The results indicate that OPEFB-B dominantly enhanced soil chemical properties by 14.0%–311%, while MC-B significantly increased available P and RH-B improved exchangeable Na (Fig. 4). OPEFB-B gave a more pronounced positive effect on Ultisol fertility compared to MC-B and RH-B, which was caused by higher C:N ratio, moisture content, BS and P content (Table 3). This finding was supported by the highest soil fertility index (0.447) observed for OPEFB-B compared to other biochar types (Fig. 6(a)). This result confirmed that the chemical properties of OPEFB-B, particularly its optimal C:N ratio, enhance soil total N content, mitigate nitrogen leaching and improve nutrient availability[22]. Similarly, the moisture retention capacity of biochar improved soil water retention, facilitating nutrient availability and uptake[23]. Saputra et al.[15] reported that the higher BS in OPEFB-B enhances essential nutrient availability closely associated with pH and CEC. The high C:N ratio, moisture retention and BS of OPEFB-B collectively contribute to significant improvements in key soil

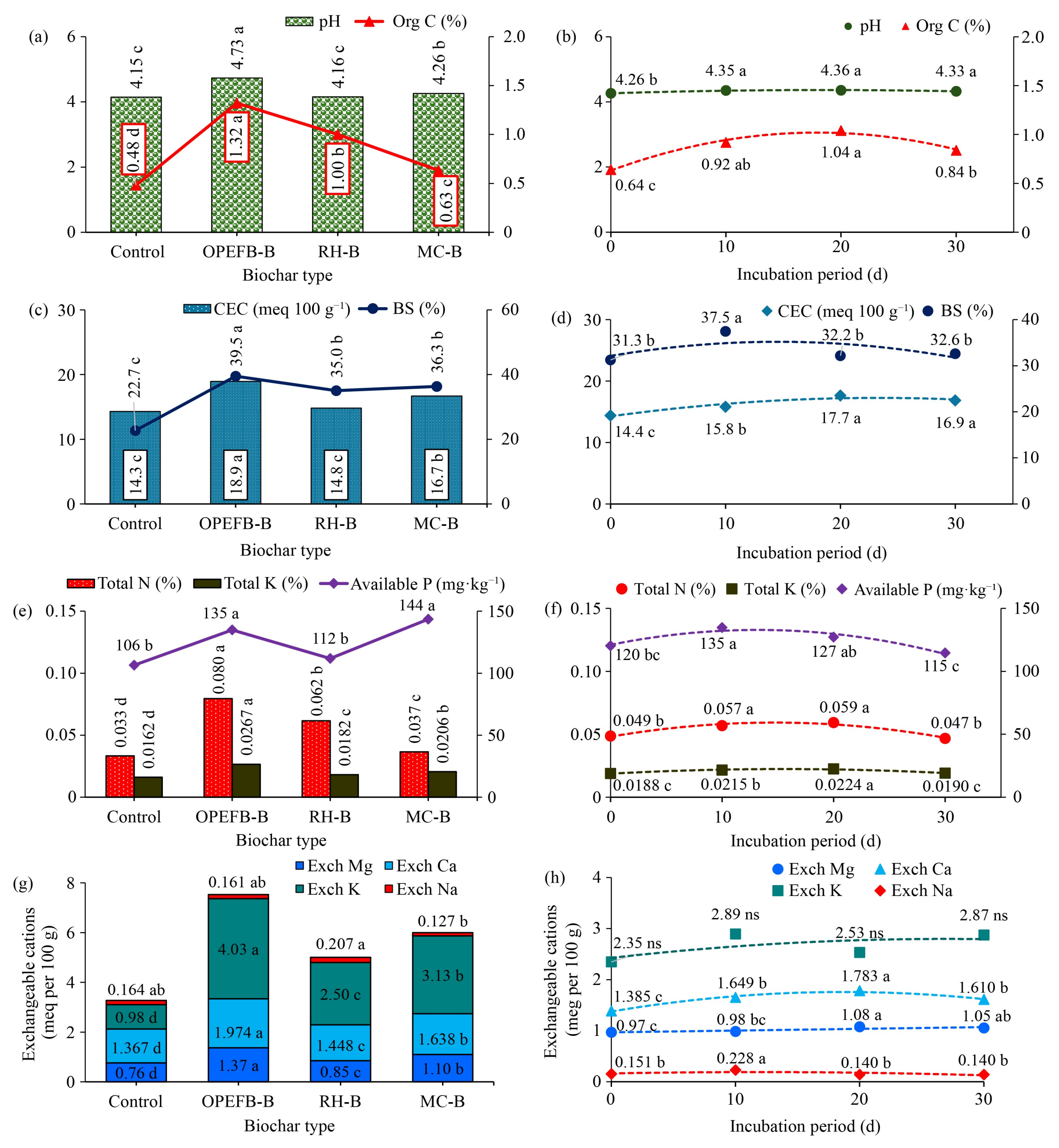

Fig. 4 Effect of biochar types (a, c, e, g) and incubation periods (b, d, f, h) on chemical characteristics of Ultisol in cucumber cropping. OPEFB-B, oil palm empty fruit bunches biochar; RH-B, rice husk biochar; MC-B, maize cob biochar; CEC, cation exchange capacity; BS, base saturation; ns, not significant.

fertility parameters, including pH, organic C, CEC, BS, total N, total K and exchangeable cations (Mg^{2+}, Ca^{2+} and K^+). This mechanism is consistent with Shi et al.[24], who showed that plant-derived biochar enhances soil pH buffering capacity

Table 8 Interactive effect of biochar types and incubation periods on chemical properties of Ultisol

Interaction (B × T)		pH	Org C (%)	CEC (meq per 100 g)	Total N (%)	Available P ($mg\cdot kg^{-1}$)	Total K (%)	BS (%)	Exchangeable cations (meq per 100 g)			
									Mg^{2+}	Ca^{2+}	K^+	Na^+
Control	0	4.02 g	0.32 i	10.3 j	0.014 i	82.4 gh	0.0168 d	14.6 i	0.38 j	0.803 f	0.45 f	0.136 ns
	10	4.16 def	0.53 hi	12.0 i	0.041 f	83.4 gh	0.0165 d	29.7 ef	0.82 h	1.525 bcd	0.42 f	0.275 ns
	20	4.23 c-f	0.57 ghi	16.9 c-f	0.054 e	131 cd	0.0166 d	24.6 fgh	0.99 efg	1.644 bcd	1.60 ef	0.130 ns
	30	4.18 def	0.51 hi	18.0 bcd	0.024 h	129 cd	0.0149 e	21.8 gh	0.86 gh	1.494 cd	1.45 ef	0.114 ns
OPEFB-B	0	4.65 b	0.64 f-i	17.5 cde	0.061 d	155 b	0.0252 b	29.0 ef	1.38 ab	1.591 bcd	1.96 e	0.140 ns
	10	4.78 a	1.22 cd	19.4 ab	0.079 b	139 bc	0.0294 a	46.8 b	1.44 a	2.342 a	5.09 a	0.185 ns
	20	4.83 a	1.81 a	20.4 a	0.104 a	139 bc	0.0255 b	42.5 bc	1.36 ab	2.332 a	3.99 abc	0.182 ns
	30	4.67 b	1.61 ab	18.5 bc	0.075 bc	107 ef	0.0265 b	39.8 c	1.29 bc	1.630 bcd	5.06 a	0.137 ns
RH-B	0	4.18 def	1.02 de	13.8 h	0.079 b	68.9 h	0.0167 d	53.4 a	0.94 fgh	1.474 d	4.75 ab	0.187 ns
	10	4.22 def	1.39 bc	13.3 hi	0.072 c	133 cd	0.0177 d	33.3 de	0.61 i	1.171 e	2.29 de	0.343 ns
	20	4.11 fg	0.90 ef	17.7 b-e	0.052 e	125 cde	0.0210 c	21.4 h	0.86 gh	1.503 bcd	1.15 ef	0.105 ns
	30	4.12 efg	0.69 fgh	14.5 gh	0.045 f	120 c-f	0.0174 d	32.0 de	0.98 efg	1.646 bcd	1.82 e	0.191 ns
MC-B	0	4.20 def	0.58 ghi	16.2 efg	0.041 f	175 a	0.0164 d	28.0 efg	1.18 cd	1.673 b	2.23 de	0.141 ns
	10	4.24 cde	0.53 hi	18.6 bc	0.036 g	183 a	0.0223 c	40.2 c	1.06 def	1.558 bcd	3.77 bc	0.109 ns
	20	4.26 cd	0.88 efg	15.6 fg	0.027 h	113 def	0.0265 b	40.3 c	1.10 de	1.653 bc	3.38 cd	0.141 ns
	30	4.34 c	0.54 hi	16.4 def	0.043 f	102 fg	0.0172 d	36.9 cd	1.08 def	1.668 bc	3.15 cd	0.116 ns
CV (%)		1.48	19.7	5.98	5.78	9.25	4.11	10.7	8.30	5.67	24.5	21.9

Note: Means followed by the same letter with columns are not significantly different at $p = 0.05$. OPEFB-B, oil palm empty fruit bunches biochar; RH-B, rice husk biochar; MC-B, maize cob biochar; CV, coefficient of variation; CEC, cation exchange capacity; BS, base saturation; ns, not significant.

through protonation of carboxyl groups and carbonate release, leading to increased pH and the mobilization of exchangeable cations in Ultisol. Xu et al.[25] added that the surface functional groups of biochar including carboxyl, phenolic, hydroxyl, carbonyl and quinone are crucial for improving critical soil chemical properties, such as CEC, pH and nutrient-water retention. Additionally, the increase in pH due to the application of these three biochars also varied greatly. OPEFB-B showed a linear increase in soil pH up to 15-d after incubation, followed by a gradual decline until 35-d[26]. In contrast, MC-B increased the Ultisol pH more rapidly (within 7-d incubation) compared to RH-B which required 21-d[27]. The prolonged pH elevation period of OPEFB-B compared to MC-B resulted in lower nutrient uptake efficiency.

MC-B dominantly improved agronomic characteristics and cucumber yield, with increases ranging from 7.30% to 223%, the leaf phosphorus content by 9.88%, enhanced macronutrient uptake by about 125%, and accelerated harvest period at 47.3 d. However, OPEFB-B significantly increased the SPAD total chlorophyll, fruit length and diameter, fruit neck width, and nutrient contents (N and K). In contrast, RH-B enhanced the number of leaves in cucumber plants. In general, MC-B showed a significant effect on increasing cucumber yield due to higher nutrient uptake, linked to its improved physicochemical properties. As shown in Table 3, MC-B had higher pH, organic C, CEC and nutrient levels (N, K, Mg and Ca) than OPEFB-B and RH-B. The elevated organic C, pH and CEC in MC-B significantly increased the availability of N, P and K nutrient uptake in Ultisol (Table 10), thereby supporting cucumber agronomy and productivity. This result was evidenced by the organic C and soil CEC had a positive and significant impact on increasing SPAD total chlorophyll, dry weight, fruit weight and cucumber yield (Table 11). Han et al.[28] found that increasing organic C and nutrient contents (N, P and K) had a positive impact on cucumber growth and yield. Additionally, Mahmoud et al.[29] also demonstrated that MC-B had chemical characteristics such as pH, organic C, C:N ratio, total N, total P and total K were 6.12, 52.2%, 99.4, 0.24%, 0.22%, and 0.27% respectively, significantly increased cucumber yield by 41.5%

Table 9 PCA results of biochar types, incubation periods, and their interactions on Ultisol chemical properties in cucumber cropping

Parameter	PC1	PC2	PC3
Eigenvalue	5.921	1.895	1.014
Proportion	0.592	0.190	0.101
Cumulative	0.592	0.782	0.883
pH	0.814	−0.095	0.434
Organic C	0.758	0.442	0.199
CEC	0.694	−0.578	0.002
Total N	0.787	0.400	0.216
Available P	−0.578	−0.206	0.550
Total K	0.749	−0.231	0.387
BS	0.737	0.345	−0.377
Exchangeable Mg	0.866	−0.358	−0.022
Exchangeable Ca	0.824	−0.135	−0.133
Exchangeable K	0.846	0.078	−0.282
Exchangeable Na	−0.017	0.910	0.216

Note: The factor loading value in each principal component (PC) indicates the contribution of each soil chemical characteristic. pH, PC loading; CEC, cation exchange capacity; BS, base saturation.

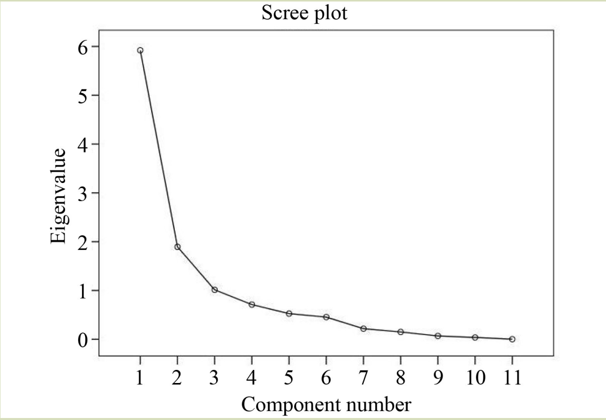

Fig. 5 Relationship between eigenvalues and principal components of PCA.

compared to the control. The application of MC-B in acidic soil conditions has also been shown to significantly enhance the growth and yield of various other horticultural crops. This positive response has been well-documented in chili pepper[30-32], tomato[33, 34], basil[35, 36], lettuce[36, 37] and others. While the efficacy of MC-B in enhancing crop productivity across acidic soils is well-established, it is crucial to recognize that these positive outcomes are not inherent to biochar itself. Rather, they are highly dependent on the specific pyrolysis conditions, such as temperature, feedstock type, and heating rate which ultimately dictate its physicochemical properties.

4.2 Effects of incubation periods on Ultisol fertility and cucumber yield

Extended incubation up to 20-d significantly enhanced soil chemical characteristics from 2.35% to 62.5% compared to non-incubated (Fig. 4). However, 10-d of incubation notably increased available P, BS and exchangeable Na of Ultisol. The optimal biochar incubation period for improving Ultisol fertility in this study was 20-d. This is attributed to the higher organic C content of the three biochars (Table 3), which subsequently increased soil pH and organic C until 20-d (Fig. 4(b)). Also, the soil fertility index at 20-d incubation significantly increased to 0.408 compared to the control (Fig. 6(b)). The rise in soil pH up to day 20 was driven by the dissolution of organic and mineral compounds from biochar, leading to increased concentrations of dissolved organic C, cations and anions in the soil solution[38,39]. Dissolved organic C release occurred rapidly during the first week but slowed significantly in subsequent weeks[40,41]. This dissolution process tends to be faster in nutrient-deficient soils like Ultisol[42] and correlates with enhanced soil respiration rates. Frimpong et al.[17] added that soil respiration increased at 7-d after biochar incubation and then decreased in 14 to 30-d. Additionally, soils amended with MC-B had higher respiration rates than RH-B, linked to increased microbial biomass C and soil pH. These findings are supported by Ebido et al.[16], who found significant improvements in soil organic C and total N due to RH-B at 8 weeks after incubation. Similarly, Lubis et al.[43] documented increased soil respiration with OPEFB-B up to 8 weeks after incubation, marked by a rise in soil pH and organic C of 5.73% and 2.35%, respectively.

The longer incubation up to 20-d significantly increased agronomic characteristics and harvest attributes of cucumber plants by 9.51%–65.8%, nutrient contents of P and K in the shoot of 15.2% and 14.7%, macronutrient uptake were 100% to 106%, widened fruit neck was 15.3% and accelerated the harvest period to 48.4-d compared to non-incubated treatments (Tables 4–7 and 10). However, a 30-d incubation significantly increased SPAD total chlorophyll and shortened seed cavity in cucumbers (Tables 5 and 7), while a 10-d

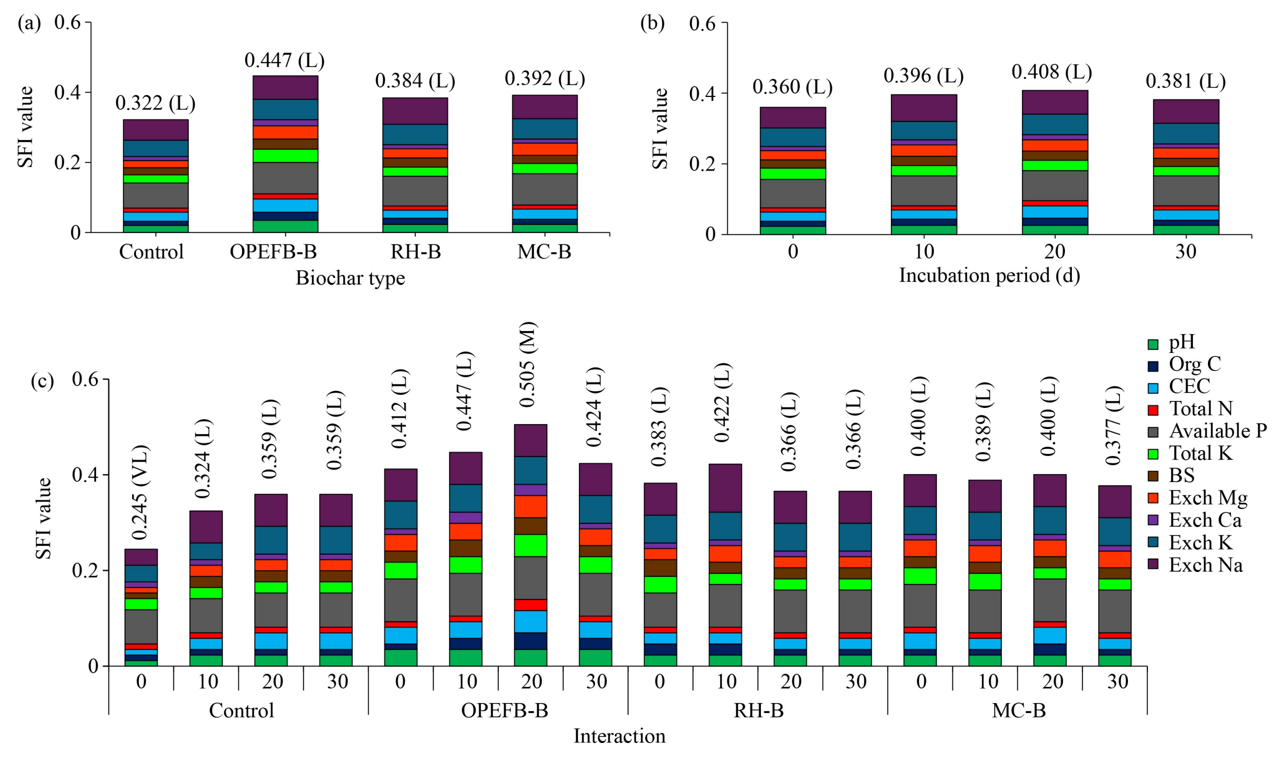

Fig. 6 Effects of biochar types (a), incubation periods (b), and their interactions (c) on soil fertility index (SFI) of Ultisol in cucumber cropping. OPEFB-B, oil palm empty fruit bunches biochar; RH-B, rice husk biochar; MC-B, maize cob biochar; CEC, cation exchange capacity; BS, base saturation. SFI values: VL, very low; L, low; and M, moderate.

incubation increased N content in the shoots (Table 10). The highest cucumber yield of 38.2 t·ha^{-1} was found with a 20-d incubation, although the effect was insignificant (Fig. 2(b)). Overall, the optimal biochar incubation period for enhancing agronomic performance and harvest attributes in this study was 20-d. This treatment resulted in the highest nutrient content and uptake compared to other incubation periods. Enhanced uptake of N, P and K in plant shoots had a significant positive correlation with increased plant height, leaf number and area, stem diameter, SPAD total chlorophyll and dry biomass of cucumber (Table 11). These findings align with Yang et al.[44], who reported that elevated N and K contents in shoots contribute to leaf expansion, stem thickening, improved photosynthetic capacity (chlorophyll content), and increased cucumber biomass. Afrida and Tampubolon[45] emphasized that nitrogen availability is a limiting factor in plant growth. Additionally, Saghaiesh et al.[46] demonstrated that optimal shoot P content enhances leaf protein synthesis and enzymatic activity, contributing to plant growth and yield. The period of the incubation process is a critical factor influencing the efficacy of biochar. Extended incubation periods have been shown to enhance microbial activation, facilitate nutrient mineralization and improve pH buffering capacity. Concurrently, soil enzyme activity which is integral to nutrient cycling processes tends to increase over time[47]. These changes directly impact nitrogen dynamics, as longer incubation increases the availability of mineral nitrogen forms (NH_3^+ and NO_3^-) and reducing nitrogen leaching in the soil[48]. Also, the pH buffering effect of biochar is more pronounced with longer incubation times, as biochar undergoes chemical transformations that enhance its buffering properties[49].

4.3 Interactive effects of biochar types with incubation periods on Ultisol fertility and cucumber yield

The interactions between OPEFB-B with incubation periods of 10- and 20-d significantly improved total K, exchangeable Mg,

Table 10 Effect of biochar types, incubation periods and their interactions on content and uptake of N, P and K nutrients in plant shoots

Treatment		N nutrient		P nutrient		K nutrient	
		Content (%)	Uptake (g per plant)	Content (%)	Uptake (g per plant)	Content (%)	Uptake (g per plant)
Biochar types (B)							
Control		2.12 c	0.374 b	0.172 c	0.031 b	2.80 c	0.51 b
OPEFB-B		2.41 a	0.761 a	0.185 ab	0.059 a	3.29 a	1.04 a
RH-B		2.16 bc	0.620 ab	0.178 bc	0.051 ab	2.92 bc	0.84 ab
MC-B		2.29 ab	0.842 a	0.189 a	0.069 a	3.09 b	1.14 a
Incubation periods (T days)							
0		2.09 b	0.405 b	0.165 b	0.032 b	2.76 b	0.54 b
10		2.39 a	0.683 ab	0.185 a	0.052 ab	3.11 a	0.90 ab
20		2.33 a	0.812 a	0.190 a	0.066 a	3.16 a	1.10 a
30		2.15 b	0.698 ab	0.184 a	0.059 a	3.07 a	0.99 a
Interactions (B × T)							
Control	0	2.03 d	0.147 ns	0.152 f	0.011 ns	2.46 f	0.18 ns
	10	2.16 cd	0.244 ns	0.176 cd	0.020 ns	2.63 ef	0.30 ns
	20	2.12 d	0.605 ns	0.170 de	0.048 ns	3.04 b-e	0.87 ns
	30	2.15 cd	0.498 ns	0.189 a-d	0.044 ns	3.07 bcd	0.71 ns
OPEFB-B	0	2.19 cd	0.379 ns	0.177 cd	0.031 ns	3.09 bcd	0.54 ns
	10	2.77 a	0.812 ns	0.186 bcd	0.054 ns	3.67 a	1.08 ns
	20	2.56 ab	0.934 ns	0.192 abc	0.070 ns	3.18 bc	1.16 ns
	30	2.12 d	0.920 ns	0.187 a-d	0.081 ns	3.23 bc	1.40 ns
RH-B	0	2.05 d	0.563 ns	0.157 ef	0.043 ns	2.74 def	0.76 ns
	10	2.08 d	0.607 ns	0.182 bcd	0.053 ns	2.82 c-f	0.82 ns
	20	2.43 bc	0.817 ns	0.191 abc	0.064 ns	3.10 bcd	1.04 ns
	30	2.06 d	0.494 ns	0.183 bcd	0.044 ns	3.00 b-e	0.72 ns
MC-B	0	2.07 d	0.530 ns	0.174 cd	0.045 ns	2.74 def	0.70 ns
	10	2.56 ab	1.069 ns	0.196 ab	0.082 ns	3.32 ab	1.39 ns
	20	2.23 cd	0.891 ns	0.205 a	0.082 ns	3.34 ab	1.33 ns
	30	2.28 bcd	0.880 ns	0.179 bcd	0.069 ns	2.96 b-e	1.14 ns
CV (%)		7.13	17.4	5.47	16.8	7.20	16.9

Note: Means followed by the same letter with columns are not significantly different at $p = 0.05$. OPEFB-B, oil palm empty fruit bunches biochar; RH-B, rice husk biochar; MC-B, maize cob biochar; CV, coefficient of variation; ns, not significant.

Ca and K, pH, organic C, CEC, and total N in Ultisol (Table 8). However, soil available P was significantly enhanced by the interactions of MC-B with a 10-d incubation, while BS increased under the interactions of RH-B without incubation. The interaction of OPEFB-B with 10- and 20-d incubations significantly enhanced soil chemical properties, and the fertility status of Ultisol improved from low to moderate (Fig. 6(c)).

This improvement can be attributed to the mechanisms of biochar in the soil during the initial 1-3 weeks of incubation, which primarily involve the dissolution of organic and mineral compounds as characterized by an increase in soil pH, dissolved organic C and cation-anion concentrations in the soil solution[50]. Also, functional groups in OPEFB-B such as carboxylate and phenolic groups are crucial for facilitating the

Table 11 Correlation between soil characteristics and nutrient uptake with agronomic yield of cucumber plants as affected by biochar types, incubation periods and their interactions.

Correlation value	N uptake	P uptake	K uptake	Plant height	Number of leaves	Leaf area	Leaf thickness	Stem diameter	Total chlorophyll	Fresh weight	Dry weight	Number of fruits	Fruit length	Fruit diameter	Productivity
pH	0.002	−0.008	0.004	−0.124	−0.134	−0.057	0.402**	0.167	0.053	0.003	−0.109	−0.164	0.041	−0.099	−0.033
Org C	0.303*	0.303*	0.310*	0.208	0.207	0.241	0.001	0.070	0.314*	0.211	0.290*	0.221	0.439**	0.348*	0.321*
CEC	0.201	0.187	0.199	0.172	0.141	0.274	−0.186	0.018	0.320*	0.228	0.313*	0.323*	0.273	0.433**	0.342*
Total N	−0.009	−0.046	−0.022	0.089	0.044	0.208	0.177	0.050	0.298*	0.144	0.057	0.120	0.441**	0.344*	0.259
Available P	0.646**	0.636**	0.634**	0.147	0.217	0.282	−0.170	0.208	0.304*	0.075	0.241	0.088	0.108	0.181	0.172
Total K	0.640**	0.627**	0.656**	0.092	0.125	0.251	0.181	0.235	0.436**	0.241	0.320*	0.067	0.296*	0.269	0.239
BS	0.226	0.209	0.227	0.281	0.195	0.428**	−0.047	0.067	0.320*	0.338*	0.402**	0.414**	0.366*	0.371**	0.420**
Exchangeable Mg	0.692**	0.674**	0.700**	0.046	0.173	0.347*	0.106	0.352*	0.510**	0.193	0.283	0.116	0.277	0.263	0.267
Exchangeable Ca	−0.238	−0.269	−0.246	0.066	−0.105	0.206	0.465**	0.184	0.324*	0.314*	0.051	0.260	0.399**	0.415**	0.392**
Exchangeable K	0.309*	0.291*	0.321*	0.236	0.162	0.444**	0.067	0.109	0.354*	0.378**	0.457**	0.431**	0.393**	0.321*	0.487**
Exchangeable Na	0.535**	0.540**	0.531**	−0.044	0.091	−0.068	−0.238	0.150	0.148	−0.205	−0.001	−0.256	−0.005	−0.122	−0.203
N uptake	–	–	–	0.285*	0.465**	0.375**	0.077	0.528**	0.352*	0.267	0.622**	0.106	0.151	0.217	0.233
P uptake	–	–	–	0.296*	0.477**	0.361*	0.080	0.533**	0.362*	0.275	0.637**	0.089	0.162	0.210	0.208
K uptake	–	–	–	0.282	0.469**	0.370**	0.079	0.536**	0.364*	0.270	0.634**	0.097	0.173	0.216	0.223

Note: * and ** significant correlations at the 0.05 and 0.01 levels. *n*= 48. CEC, cation exchange capacity; BS, base saturation.

dissolution process of organic C[51]. These mechanisms collectively contribute to enhanced soil quality as evidenced by an increase in pH, total organic C, microbial biomass C, CEC, and total N in the Ultisol. The dissolution of biochar compounds and the interaction of their functional groups with the soil during the early weeks of application are key factors in improving Ultisol quality, influencing its chemical, physical, and biological properties.

The interaction between OPEFB-B with a 10-d incubation resulted in the highest N and K contents in the shoots, while the highest P content was found in the interaction between MC-B and a 20-d incubation (Table 8). The N and K contents in cucumber shoots increased significantly due to the high soil BS and total K in the OPEFB-B interaction with 10-d incubation compared to other incubation periods. Similarly, the higher P content in shoots under MC-B with 20-d incubation correlated with increased soil organic C and BS, compared to different incubation periods. Overall, soil organic C and BS of these interactions greatly affect the availability of N, P and K in cucumber shoots. This finding is consistent with Yuan et al.[52], who showed that soil BS due to biochar application can enhance CEC and retention of exchangeable cations (K, Ca and Mg) by reducing leaching. Dong et al.[53] demonstrated that biochar application significantly increases soil organic C content by 26.9%–65.3% in surface layers, with fulvic and humic acid derivatives promoting nutrient mobilization. Additionally, Zhang et al.[54] identified organic acids (e.g., acetate, citrate, glycolate and tartrate) are important for P and K release from biochar. Contrastingly, the interaction between biochar types and incubation periods had an insignificant effect on agronomic traits, harvest attributes, yield, fruit structure cross-section and macronutrient uptake in cucumbers. This lack of response may be attributed to the relatively short incubation period, which likely limited the optimal release and availability of nutrients from biochar to support cucumber growth and productivity. These results indicate that extended incubation periods with MC-B and OPEFB-B should be investigated to evaluate their potential for improving cucumber growth and productivity.

5 Conclusions

MC-B biochar is recommended for direct productivity enhancement (47.4 $\mathrm{t \cdot ha^{-1}}$), as it was more effective in promoting the nutrients uptake of N, P and K by cucumbers. In contrast, OPEFB-B biochar was superior for soil fertility with SFI value was 0.447. An incubation period of 20-d was identified as optimal for maximizing yield and Ultisol fertility. While the interaction of biochar type and incubation period (OPEFB-B with 10–20 d) significantly improved overall soil fertility (excluding available P and BS). However, the interaction between biochar types and incubation periods were significant effects on plant height and leaf area. Cucumber productivity was most strongly correlated with key soil chemical properties, particularly organic C, cation exchange capacity, base saturation, and exchangeable K and Ca, underscoring their critical contribution to crop performance. Optimizing the types and incubation periods of biochar represents a critical preplant management strategy in crop rotation, offering an effective means of improving the fertility of acidic soils and crop productivity. For future studies, it is recommend that field trials be conducted to determine optimal biochar types and incubation periods, investigating combined applications of OPEFB-B and MC-B biochars, a comprehensive analysis be undertaken of the financial feasibility of biochar application, and an evaluation made of biochar ability under various environmental stress conditions.

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Compliance with ethics guidelines

Alridiwirsah, Koko Tampubolon, Muhammad Alqamari, Posma Mangasi Pintaria Marbun, Delima Napitupulu, Novilda Elizabeth Mustamu, and Fransisca Natalia Sihombing declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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