Leaching of nutrients from peat soil and nutrient uptake by oil palm seedlings: Effects of biochar from empty oil palm fruit bunches and nitrogen fertilisation

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SUMMARY

The chemical characteristics of peat soil can be improved with soil amendments such as biochar derived from Oil Palm Empty Fruit Bunches (OPEFB), or by nitrogen (N) fertilisation. Our study aimed to determine the separate effects of OPEFB biochar and N fertiliser, along with their interaction, on the dynamics (loss, content, uptake) of nutrients in peat soil as well as on the growth of oil palm seedlings. A glasshouse experiment was carried out in North Sumatra (Indonesia) from December 2020 to February 2021 using a Complete Randomised Factorial design. The first factor was the OPEFB biochar dosages (0, 5, 10, 15 t ha^{-1}) and the second factor was the dosage of N fertiliser (30, 45, 60 kg ha^{-1}), with three replicates. The data were analysed using ANOVA and continued with Duncan at $P < 0.05$. The results showed that biochar doses of 10 and 15 t ha^{-1} effectively reduced the losses of N and magnesium (Mg) by 15.7 and 7.56 %, respectively. These reductions were accompanied by increases in soil pH (by 5.12 %) and exchangeable potassium (by 48.3 %). The levels of the plant nutrients phosphorus (P), copper (Cu), potassium (K), calcium (Ca) and boron (B) in the oil palm seedlings were 17.8, 27.0, 5.88, 7.89 and 0.18 %, respectively. Furthermore, N fertiliser doses of 30–45 kg ha^{-1} increased pH, total N and nutrient (N, B) content as well as the uptake of N, P, K, Mg, Ca, B and Cu. The interaction of 10–15 t ha^{-1} biochar with 30–45 kg ha^{-1} nitrogen fertiliser inhibited leaching of N but increased exchangeable-K and nutrient (N, P, K, Mg, Ca, B, Cu) contents. Based on our results, only N doses of 30–45 kg ha^{-1} were effective in increasing the number of leaves, stem diameter and biomass of oil palm seedlings, while the effects of biochar and the interaction were insignificant. The findings of this study are relevant for oil palm plantations in peatland areas.

KEY WORDS: dosage, growth, nutrient content, nutrient loss, soil chemistry

INTRODUCTION

In 2011, tropical peatlands in Indonesia were estimated to cover a total area of 14.9 million ha distributed across the islands of Sumatra (6.44 million ha), Borneo (Kalimantan; 4.78 million ha) and Papua (3.69 million ha), of which 30 % could potentially be used for agriculture (Ritung *et al.* 2011). On Sumatra, peat thickness exceeds three metres on approximately 46 % of the total peatland area, and it has been reported that 19.6 % (1,262,530 ha) of Sumatran peatland has been utilised for plantation activities (Agus *et al.* 2016). The use of peatlands for plantation activities has several pitfalls including effects on the availability of plant nutrients. For example, Pulunggono *et al.* (2019) reported that the nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) contents of peat soils in oil palm plantations were lower than in secondary forests and shrublands, indicating a requirement for re-balancing through fertilisation. According to Daryono (2009), peatlands that have been converted to plantations have several undesirable characteristics such as subsidence (degradation of the peatland surface due to a decrease or loss of groundwater, an increase in peat decomposition, and the occurrence of fires and greenhouse gas emissions), irreversible drying, low nutrient availability, high acidity and high combustibility when dry.

North Sumatra Province has a peatland area of 261,234 ha (Ritung *et al.* 2011). Sitohang *et al.* (2021) reported that peat from depth 0–130 cm in Labuhanbatu, North Sumatra had a pH of 3.38–3.52 (very acidic), an organic C content of 21.8–24.2 %, and a Cation Exchange Capacity (CEC) of 103–133 mg 100 g^{-1}. Hutagaol *et al.* (2021) added that peatlands from Humbang Hasundutan, North Sumatra had average values of bulk density, water content pH of 0.35 g cm^{-3}, 220 % and 3.98 (very acidic). On the basis of previous studies, it can be stated that these peatlands have low pH and nutrient availability as well as high organic acid content.

In the context of agricultural use of peatlands, these soil characteristics can be improved using various methods including soil amelioration and fertilisation. One of the effective soil amelioration methods is the use of biochar from plant residues. Aller (2016) reported that biochars prepared from animal waste, plant residue and seaweed had higher nutrient and pH levels than biochars derived from wood. Amer (2017) showed that the use of 2 t ha^{-1} of rice straw biochar and 400 ml of tea compost significantly increased crop yield and the uptake of N, P and K. Likewise, Xiao *et al.* (2016) reported that using 10–30 t ha^{-1} of maize cob biochar significantly increased the availability of total N, P and K. The application of oil palm empty fruit bunches has been reported by Ichriani *et al.* (2021) to significantly increase pH, exchangeable-Ca, exchangeable-K and available P compared to compost. Azis *et al.* (2022) also found a significant decrease in nitrogen loss with increasing doses of Oil Palm Empty Fruit Bunches (OPEFB) biochar. According to Bakar *et al.* (2015) the application of OPEFB biochar significantly increased total C, available P, CEC, exchangeable-Ca and -K of the soil and significantly affected root performance in absorbing nutrients, thereby increasing plant biomass.

Another approach to improving soil chemical characteristics and supporting plant growth is nitrogen (N) fertilisation. Valentinuz & Tollenaar (2006) stated that N is the main nutrient limiting plant growth if it is not provided in sufficient amounts. Rafiq *et al.* (2010) added that it plays an important role in increasing plant protein content due to the presence of amino groups, and in protein-building. Furthermore, according to Afrida & Tampubolon (2022), N is the limiting factor that inhibits plant growth. Wang *et al.* (2019) reported that N fertilisation can decrease total N loss in peatlands. Xia *et al.* (2022) also stated that N fertilisation significantly increased pH, nitrate, ammonium and dissolved organic C (DOC). Biochar application with the addition of N fertiliser significantly affects soil aggregates (Li *et al.* 2019, Tian *et al.* 2020) by reducing soil erosion, permeability, infiltration and nutrient cycling (Ramos *et al.* 2019, Shen *et al.* 2019). In addition, it significantly reduces N loss, but increases root growth and N uptake for plants (Xia *et al.* 2022).

This indicates that further assessment is needed on the role of these materials in nutrient retention and nutrient dynamics in peatlands, as well as in oil palm seedling growth. Undertaking such studies is imperative to generate scientific knowledge that can effectively inform oil palm stakeholders about responsible peatland management. Therefore, this study aims to determine the effects of OPEFB biochar, N fertiliser and their interaction on nutrient dynamics (loss, contents, and uptake) in peatlands and its effects on growth metrics for oil palm seedlings such as plant height, number of leaves, stem diameter and biomass.

METHODS

Design of the study

The research was conducted in the Greenhouse Research and Development Centre Bahilang (R&D Bahilang), Asian Agri, Tebing Tinggi, North Sumatra, Indonesia from December 2020 to February 2021. The conditions in the glasshouse were: temperature 38.2 °C; relative humidity 46 %; and air pressure 1011 hPa. The experimental setup followed a completely randomised design (CRD) with two factors. The first factor was the application rates of OPEFB biochar (0, 5, 10 or 15 t ha^{-1}) following Syuhada *et al.* (2016). The second factor was the dosage rates of nitrogen fertiliser (urea, 46 % N). The N dosage rates were 30, 45 and 60 kg ha^{-1}, providing reductions of 90 %, 85 % and 80 %, respectively, relative to the optimum (300 kg ha^{-1}; Zhang *et al.* 2017). All treatments were replicated three times.

Preparation of biochar

The raw material for the biochar was fresh empty fruit bunches discarded by palm oil mills, which was processed using a simple pyrolysis reactor. Residence time in the reactor was 120 minutes and the final pyrolysis temperature was 450 °C. The chemical characteristics of the biochar produced were determined after calcination at 950 °C followed by borate fusion (Chao & Sanzolone 1992) and are presented in Table 1.

Growing medium

The peat soil used as the planting medium for oil palm seedlings in this study was collected from the oil palm plantation area in South Labuhanbatu District, North Sumatra, Indonesia (2° 23' 38.63" N, 99° 58' 35.64" E). Peat (depth 0–60 cm) was collected from six locations and mixed (Hodgkins *et al.* 2018). The peat soil was classified as typic haplosaprists and the chemical characteristics such as pH, C content and cation exchange capacity (CEC) were determined. For this, the soil was sampled after two days of incubation, air-dried at room temperature for 48 hours, and sifted through a 1-cm sieve. Based on this analysis it was found that the pH was 3.50 (very acid), organic C content was 46.4 % and CEC was 60.9 cmol kg^{-1}.

Table 1. Various chemical characteristics of the biochar used in this study. The laboratory method used for determination of each characteristic is also shown.

Chemical characteristics	Methods	Value
pH	Electrometry	9.44
C/N	Dry ashing	20.8
Organic C (%)	Walkley & Black	37.5
N (%)	Kjeldahl	1.80
P (%)	Perchloric acid	0.49
K (%)	Perchloric acid	5.10
Mg (%)	Ammonium acetate	0.46
Ca (%)	Ammonium acetate	0.75

The prepared biochar was mixed with peat soil in the required proportions and the mixture was used to fill 20 kg polybags which were arranged in a glasshouse according to the study design. For the determination of leached nutrients, a water storage container was made for each polybag.

Oil palm seedlings

Oil palm seedlings (variety dura×pisifera (D×P) Topaz; age three months) were selected for homogeneous growth and planted into the polybags. Plant height was measured and the number of leaves per plant was recorded. At the time of planting, a basic fertiliser (rock phosphate, 27 % P_2O_5) was applied at a rate of 60 g polybag^{-1}. After that the oil palm seedlings were treated and watered daily. The amount of water applied was based on water holding capacity and was 0.5 L polybag^{-1} at age two months and 1.0 L polybag^{-1} at age three months.

Data collection and analysis

Measurements of leached nutrients, plant height, number of leaves and stem diameter were made at monthly intervals for three months after treatment (MAT). At the end of the study, data were collected on nutrient residues, nutrient content and uptake, and fresh and dry mass of the oil palm seedlings. The measurement of fresh mass was conducted by separating the roots from the shoots and weighing the two fractions separately, and dry mass was determined after oven drying at 80 °C for 24 hours. The stem diameter was measured using a caliper. The measurements of leached nutrients were carried out by taking 500 ml samples from storage containers that collected drainage from the polybags. The nutrient content of the peat soil was determined from a 1 kg sample. The nutrient content of tissue from the oil palm seedlings was determined by taking 100 g samples of leaves and roots. The measurement methods are shown in Table 2.

Nutrient uptake (g plant^{-1}) was then calculated as the product of nutrient content (g kg^{-1}) and dry mass (kg plant^{-1}). The data were analysed by ANOVA followed by the Duncan test at $P < 0.05$ using IBM SPSS software. The data on chemical characteristics of the soil were correlated with nutrient content and nutrient uptake into the tissue of oil palm seedlings using Pearson correlation.

RESULTS

Leached nutrients

Biochar had a significant effect on the amount of N, P, K and Mg leached from the peat soil by the end of the study (3 MAT), while nitrogen fertilisation influenced the amount of N and Mg leaching. The interaction (of biochar and N fertilisation) significantly affected the amount of leached N, P, and K (Table 3). Increasing the dose of biochar up to 15 t ha^{-1} caused increases in the losses of P and K by 31.9 % and 117 %, respectively, compared to the control, but there was a decrease in leaching of P and K with time from one to three MAT. Biochar doses of 10 and 15 t ha^{-1} caused the greatest reductions in losses of N (by 15.8 %) and Mg (by 7.56 %). Nitrogen fertilisation at 30 kg ha^{-1} was accompanied by lower leaching of N (by 16.8 ppm) and Mg (by 16.9 ppm) compared to other dosages. The interaction B0N2 (no biochar with 30 kg ha^{-1} N) showed the lowest losses of P and K at 32.5 and 83.3 ppm, respectively; and the B2N1 interaction (10 t ha^{-1} biochar with 30 kg ha^{-1} N) had the lowest leaching of N (14.6 ppm) at the end of the observation period.

Table 2. Methods used for measuring the chemical characteristics of leachates, peat soil and plant tissues.

	Chemical characteristics	Methods
Leached nutrients	N	Kjeldahl
	P	Perchloric acid
	K	Perchloric acid
	Mg	Ammonium acetate
Nutrient content in the peat soil	pH	Electrometry
	CEC	Tritimetry
	Organic C	Walkley & Black
	Total N	Kjeldahl
	Available P	Spectrophotometric
	Exchangeable-K	Atomic Absorption Spectroscopy (AAS)
	Exchangeable-Mg	Atomic Absorption Spectroscopy (AAS)
	Exchangeable-Ca	Atomic Absorption Spectroscopy (AAS)
	Exchangeable-Na	Atomic Absorption Spectroscopy (AAS)
Nutrient content in the oil palm seedlings tissue	N	Kjeldahl
	P	Perchloric acid
	K	Perchloric acid
	Mg	Ammonium acetate
	Ca	Ammonium acetate
	B	Atomic Absorption Spectroscopy (AAS)
	Cu	Atomic Absorption Spectroscopy (AAS)

Growth and biomass of oil palm seedlings

Nitrogen fertilisation significantly increased the number of leaves and stem diameter, as well as the fresh and dry weights of shoots, but there was no significant effect for plant height. Biochar had a significant effect on the fresh and dry mass of roots, but no significant effect on the other growth metrics. The effect of the interaction was insignificant for all growth characteristics of oil palm seedlings (Table 4 and Figures 1–2). Nitrogen fertilisation at 30 kg ha^{-1} was accompanied by the greatest increases in number of leaves (by 10.1) and fresh and dry mass of roots (by 37.9 g and 8.63 g, respectively); while a dose of 45 kg ha^{-1} N caused the greatest increases in stem diameter (by 3.09 cm), fresh mass (by 209 g) and dry mass (by 56.5 g) of shoots. Moreover, the fresh and dry mass of shoots displayed a quadratic relationship ($\hat{y}$= -35.5x^2+126x+98.4 and $\hat{y}$= -8.94x^2+31.6x+29.1), while the fresh and dry mass of roots had a linear relationship ($\hat{y}$= -5.93x+45.3 and $\hat{y}$= -1.27x+10.2) owing to nitrogen fertilisation. The treatment without biochar had the highest fresh mass (38.7 g) and dry mass (8.91 g) of roots compared to other doses.

Chemical characteristics of the peat soil

Biochar significantly affected soil pH and the exchangeable cations K^+ and Ca^{2+} in the peat soil, but not CEC, organic C, total N, available P or the exchangeable cations Mg^{2+} and Na^+. Nitrogen fertilisation had a significant effect on soil pH, total N and exchangeable-Ca. However, the interaction influenced exchangeable-K only (Table 5). A high biochar dose of up to 15 t ha^{-1} significantly increased pH and exchangeable-K by 5.12 and 48.3 %, respectively. It also reduced exchangeable-Ca by 7.16 % compared to the control. High nitrogen doses from 30 to 60 kg ha^{-1} significantly increased soil pH and total N by 4.08 and 1.31 %, respectively, and significantly reduced exchangeable-Ca to 4.27 cmol kg^{-1}. Compared to the other interactions, the interaction B3N1 (15 t ha^{-1} biochar with 30 kg ha^{-1} N) had the highest exchangeable-K at 1.85 cmol kg^{-1}.

Table 3. Leached nutrients (N, P, K, Mg) collected in the oil palm nursery for each of the different treatments with OPEFB biochar, N fertiliser and interactions of these two factors. Mean values are shown. Values followed by different letters in the same column are significantly different (Duncan's test at 5 %). MAT = months after treatment; CV = coefficient of variation; ns = not significant.

Treatments	Leached nutrients (ppm)											
	1 MAT				2 MAT				3 MAT			
	N	P	K	Mg	N	P	K	Mg	N	P	K	Mg
OPEFB biochar (t ha^{-1})												
0 (B_0)	22.5 ns	255 a	261 a	46.7 ns	32.6 c	80.7 a	137 a	25.4 c	33.3 b	35.7 a	85.2 a	21.6 ab
5 (B_1)	20.8 ns	253 a	354 b	44.6 ns	29.1 b	89.5 b	155 b	25.1 c	37.7 c	41.7 b	119 b	22.3 b
10 (B_2)	20.4 ns	268 b	415 c	48.0 ns	27.2 ab	96.7 c	194 c	22.5 b	28.0 a	44.1 b	176 c	22.2 b
15 (B_3)	20.6 ns	268 b	452 c	45.6 ns	25.8 a	100.9 c	216 d	20.1 a	30.1 ab	47.2 c	185 c	19.9 a
N fertiliser (kg ha^{-1})												
30 (N_1)	22.2 ns	260 ns	361 ns	46.4 ns	23.5 a	92.3 ns	172 ns	20.7 a	16.8 a	43.1 ns	137 ns	16.9 a
45 (N_2)	19.2 ns	263 ns	368 ns	45.7 ns	32.3 b	92.2 ns	178 ns	24.6 b	34.3 b	41.0 ns	142 ns	22.7 b
60 (N_3)	21.9 ns	260 ns	382 ns	46.5 ns	30.2 b	91.3 ns	177 ns	24.6 b	45.8 c	42.4 ns	144 ns	24.8 c
Interactions												
B_0N_1	27.4 ns	257 ns	244 ns	46.3 ns	24.7 ab	82.9 ab	144 ab	22.4 bc	17.5 a	34.1 a	83.3 a	17.3 ns
B_0N_2	19.4 ns	252 ns	239 ns	46.3 ns	35.2 de	76.6 a	144 ab	25.1 cd	33.2 c	32.5 a	83.3 a	22.7 ns
B_0N_3	20.6 ns	255 ns	300 ns	47.5 ns	38.1 e	82.6 ab	122 a	28.8 e	49.1 d	40.7 b	88.9 ab	24.7 ns
B_1N_1	20.2 ns	248 ns	322 ns	43.5 ns	24.3 ab	82.3 ab	139 ab	21.2 ab	20.0 ab	43.2 b	119 c	18.8 ns
B_1N_2	18.7 ns	255 ns	367 ns	43.1 ns	36.7 e	94.8 cde	161 bc	27.5 de	46.7 d	40.8 b	111 bc	23.5 ns
B_1N_3	23.4 ns	257 ns	372 ns	47.1 ns	26.2 abc	91.3 bcd	164 bc	26.7 de	46.4 d	41.0 b	125 c	24.5 ns
B_2N_1	19.5 ns	270 ns	433 ns	50.2 ns	22.7 a	103.0 ef	197 de	21.0 ab	14.6 a	45.0 bc	194 ef	16.9 ns
B_2N_2	17.2 ns	267 ns	422 ns	47.1 ns	31.5 cd	100.0 def	208 e	25.1 cd	25.2 ab	44.9 bc	181 e	24.3 ns
B_2N_3	24.5 ns	268 ns	389 ns	46.7 ns	27.4 abc	86.3 bc	178 cd	21.4 ab	44.3 d	42.4 b	153 d	25.5 ns
B_3N_1	21.6 ns	267 ns	444 ns	45.8 ns	22.4 a	100.0 def	206 e	18.2 a	15.1 a	50.0 c	153 d	14.7 ns
B_3N_2	21.4 ns	277 ns	444 ns	46.4 ns	25.8 ab	97.6 def	197 de	20.6 ab	32.1 c	45.7 bc	192 ef	20.4 ns
B_3N_3	18.9 ns	260 ns	467 ns	44.7 ns	29.2 bc	105.0 f	244 f	21.6 b	43.2 d	45.8 bc	211 f	24.7 ns
CV (%)	17.5	4.88	11.0	8.33	10.2	5.33	8.01	7.20	10.8	6.98	9.87	8.38

Table 4. Growth characteristics of oil palm seedlings in the different treatments with OPEFB biochar, nitrogen fertiliser, and interactions. Mean values are shown. Values followed by different letters in the same column are significantly different (Duncan's test at 5 %). MAT = months after treatment; CV = coefficient of variation; ns = not significant.

Treatments	Growth characteristics of oil palm seedlings										
	Plant height (cm)				Number of leaves				Stem diameter (cm)		
	Initial	1 MAT	2 MAT	3 MAT	Initial	1 MAT	2 MAT	3 MAT	1 MAT	2 MAT	3 MAT
OPEFB biochar (t ha^{-1})											
0 (B_0)	28.0	35.2 ns	42.5 ns	58.7 ns	4.62	7.20 ns	8.58 ns	10.0 ns	1.67 ns	2.37 ns	3.02 ns
5 (B_1)	28.3	35.8 ns	43.0 ns	60.2 ns	4.56	7.11 ns	8.42 ns	9.71 ns	1.67 ns	2.39 ns	2.93 ns
10 (B_2)	27.8	35.5 ns	42.7 ns	58.2 ns	4.71	6.96 ns	8.47 ns	9.71 ns	1.68 ns	2.33 ns	2.95 ns
15 (B_3)	27.7	35.7 ns	41.5 ns	58.7 ns	4.58	7.00 ns	8.36 ns	9.73 ns	1.64 ns	2.30 ns	2.88 ns
N fertiliser (kg ha^{-1})											
30 (N_1)	28.1	35.7 ns	42.3 ns	60.3 ns	4.55	7.02 ns	8.50 ns	10.1 a	1.68 ns	2.38 a	2.96 a
45 (N_2)	27.7	35.6 ns	43.2 ns	60.1 ns	4.67	7.08 ns	8.43 ns	9.77 ab	1.66 ns	2.45 a	3.09 a
60 (N_3)	28.1	35.4 ns	41.7 ns	56.5 ns	4.63	7.10 ns	8.43 ns	9.56 b	1.66 ns	2.21 b	2.79 b
Interactions											
B_0N_1	28.0	35.5 ns	42.2 ns	58.0 ns	4.67	7.07 ns	8.73 ns	10.3 ns	1.71 ns	2.39 ns	3.02 ns
B_0N_2	28.1	35.5 ns	44.1 ns	62.0 ns	4.87	7.27 ns	8.73 ns	10.1 ns	1.68 ns	2.50 ns	3.16 ns
B_0N_3	27.9	34.7 ns	41.3 ns	56.2 ns	4.33	7.27 ns	8.27 ns	9.63 ns	1.63 ns	2.21 ns	2.89 ns
B_1N_1	28.6	36.5 ns	44.3 ns	63.8 ns	4.40	7.00 ns	8.47 ns	10.0 ns	1.69 ns	2.42 ns	2.94 ns
B_1N_2	27.6	35.7 ns	43.0 ns	60.0 ns	4.53	7.13 ns	8.40 ns	9.67 ns	1.66 ns	2.50 ns	3.08 ns
B_1N_3	28.5	35.4 ns	41.7 ns	56.8 ns	4.73	7.20 ns	8.40 ns	9.47 ns	1.67 ns	2.25 ns	2.78 ns
B_2N_1	27.6	35.2 ns	41.9 ns	59.9 ns	4.67	6.93 ns	8.60 ns	9.73 ns	1.68 ns	2.42 ns	3.05 ns
B_2N_2	27.4	35.6 ns	43.2 ns	58.9 ns	4.60	7.00 ns	8.33 ns	9.67 ns	1.70 ns	2.45 ns	3.12 ns
B_2N_3	28.4	35.7 ns	42.8 ns	55.8 ns	4.87	6.93 ns	8.47 ns	9.73 ns	1.65 ns	2.12 ns	2.68 ns
B_3N_1	28.0	35.6 ns	40.9 ns	59.4 ns	4.47	7.07 ns	8.20 ns	10.1 ns	1.65 ns	2.27 ns	2.81 ns
B_3N_2	27.6	35.8 ns	42.3 ns	59.5 ns	4.67	6.93 ns	8.27 ns	9.67 ns	1.59 ns	2.36 ns	3.00 ns
B_3N_3	27.6	35.6 ns	41.2 ns	57.3 ns	4.60	7.00 ns	8.60 ns	9.40 ns	1.68 ns	2.26 ns	2.82 ns
CV (%)	-	2.27	6.12	7.43	-	2.90	4.01	4.14	2.68	5.56	5.58

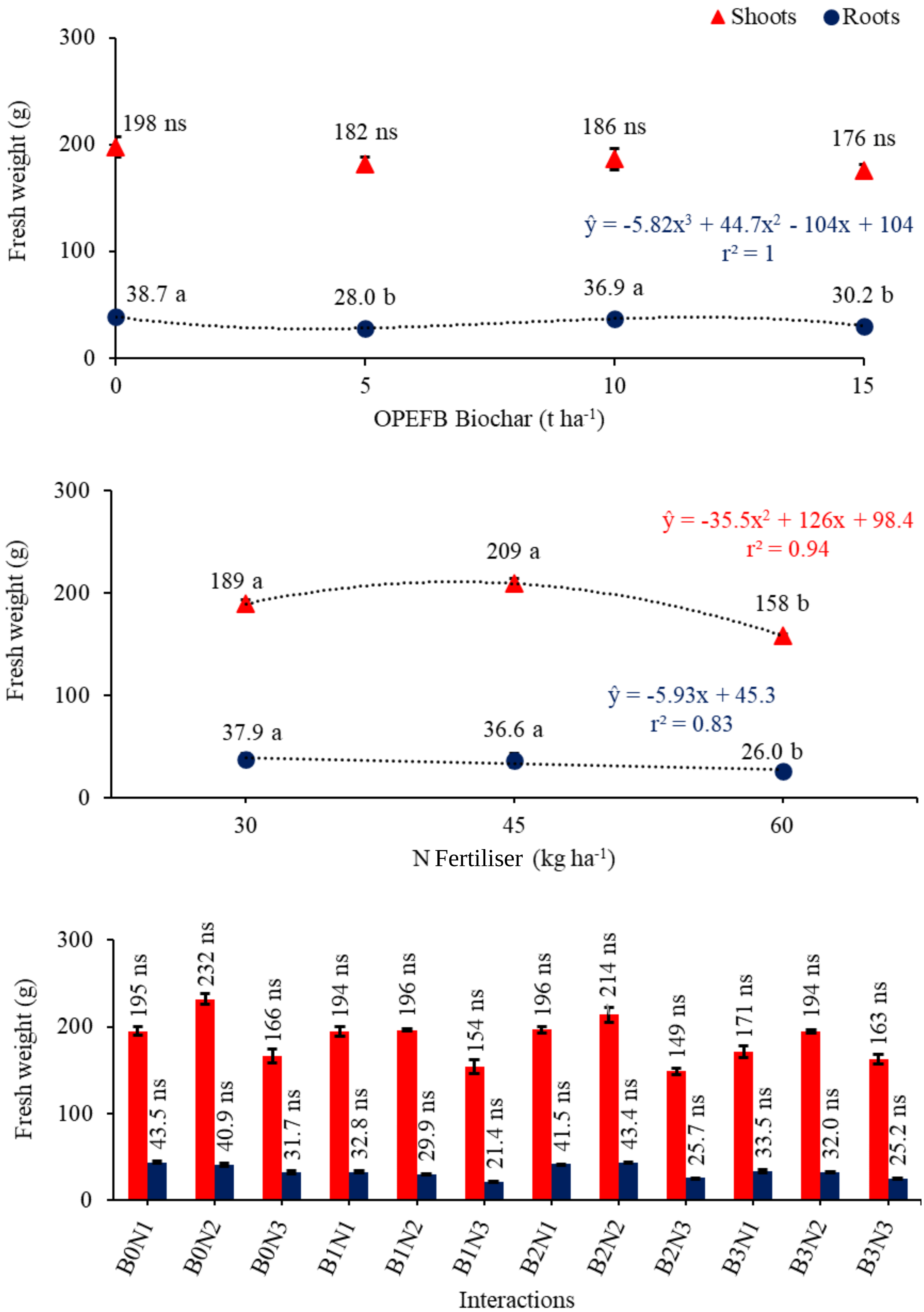

Figure 1. Fresh weights (mass) of the shoots and roots of oil palm seedlings treated with OPEFB biochar (A), nitrogen fertiliser (B) and combinations (interactions) (C). Error bars indicate standard error; ns = not significant.

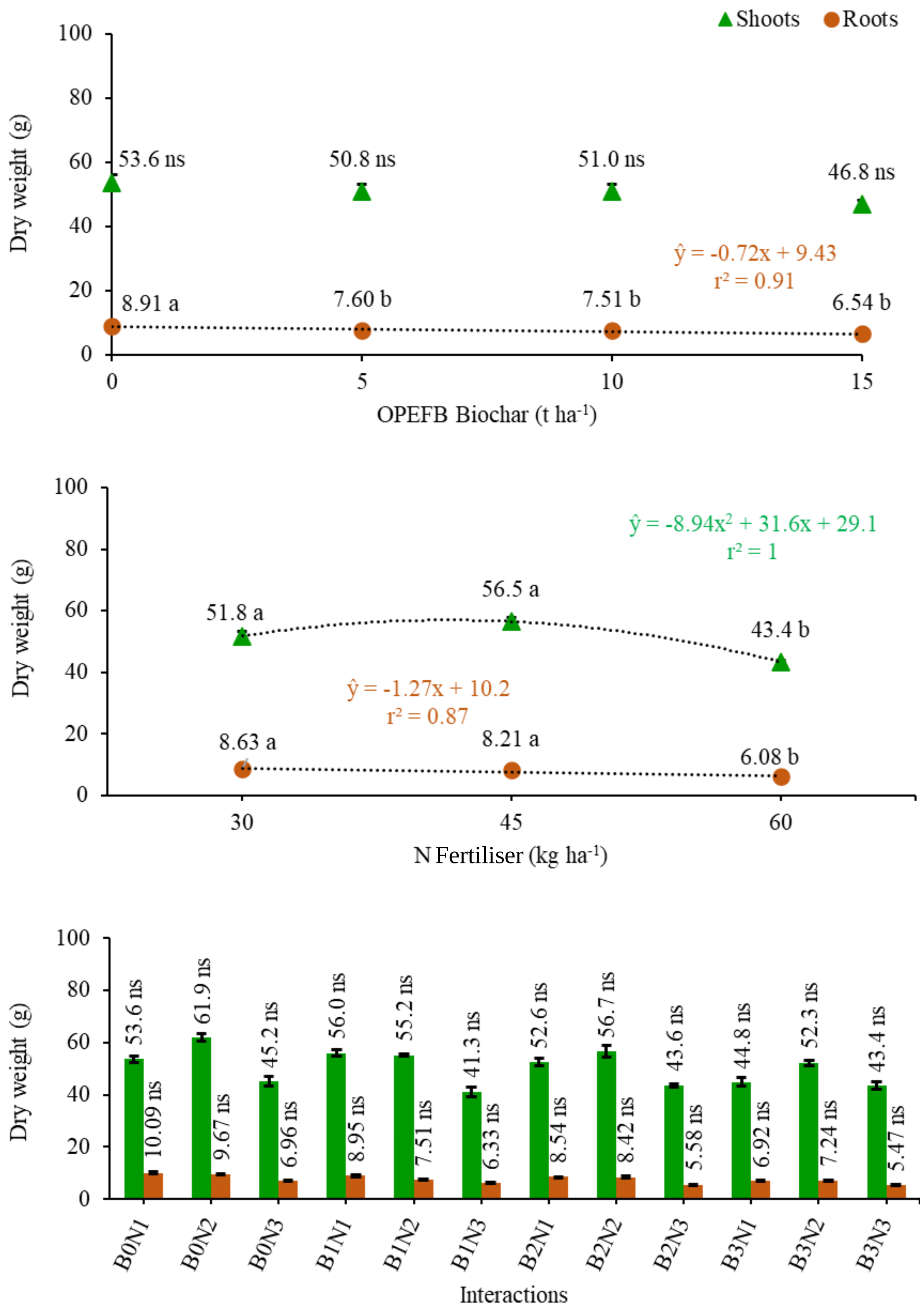

Figure 2. Dry weights (mass) of the shoots and roots of oil palm seedlings treated with OPEFB biochar (A), nitrogen fertiliser (B) and combinations (interactions) (C). Error bars indicate standard error; ns = not significant.

Table 5. Chemical characteristics of the peat soil used for growing oil palm seedlings in the different treatments with OPEFB biochar, nitrogen fertiliser, and interactions. Mean values are shown. Values followed by different letters in the same column are significantly different (Duncan's test at 5 %); CV = coefficient of variation; ns = not significant.

Treatments	Chemical characteristics of the peat soil								
	pH	CEC (cmol kg^{-1})	Organic C (%)	Total N (%)	Available P (mg kg^{-1})	Exchangeable cations (cmol kg^{-1})			
						K^+	Mg^{2+}	Ca^{2+}	Na^+
OPEFB biochar (t ha^{-1})									
0 (B_0)	3.91 c	57.7 ns	33.5 ns	1.27 ns	171 ns	1.20 b	1.46 ns	4.75 a	0.81 ns
5 (B_1)	3.97 bc	56.2 ns	32.7 ns	1.27 ns	161 ns	1.33 b	1.47 ns	4.51 a	0.76 ns
10 (B_2)	4.02 ab	56.1 ns	32.2 ns	1.28 ns	165 ns	1.69 a	1.46 ns	4.42 ab	0.79 ns
15 (B_3)	4.11 a	55.0 ns	32.5 ns	1.28 ns	146 ns	1.78 a	1.42 ns	4.41 b	0.79 ns
N fertiliser (kg ha^{-1})									
30 (N_1)	3.97 b	58.5 ns	31.7 ns	1.24 b	167 ns	1.56 ns	1.58 ns	4.77 a	0.81 ns
45 (N_2)	3.96 b	55.2 ns	33.3 ns	1.29 ab	167 ns	1.49 ns	1.42 ns	4.52 ab	0.75 ns
60 (N_3)	4.08 a	55.0 ns	33.2 ns	1.31 a	147 ns	1.46 ns	1.36 ns	4.27 b	0.81 ns
Interactions									
B_0N_1	3.90 ns	63.7 ns	32.7 ns	1.24 ns	190 ns	1.28 bc	1.71 ns	5.09 ns	0.87 ns
B_0N_2	3.82 ns	52.2 ns	34.1 ns	1.27 ns	184 ns	1.17 c	1.47 ns	4.92 ns	0.77 ns
B_0N_3	4.01 ns	57.1 ns	33.7 ns	1.31 ns	139 ns	1.15 c	1.20 ns	4.22 ns	0.80 ns
B_1N_1	3.93 ns	63.1 ns	31.8 ns	1.24 ns	170 ns	1.32 bc	1.53 ns	4.84 ns	0.75 ns
B_1N_2	3.94 ns	56.0 ns	33.1 ns	1.29 ns	159 ns	1.45 abc	1.48 ns	4.40 ns	0.75 ns
B_1N_3	4.02 ns	49.6 ns	33.1 ns	1.29 ns	153 ns	1.23 c	1.40 ns	4.30 ns	0.78 ns
B_2N_1	3.96 ns	53.2 ns	29.7 ns	1.22 ns	137 ns	1.78 a	1.44 ns	4.41 ns	0.80 ns
B_2N_2	3.94 ns	56.6 ns	33.6 ns	1.27 ns	183 ns	1.51 abc	1.39 ns	4.23 ns	0.67 ns
B_2N_3	4.17 ns	58.5 ns	33.3 ns	1.35 ns	174 ns	1.78 a	1.53 ns	4.61 ns	0.91 ns
B_3N_1	4.07 ns	54.0 ns	32.6 ns	1.25 ns	173 ns	1.85 a	1.66 ns	4.75 ns	0.82 ns
B_3N_2	4.14 ns	56.1 ns	32.3 ns	1.30 ns	142 ns	1.82 a	1.32 ns	4.53 ns	0.80 ns
B_3N_3	4.11 ns	54.8 ns	32.6 ns	1.30 ns	122 ns	1.68 ab	1.29 ns	3.95 ns	0.75 ns
CV (%)	2.15	12.5	8.23	4.33	37.5	14.2	21.5	19.7	12.0

Nutrient contents of seedling tissues

The biochar doses significantly affected P and Cu content in the shoots, as well as P, K, Ca and B content in the roots of the oil palm seedlings. Nitrogen fertilisation significantly influenced N, Mg, Ca and B content in the shoots, as well as N and B content in the roots. The interaction significantly affected N, Mg, Ca and Cu content in the shoots, and N, P, K, B and Cu content in the roots (Tables 6–7).

A biochar dose of 15 t ha^{-1} increased P and Cu content in the shoots by 17.8 and 27.0 %, respectively, compared to the control. A high (30–60 kg ha^{-1}) dosage of N fertiliser caused the N content of shoots to increase by 4.10 % and at the same time reduced the Mg and Ca contents of shoots. An N dosage of 30 kg ha^{-1} resulted in the highest B content in shoots. The B_2N_1 interaction (10 t ha^{-1} biochar with 30 kg ha^{-1} N) significantly increased the highest Mg and Ca contents of shoots by 0.44 and 0.46 %, respectively, compared with other interactions.

Table 6. Nutrient content in the shoots of oil palm seedlings due to the OPEFB biochar, nitrogen fertiliser and combination (interaction) treatments. Mean values are shown. Values followed by different letters in the same column are significantly different (Duncan's test at 5 %); CV = coefficient of variation; ns = not significant.

Treatments	Nutrients content in the shoots						
	N	P	K	Mg	Ca	B	Cu
OPEFB biochar (t ha^{-1})	--------------------------------%----------------------------------					---------mg kg^{-1}--------	
0 (B_0)	3.42 ns	0.45 b	1.53 ns	0.40 ns	0.38 ns	66.4 ns	4.41 b
5 (B_1)	3.75 ns	0.49 ab	1.51 ns	0.41 ns	0.38 ns	61.0 ns	4.59 b
10 (B_2)	3.84 ns	0.49 ab	1.55 ns	0.40 ns	0.40 ns	68.5 ns	4.66 b
15 (B_3)	3.78 ns	0.53 a	1.62 ns	0.40 ns	0.41 ns	66.5 ns	5.60 a
N fertiliser (kg ha^{-1})							
30 (N_1)	3.15 b	0.48 ns	1.59 ns	0.43 a	0.43 a	77.8 a	4.59 ns
45 (N_2)	3.84 a	0.49 ns	1.50 ns	0.41 a	0.39 b	46.2 b	5.03 ns
60 (N_3)	4.10 a	0.51 ns	1.58 ns	0.38 b	0.36 b	72.7 a	4.83 ns
Interactions							
B_0N_1	2.91 e	0.43 ns	1.56 ns	0.42 ab	0.41 a-d	78.2 ns	4.48 b
B_0N_2	3.48 a-e	0.45 ns	1.42 ns	0.40 a-d	0.35 d	50.7 ns	4.18 b
B_0N_3	3.86 a-d	0.48 ns	1.62 ns	0.39 bcd	0.37 cd	70.2 ns	4.57 b
B_1N_1	3.01 de	0.45 ns	1.57 ns	0.42 ab	0.41 a-d	74.9 ns	4.05 b
B_1N_2	3.87 a-d	0.49 ns	1.51 ns	0.40 a-d	0.38 bcd	41.7 ns	4.55 b
B_1N_3	4.36 a	0.53 ns	1.46 ns	0.40 a-d	0.36 cd	66.3 ns	5.17 ab
B_2N_1	3.27 cde	0.50 ns	1.58 ns	0.44 a	0.46 a	75.6 ns	4.60 b
B_2N_2	4.20 ab	0.49 ns	1.46 ns	0.42 ab	0.39 a-d	44.1 ns	4.93 ab
B_2N_3	4.05 abc	0.49 ns	1.60 ns	0.35 d	0.35 d	85.9 ns	4.45 b
B_3N_1	3.43 b-e	0.53 ns	1.64 ns	0.42 ab	0.45 ab	82.5 ns	5.23 ab
B_3N_2	3.80 a-d	0.53 ns	1.59 ns	0.41 abc	0.43 abc	48.4 ns	6.44 a
B_3N_3	4.12 abc	0.52 ns	1.64 ns	0.36 cd	0.37 cd	68.5 ns	5.14 ab
CV (%)	12.5	9.39	7.99	6.86	8.84	34.8	18.2

Likewise, the B1N3 (5 t ha^{-1} biochar with 60 kg ha^{-1} N) and B3N2 (15 t ha^{-1} biochar with 45 kg ha^{-1} N) interactions significantly increased the highest N and Cu contents of shoots by 4.36 % and 6.44 mg kg^{-1}.

Table 7 also shows that the increases of P, K, Ca and B in roots that accompanied increasing dosages of biochar up to 15 t ha^{-1} were 22.6, 18.3, 25.0 and 21.9 %, respectively, compared to the control. Nitrogen fertiliser doses of 45 and 60 kg ha^{-1} resulted in the highest contents of N and B in roots at 2.02 % and 24.8 mg kg^{-1}, respectively. The results also revealed that the interactions B_0N_2 and B_1N_3 had a similar ability to increase the N content in roots by 2.16 %. However, B_3N_1 (15 t ha^{-1} biochar with 30 kg ha^{-1} N) was the interaction that resulted in the highest P, K, and B contents in roots, which were 0.70 %, 3.17 % and 31.7 mg kg^{-1}, respectively. The B_2N_2 interaction (10 t ha^{-1} biochar with 45 kg ha^{-1} N) showed the highest Cu content that we recorded for roots, at 13.4 mg kg^{-1}.

Table 7. Content of nutrients in the roots of oil palm seedlings due to the OPEFB biochar, nitrogen fertiliser and combination (interaction) treatments. Mean values are shown. Values followed by different letters in the same column are significantly different (Duncan's test at 5 %); CV = coefficient of variation; ns = not significant.

Treatments	Content of nutrients in the roots						
	N	P	K	Mg	Ca	B	Cu
OPEFB biochar (t ha^{-1})	----------------------------------	----------------%	----------------------------------			----------mg kg^{-1}---------	
0 (B_0)	1.93 ns	0.53 c	2.57 b	0.20 ns	0.16 b	21.9 b	10.4 ns
5 (B_1)	1.90 ns	0.56 bc	2.52 b	0.21 ns	0.18 ab	20.8 b	11.0 ns
10 (B_2)	1.95 ns	0.63 ab	2.86 a	0.22 ns	0.18 ab	23.6 ab	12.1 ns
15 (B_3)	1.80 ns	0.65 a	3.04 a	0.20 ns	0.20 a	26.7 a	12.0 ns
N fertiliser (kg ha^{-1})							
30 (N_1)	1.66 b	0.60 ns	2.81 ns	0.21 ns	0.19 ns	24.4 a	11.4 ns
45 (N_2)	2.02 a	0.60 ns	2.73 ns	0.21 ns	0.17 ns	20.5 b	11.8 ns
60 (N_3)	2.01 a	0.57 ns	2.71 ns	0.20 ns	0.18 ns	24.8 a	10.8 ns
Interactions							
B_0N_1	1.65 b	0.50 d	2.56 cde	0.19 ns	0.16 ns	21.8 bc	11.6 ab
B_0N_2	2.16 a	0.51 cd	2.48 cde	0.21 ns	0.16 ns	18.3 c	9.77 b
B_0N_3	1.98 ab	0.58 a-d	2.68 b-e	0.20 ns	0.16 ns	25.5 b	9.74 b
B_1N_1	1.59 b	0.53 bcd	2.37 e	0.20 ns	0.19 ns	20.8 bc	10.4 ab
B_1N_2	1.96 ab	0.65 ab	2.81 a-d	0.21 ns	0.17 ns	21.3 bc	12.0 ab
B_1N_3	2.16 a	0.50 d	2.39 de	0.20 ns	0.18 ns	20.3 bc	10.5 ab
B_2N_1	1.83 ab	0.68 a	3.15 ab	0.21 ns	0.18 ns	23.1 bc	10.4 ab
B_2N_2	2.11 a	0.64 abc	2.70 b-e	0.23 ns	0.19 ns	20.5 bc	13.4 a
B_2N_3	1.92 ab	0.56 a-d	2.74 a-e	0.20 ns	0.18 ns	27.1 ab	12.4 ab
B_3N_1	1.58 b	0.70 a	3.17 a	0.22 ns	0.21 ns	31.7 a	13.1 a
B_3N_2	1.84 ab	0.60 a-d	2.92 abc	0.20 ns	0.18 ns	22.0 bc	12.0 ab
B_3N_3	1.99 ab	0.65 ab	3.04 ab	0.19 ns	0.19 ns	26.4 ab	10.7 ab
CV (%)	12.5	11.4	8.56	10.2	15.2	15.4	14.7

Uptake of nutrients by seedling tissues

N fertilisation significantly increased the uptake of all nutrients by both shoots and roots, while the application of biochar had less effect on nutrient uptake in both the shoots and the roots. Biochar significantly affected the uptake of N, Mg and B by roots but had insignificant effects on the uptake of P, K, Ca and Cu by roots or on the uptake of N, P, K, Mg, Ca, B and Cu by shoots. The interactions had insignificant effects on the uptake of all nutrients (Tables 8–9). It can also be seen that the treatments without biochar (B_0) showed the highest nutrient uptake in roots, especially N (0.17 g plant^{-1}), Mg (1.78×10^{-2} g plant^{-1}), and B (0.19×10^{-3} g plant^{-1}) compared to other doses. Nitrogen fertilisation at doses ranging from 30 to 45 kg ha^{-1} contributed to increased nutrient uptake in both shoots and roots. In the shoots, a dose of 45 kg ha^{-1} increased the uptake of N, P, K, Mg, Ca and Cu by 2.14, 0.28, 0.85, 0.23, 0.22 and 0.28×10^{-3} g plant^{-1}, respectively; while a dose of 30 kg ha^{-1} resulted in the highest B uptake (3.89×10^{-3} g plant^{-1}). The results for roots were slightly different in that the highest uptakes of N and Mg (0.17 and 1.76×10^{-2} g plant^{-1}) were found at a fertiliser dose of 45 kg ha^{-1}. However, the highest uptakes of P, K, Ca, B and Cu (0.05, 0.24, 1.56×10^{-2}, 0.20×10^{-3} and 0.10×10^{-3} g plant^{-1}, respectively) occurred at a dose of 30 kg ha^{-1}.

Table 8. Uptake of nutrients by the shoots of oil palm seedlings due to the OPEFB biochar, nitrogen fertiliser and combination (interaction) treatments. Mean values are shown. Values followed by different letters in the same column are significantly different (Duncan's test at 5 %); CV = coefficient of variation; ns = not significant.

Treatments	Uptake of nutrients by shoots (g plant^{-1})						
	N	P	K	Mg	Ca	B	Cu
OPEFB biochar (t ha^{-1})							
0 (B_0)	1.81 ns	0.24 ns	0.82 ns	0.22 ns	0.20 ns	3.38×10^{-3} ns	0.23×10^{-3} ns
5 (B_1)	1.85 ns	0.24 ns	0.77 ns	0.21 ns	0.19 ns	3.01×10^{-3} ns	0.23×10^{-3} ns
10 (B_2)	1.92 ns	0.25 ns	0.79 ns	0.21 ns	0.21 ns	3.36×10^{-3} ns	0.24×10^{-3} ns
15 (B_3)	1.76 ns	0.25 ns	0.76 ns	0.19 ns	0.19 ns	2.94×10^{-3} ns	0.26×10^{-3} ns
N fertiliser (kg ha^{-1})							
30 (N_1)	1.60 b	0.24 ab	0.82 a	0.22 a	0.21 a	3.89×10^{-3} a	0.23×10^{-3} b
45 (N_2)	2.14 a	0.28 a	0.85 a	0.23 a	0.22 a	2.59×10^{-3} b	0.28×10^{-3} a
60 (N_3)	1.76 b	0.22 b	0.68 b	0.16 b	0.16 b	3.04×10^{-3} b	0.21×10^{-3} b
Interactions							
B_0N_1	1.55 ns	0.23 ns	0.84 ns	0.23 ns	0.22 ns	4.15×10^{-3} ns	0.24×10^{-3} ns
B_0N_2	2.15 ns	0.28 ns	0.88 ns	0.25 ns	0.22 ns	3.03×10^{-3} ns	0.26×10^{-3} ns
B_0N_3	1.72 ns	0.21 ns	0.72 ns	0.18 ns	0.17 ns	2.97×10^{-3} ns	0.21×10^{-3} ns
B_1N_1	1.66 ns	0.25 ns	0.88 ns	0.23 ns	0.23 ns	4.14×10^{-3} ns	0.22×10^{-3} ns
B_1N_2	2.13 ns	0.27 ns	0.84 ns	0.22 ns	0.21 ns	2.32×10^{-3} ns	0.25×10^{-3} ns
B_1N_3	1.77 ns	0.21 ns	0.60 ns	0.16 ns	0.15 ns	2.57×10^{-3} ns	0.20×10^{-3} ns
B_2N_1	1.70 ns	0.26 ns	0.82 ns	0.23 ns	0.24 ns	3.82×10^{-3} ns	0.24×10^{-3} ns
B_2N_2	2.30 ns	0.28 ns	0.84 ns	0.24 ns	0.23 ns	2.50×10^{-3} ns	0.28×10^{-3} ns
B_2N_3	1.76 ns	0.21 ns	0.70 ns	0.15 ns	0.15 ns	3.77×10^{-3} ns	0.19×10^{-3} ns
B_3N_1	1.51 ns	0.23 ns	0.73 ns	0.19 ns	0.20 ns	3.46×10^{-3} ns	0.23×10^{-3} ns
B_3N_2	1.98 ns	0.28 ns	0.83 ns	0.22 ns	0.22 ns	2.53×10^{-3} ns	0.33×10^{-3} ns
B_3N_3	1.78 ns	0.22 ns	0.71 ns	0.15 ns	0.16 ns	2.84×10^{-3} ns	0.23×10^{-3} ns
CV (%)	13.4	18.2	19.4	21.8	22.5	23.4	18.6

Correlation analysis

The results of the correlation analysis for the soil chemical characteristics pH, CEC, organic C, total N, available P and exchangeable cations (K, Mg, Ca and Na) against nutrient content and uptake by shoots and roots are presented in Table 10. In the shoot tissue, soil pH was significantly correlated to the N content (0.46), P content (0.45) and Cu content (0.49); exchangeable-K to the P content (0.46), Ca content (0.42) and Cu content (0.44); total N to the N content (0.52); and exchangeable-Na to the B content (0.33). In the root tissue, soil pH was significantly correlated to the K content (0.45), Ca content (0.34) and B content (0.54); and exchangeable-K to the P content (0.46), K content (0.49), Ca content (0.40) and B content (0.47). The other results showed that several chemical characteristics of the peat soil were negatively correlated and had insignificant effects on nutrient uptake by the shoots and roots of oil palm seedlings.

Table 9. Uptake of nutrients by the roots of oil palm seedlings due to the OPEFB biochar, nitrogen fertiliser and combination (interaction) treatments. Mean values are shown. Values followed by different letters in the same column are significantly different (Duncan's test at 5 %); CV = coefficient of variation; ns = not significant.

Treatments	Uptake of nutrients by roots (g plant^{-1})						
	N	P	K	Mg	Ca	B	Cu
OPEFB biochar (t ha^{-1})							
0 (B_0)	0.17 a	0.05 ns	0.23 ns	1.78×10^{-2} a	1.44×10^{-2} ns	0.19×10^{-3} a	0.09×10^{-3} ns
5 (B_1)	0.14 bc	0.04 ns	0.19 ns	1.56×10^{-2} ab	1.34×10^{-2} ns	0.16×10^{-3} b	0.08×10^{-3} ns
10 (B_2)	0.15 ab	0.05 ns	0.22 ns	1.63×10^{-2} ab	1.37×10^{-2} ns	0.17×10^{-3} ab	0.09×10^{-3} ns
15 (B_3)	0.12 c	0.04 ns	0.20 ns	1.34×10^{-2} b	1.26×10^{-2} ns	0.17×10^{-3} ab	0.08×10^{-3} ns
N fertiliser (kg ha^{-1})							
30 (N_1)	0.14 b	0.05 a	0.24 a	1.75×10^{-2} a	1.56×10^{-2} a	0.20×10^{-3} a	0.10×10^{-3} a
45 (N_2)	0.17 a	0.05 a	0.22 a	1.76×10^{-2} a	1.42×10^{-2} a	0.17×10^{-3} b	0.10×10^{-3} a
60 (N_3)	0.12 b	0.03 b	0.16 b	1.22×10^{-2} b	1.08×10^{-2} b	0.15×10^{-3} b	0.07×10^{-3} b
Interactions							
B_0N_1	0.17 ns	0.05 ns	0.26 ns	1.94×10^{-2} ns	1.65×10^{-2} ns	0.22×10^{-3} ns	0.12×10^{-3} ns
B_0N_2	0.21 ns	0.05 ns	0.24 ns	1.99×10^{-2} ns	1.55×10^{-2} ns	0.18×10^{-3} ns	0.10×10^{-3} ns
B_0N_3	0.14 ns	0.04 ns	0.19 ns	1.41×10^{-2} ns	1.11×10^{-2} ns	0.17×10^{-3} ns	0.07×10^{-3} ns
B_1N_1	0.14 ns	0.05 ns	0.21 ns	1.78×10^{-2} ns	1.64×10^{-2} ns	0.18×10^{-3} ns	0.09×10^{-3} ns
B_1N_2	0.15 ns	0.05 ns	0.21 ns	1.60×10^{-2} ns	1.25×10^{-2} ns	0.16×10^{-3} ns	0.09×10^{-3} ns
B_1N_3	0.14 ns	0.03 ns	0.15 ns	1.29×10^{-2} ns	1.14×10^{-2} ns	0.13×10^{-3} ns	0.07×10^{-3} ns
B_2N_1	0.16 ns	0.06 ns	0.27 ns	1.81×10^{-2} ns	1.55×10^{-2} ns	0.20×10^{-3} ns	0.09×10^{-3} ns
B_2N_2	0.18 ns	0.05 ns	0.23 ns	1.98×10^{-2} ns	1.55×10^{-2} ns	0.17×10^{-3} ns	0.11×10^{-3} ns
B_2N_3	0.11 ns	0.03 ns	0.15 ns	1.10×10^{-2} ns	1.01×10^{-2} ns	0.15×10^{-3} ns	0.07×10^{-3} ns
B_3N_1	0.11 ns	0.05 ns	0.22 ns	1.49×10^{-2} ns	1.41×10^{-2} ns	0.21×10^{-3} ns	0.09×10^{-3} ns
B_3N_2	0.13 ns	0.04 ns	0.21 ns	1.46×10^{-2} ns	1.32×10^{-2} ns	0.16×10^{-3} ns	0.09×10^{-3} ns
B_3N_3	0.11 ns	0.04 ns	0.17 ns	1.06×10^{-2} ns	1.04×10^{-2} ns	0.14×10^{-3} ns	0.06×10^{-3} ns
CV (%)	22.0	19.0	15.1	19.0	12.8	14.8	26.8

Table 10. Results of the correlation analysis for the relationships between soil chemical characteristics and the content and uptake of nutrients of oil palm shoots and roots due to the treatments with OPEFB biochar, nitrogen fertiliser, and their interactions. Asterisks indicate correlations that are significant at the 1 % (**) and 5 % (*) levels (2-tailed). N = 36 samples.

	Chemical characteristics of the peat soil	N	P	K	Mg	Ca	B	Cu
Nutrient content in shoots	pH	0.46**	0.45**	0.07	-0.22	0.06	0.10	0.49**
	CEC	-0.39*	-0.31	-0.02	0.04	0.05	-0.12	-0.17
	Organic C	0.03	-0.08	-0.10	-0.17	-0.14	-0.32	-0.11
	Total N	0.52**	0.18	-0.03	-0.27	-0.37*	-0.02	0.24
	Available P	-0.03	0.12	-0.35*	0.13	0.08	-0.02	0.05
	Exch-K	0.05	0.46**	0.25	0.01	0.42*	0.24	0.44**
	Exch-Mg	-0.12	0.07	-0.30	0.10	0.15	0.05	0.14
	Exch-Ca	-0.27	-0.05	-0.32	0.11	0.10	-0.13	-0.03
	Exch-Na	-0.09	0.17	0.00	-0.18	0.04	0.33*	-0.07
Nutrient content in roots	pH	-0.05	0.32	0.45**	0.14	0.34*	0.54**	0.01
	CEC	-0.12	-0.01	-0.12	-0.13	-0.06	-0.17	0.14
	Organic C	0.00	-0.07	-0.20	-0.05	-0.12	-0.19	0.01
	Total N	0.30	-0.13	-0.04	-0.17	0.01	0.22	0.07
	Available P	0.00	-0.21	-0.15	0.23	0.14	0.03	0.10
	Exch-K	0.01	0.46**	0.49**	0.07	0.40*	0.47**	0.27
	Exch-Mg	-0.07	0.01	0.02	0.18	0.12	0.13	0.06
	Exch-Ca	-0.09	-0.16	-0.11	0.10	-0.03	-0.11	0.14
	Exch-Na	-0.25	-0.21	-0.04	-0.07	0.16	0.28	-0.07
Nutrient uptake by shoots	pH	-0.26	-0.40*	-0.57**	-0.59**	-0.46**	-0.28	-0.07
	CEC	-0.00	0.18	0.29	0.28	0.28	0.12	0.14
	Organic C	0.18	0.13	0.13	0.09	0.09	-0.29	0.03
	Total N	0.13	-0.24	-0.34*	-0.35*	-0.44**	-0.26	-0.06
	Available P	0.02	0.12	-0.07	0.09	0.06	-0.03	0.08
	Exch-K	-0.22	-0.01	-0.16	-0.22	-0.02	0.11	0.20
	Exch-Mg	-0.20	-0.05	-0.18	-0.03	-0.02	0.00	0.05
	Exch-Ca	-0.05	0.17	0.06	0.19	0.17	-0.03	0.12
	Exch-Na	-0.45**	-0.25	-0.29	-0.32	-0.24	0.20	-0.33*
Nutrient uptake by roots	pH	-0.70**	-0.45**	-0.48**	-0.60**	-0.56**	-0.34*	-0.55**
	CEC	0.12	0.17	0.14	0.13	0.22	0.10	0.29
	Organic C	0.04	-0.02	-0.06	0.01	-0.06	-0.18	0.04
	Total N	-0.22	-0.48**	-0.46**	-0.46**	-0.53**	-0.33*	-0.29
	Available P	0.04	-0.11	-0.08	0.07	0.04	0.02	0.03
	Exch-K	-0.35*	-0.07	-0.15	-0.34*	-0.18	-0.02	-0.18
	Exch-Mg	-0.06	-0.04	-0.04	-0.00	-0.03	0.07	-0.05
	Exch-Ca	0.10	0.01	0.07	0.11	0.08	0.06	0.13
	Exch-Na	-0.34*	-0.35*	-0.24	-0.29	-0.18	-0.03	-0.25

DISCUSSION

Biochar effect

The use of biochar in this study caused changes in the nutrients found in the peat soil. When the biochar dose was raised to 15 t ha^{-1} there were losses of P and K, but leaching of N and Mg was reduced. The application of 15 t ha^{-1} biochar also increased soil pH and exchangeable-K, but reduced exchangeable-Ca. This was due to the presence of 37.5 % organic C in the biochar (Table 1), which raised the pH (Table 4) and thereby reduced nutrient losses through increased adsorption of ions onto its surface. This is supported by Maftu'ah & Nursyamsi (2019) who also found that biochar could change characteristics of peat soil such as pH, available P, exchangeable-K and nutrient uptake. Karimi *et al*. (2020) reported that biochar significantly reduced nutrient leaching from the soil by increasing its nutrient retention, organic C content and water holding capacity. According to Chathurika *et al.* (2016), there was a significant increase in soil pH at 70 days after application of biochar.

Increasing the dose of biochar to 15 t ha^{-1} also affected the nutrient content of the oil palm seedling tissues. There were increases of P and Cu in the shoots, and of P, K, Ca and B in the roots. However, the biochar had an insignificant effect on the nutrient uptake by shoots and an even smaller effect on the nutrient uptake by roots. The highest uptake of N, Mg and B was observed in untreated roots because increasing the biochar doses up to 15 t ha^{-1} significantly increased soil pH and exchangeable-K (Table 4). Moreover, soil pH and exchangeable-K were significantly correlated with increases in the content of several nutrients in the shoots and roots (Table 10). This is supported by the finding of Karimi *et al.* (2020) that biochar at doses up to 15 t ha^{-1} can improve soil physical and chemical characteristics such as CEC and surface oxidation, which in turn improves the availability of plant nutrients. Adekiya *et al.* (2020) found that biochar application at a dose of 30 t ha^{-1} could improve soil physical properties such as bulk density, porosity, moisture, aggregate structure and infiltration rate, as well as chemical properties (pH, N, P, K, Ca, Mg, CEC). Akhtar *et al.* (2015) added that the use of biochar could increase the exchangeable cations K, Ca and Mg but reduced exchangeable-Na. According to Mousa (2017), biochar application significantly increased CEC, organic C and total N, and thus made P, K, Fe, Mn, Zn and Cu more available to plants. Syuhada *et al.* (2016) added that increasing the dose of biochar up to 15 t ha^{-1} was accompanied by increases in pH, CEC, total C, exchangeable cations (K, Mg, Ca) and K-content in plant tissue.

Our results showed that the highest fresh (38.7 g) and dry (8.91 g) mass of roots was attained in the treatment without biochar, meaning that biochar offers no potential for increasing the growth of oil palm seedlings. It also significantly affected nutrient uptake by roots, the treatment without biochar having the highest uptake of N (0.17 g $plant^{-1}$), Mg (1.78×10^{-2} g $plant^{-1}$) and B (0.19×10^{-3} g $plant^{-1}$) compared to other treatments (Table 9). This was due to the limiting factors soil pH and total N availability, which were negatively correlated with nutrient uptake by this tissue (Table 10). A negative correlation here can be interpreted as a change in total N availability due to NH_3 volatilisation caused by increased soil pH in response to biochar treatment. This is supported by the finding of Huang *et al.* (2017, 2018) that N loss due to NH_3 volatilisation increased with the application of biochar, and the increase was positively correlated with an increase in soil pH. In a similar study by Syuhada *et al.* (2016), the uptake of N, Ca, and Mg by plant tissue decreased as biochar dose increased up to 15 t ha^{-1}.

Effects of nitrogen fertilisation

The application of nitrogen fertiliser at a dosage of 30–60 kg ha^{-1} could affect nutrient dynamics in peat soil. As the nitrogen dose increased up to 60 kg ha^{-1}, the N and Mg losses due to leaching also increased, thereby reducing exchangeable-Ca in the soil as well as the Mg and Ca contents of the oil palm shoots. However, there were significant increases in pH and total N in the soil, N-content in the shoots, and B-content in the roots. A nitrogen dose of 30 kg ha^{-1} gave the highest B-content in shoots, and a dosage of 45 kg ha^{-1} resulted in the highest N-content in roots. This was due to a decrease in activity of the urease inhibitor enzyme caused by an increase in soil pH, which changed the form of N through nitrification and thus increased N loss by leaching. This is supported by the finding of Singh & Nye (1984) that urease activity decreased as soil pH increased. Furthermore, Cai & Akiyama (2017) found that the use of urease inhibitors can retain N in the ammonium form rather than nitrate due to nitrification and this is more effective in reducing nitrate leaching. According to Zhang *et al.* (2017), the amount of leached N increases with the quantity of nitrogen fertiliser applied. Wang *et al.* (2019) found that reducing the N dose by 20 % and 50 % could reduce the N-total loss by 18.3 % and 43.0 %, respectively. Nitrogen fertilisation can result in increased nutrients, as demonstrated by Xia *et al.* (2022) who found that N doses of 50–200 mg kg^{-1} significantly increased NO_3^-, NH_4^+ and DOC to 8.28, 40.5, 7.78 mg kg^{-1}, respectively, and soil pH to 4.91.

A nitrogen dosage of 30–45 kg ha^{-1} had a greater effect on nutrient uptake by oil palm seedling tissues than a dosage of 60 kg ha^{-1}. This was indicated by the ability of the 30 kg ha^{-1} dose to significantly increase the uptake of B by the shoots, as well as the uptake of P, K, Ca, B and Cu by the roots. Furthermore, a dose of 45 kg ha^{-1} significantly increased the uptake of N, P, K, Mg, Ca and Cu by shoots as well as the uptake of N and Mg by roots. N fertiliser doses of 30–45 kg ha^{-1} significantly increased the growth of oil palm seedlings, due to the significant effects of N fertilisation on soil pH and exchangeable-Ca (Table 4). There was also an increase in organic C at an N dosage of 30–45 kg ha^{-1}, but the effect was not significant.

CEC and exchangeable-Ca were positively correlated with P, K, Mg, Ca and Cu uptake in the shoots, as well with the uptake of all nutrients by the roots (Table 10). This result is supported by the finding of Czarnecki & Düring (2015) that there was an increment in organic C and CEC at a dose of 320 kg ha^{-1} compared to the control. According to Zhou *et al.* (2012), soil pH had a highly significant and positive correlation (0.81^{**}) with exchangeable-Ca in the soil. Messiga *et al.* (2013) revealed that the levels of total N and organic C increased along with nitrogen concentration, and significantly affected exchangeable-K. Based on the study by McCauley *et al.* (2009), soil organic matter facilitates nutrient availability by increasing soil CEC.

As metrics of seedling growth, the number of leaves, stem diameter, shoot and root biomass of the oil palm seedlings all increased at nitrogen fertilisation doses of 30–45 kg ha^{-1}. This was caused by exchangeable-Ca in the soil which was positively correlated with nutrient uptake. Similarly, Zhou *et al.* (2012) found that exchangeable-Ca was significantly correlated with increasing root volume, root and shoot dry weight. Mohidin *et al.* (2015) reported increased leaf number (by 6.98 %) and area (by 48.9 %), shoot/root quotient (by 35.7 %) and SPAD total chlorophyll (by 6.14 %) due to nitrogen fertilisation at a dose of 100 mg L^{-1} compared to a dose of 50 mg L^{-1}. According to McLaughlin & Wimmer (1999), Ca^{2+} has an important physiological role in plants, such as cell signalling, structure, and cell division.

Interaction of biochar and N fertilisation effects

The interaction of biochar with N fertilisation significantly affected nutrient leaching, exchangeable cations in the soil, and nutrient content in the shoots and roots of oil palm seedlings. The lowest leaching of P and K was found in the interaction treatment B0N2, while the lowest leaching of N was found in B2N1. However, B2N1 (10 t ha^{-1} biochar with 30 kg ha^{-1} N) significantly increased the Mg and Ca content in shoots by 0.44 % and 0.46 %. The highest values for exchangeable-K in soil and P, K and B content in roots were found in treatment B3N1 (15 t ha^{-1} biochar with 30 kg ha^{-1} N). Treatment B1N3 (5 t ha^{-1} biochar with 60 kg ha^{-1} N) also increased N-content in the shoots and roots of the oil palm seedlings. The interaction of 10–15 t ha^{-1} biochar and 45 kg ha^{-1} N (B2N2 and B3N2) significantly increased Cu-content in the roots and shoots by 13.4 and 6.44 mg kg^{-1}, respectively. However, the combination treatments insignificantly affected plant height, number of leaves, stem diameter, fresh and dry weight of the seedlings, and nutrient uptake.

Overall, even when applied in combination, a biochar dose of 10–15 t ha^{-1} and nitrogen fertilisation at 30–45 kg ha^{-1} had different roles in reducing N loss due to leaching as well as in increasing exchangeable-K in soil, and nutrient contents (N, P, K, Mg, Ca, B, Cu) in the shoots and roots of the seedlings. Biochar can improve soil physical and chemical properties such as porosity, soil water holding capacity, organic matter, bulk density, pH, CEC and nutrient availability, and reduce nutrient loss (Alkharabsheh *et al.* 2021). Li *et al.* (2019) found that the combination of biochar and nitrogen fertilisation significantly increased soil aggregates. According to Tian *et al.* (2020), the addition of 10 t ha^{-1} biochar and 108–180 kg ha^{-1} N significantly increased soil aggregate stability. The soil aggregates influence soil fertility by reducing soil erosion, permeability, infiltration and nutrient cycling (Ramos *et al.* 2019, Shen *et al.* 2019). Similarly, Xia *et al.* (2022) found that the combination of biochar and nitrogen fertilisation significantly reduced N loss and increased root growth and N uptake through the improvement of pH, organic matter, electrical conductivity and C/N quotient.

Based on our results, there are only slight effects from applications of biochar or N fertiliser on the growth of oil palm seedlings and the improvement of peat soils in terms of factors such as the leaching, content and uptake of nutrients. However, a combination of 10–15 t ha^{-1} biochar and 30–45 kg ha^{-1} N can be recommended to improve the chemical characteristics of peat soils and the growth of oil palm seedlings. With a dose of 15 t ha^{-1} biochar we found increases of pH and exchangeable-K in the peat soil, and of P, Cu, K, Ca and B content in the roots and shoots of oil palm seedlings. Nitrogen fertilisation at a dosage of 30–60 kg ha^{-1} increased pH and total N in the soil, along with N and B content in the tissues of oil palm seedlings. However, it was less effective in reducing losses of N and Mg from the soil. A dosage of 30–45 kg ha^{-1} increased the uptake of N, P, K, Mg, Ca, B and Cu by shoots and roots, and additionally enhanced the growth of oil palm seedlings. The interaction of 10–15 t ha^{-1} biochar with 30–45 kg ha^{-1} nitrogen fertiliser reduced leaching of N as well as the exchangeable-K and nutrient contents in shoots and roots. However, it had insignificant effects on nutrient uptake and growth in oil palm seedlings.

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AUTHOR CONTRIBUTIONS

AA and AR: conceptualisation and methodology; AA: biochar collecting and preparation of oil palm seedlings; HH: measurement of oil palm seedlings; AA, HH and FA: measurement of leached nutrients and nutrient uptake; AA, AR and FA: validation and data analysis. All authors: writing, revision and editing of this manuscript.

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