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Agro-Industrial Waste Biochar Abated Nitrogen Leaching from Tropical Sandy Soils and Boosted Dry Matter Accumulation in Maize

Michael Egyir [1,2], Innocent Yao Dotse Lawson [1,*], Daniel Etsey Dodor [1] and Deogratius Luyima [2,*]

[1] Department of Soil Science, College of Basic and Applied Sciences, University of Ghana, Legon P.O. Box LG 25, Ghana
[2] Department of Agricultural Chemistry, College of Agriculture and Life Sciences, Chungnam National University, Daejeon 34134, Republic of Korea
* Correspondence: idlawson@ug.edu.gh (I.Y.D.L.); deoluyima@gmail.com or deoluyima@o.cnu.ac.kr (D.L.)

Abstract: This study was conducted to assess the effects of amending tropical sandy soils with biochar derived from agro-industrial wastes on the leaching and utilization of nitrogen (N) by maize. The experiment was conducted in pots in a greenhouse with two sandy soil types and two different biochars. The biochars used in this experiment were preselected in a preliminary column experiment that assessed the N retention capacities of the different biochars and those that exhibited the best retention capacities chosen for experimentation. The biochars evaluated included saw dust, rice husk and corncob pyrolyzed at 500 °C and the results from the column leaching experiment showed that sawdust biochar had superior retention capacities for both NO_3^- and NH_4^+, followed by rice husk biochar. The pot experiment utilized sawdust and rice husk biochars applied at rates of 0, 20 and 40 t/ha to the soil treated with different N sources including cow dung and ammonium sulfate and growing maize on the amendments for two seasons with each season lasting for five weeks. The soils were leached on the 14th and 28th days after planting to determine the amount of leachable N. Biochar amendments reduced the leaching of NO_3^-N and NH_4^+N with no significant differences observed between biochar types, but between soil types. The abatement of leaching by biochar amendments consequently enhanced N uptake by maize and dry matter production and thus, agro-industrial waste biochar amendment is recommended for reducing leaching in tropical sandy soils.

Keywords: biochar; dry matter accumulation; leaching of nitrogen; nitrogen uptake; tropical sandy soils

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1. Introduction

Despite the fact that nitrogen (N) is by far the largest component in the atmospheric air, it is the major limiting factor for the productivity of agricultural crops and is hence an indispensable input in crop production [1,2]. However, N applied to the soil is highly prone to leaching and volatilization, with nitrous oxide (N_2O) and ammonia (NH_3) being the gaseous emissions of great environmental concern, while NO_3^- ions are the main form of N leached [3]. Indeed, McAllister et al. [4] indicated that about 50% to 70% of N applied to the soil is lost through a combination of pathways, including leaching, erosion, denitrification, incorporation into microbial biomass and volatilization. N lost from the soil causes or exacerbates environmental pollution through triggering/heightening eutrophication, global warming, loss of biodiversity and depletion of ozone in the stratosphere [1,2]. The vast majority of West Africa is rich in low activity clay soils [5], on which leaching of nutrients, including N, is severe. The low nutrient retention capacities of these soils coupled with high infiltration rates, low organic matter (OM) content and high water conductivity culminate into low nutrient uptake by plants, fertilizer use efficiency and yield [6,7].

The use of biochar to check the leaching of applied N fertilizers has attracted a lot of interest in recent years and several studies have been conducted. An early study by Yao et al. [8] showed that only a few of the thirteen biochars used in their experiment could reduce leaching of nitrates in a batch experiment, but nine of the thirteen biochars attenuated ammonium leaching. Another study by Major et al. [9] found that biochar applied to a Columbian savanna oxisol at a rate of 20 tons per hectare increased nitrate leaching up to a soil depth of 0.6 m but the leaching was reduced by 8% at a 1.2 m soil depth. Sika and Hardie [10] showed that the pine wood sawmill waste biochar applied to a South African sandy soil at rates of 0.5, 2.5 and 10% reduced the leaching of ammonium nitrogen by 12, 50 and 86%, respectively, while the reduction rates of nitrate leaching stood at 26, 42 and 96%, respectively. Later on, Xu et al. [11] found that the application of maize straw biochar at 2, 4 and 8% to fluvo-aquic soil layered in columns reduced the leaching of urea by 18.8, 19.5 and 20.2%, respectively. A study by Sun et al. [12] showed that wheat straw biochar applied to saline coastal soils at rates of 0.5, 1.0, 2.0 and 4.0% reduced the leaching of ammonium by 11.64–27.68% and nitrate by 13.19–36.26%, with the leaching reduction power of the biochar increasing with increasing application rates.

However, its worth noting that the biochar-induced reductions in N leaching may not be agronomically beneficial, as has been demonstrated by numerous studies. For example, Sika and Hardie [10] noted that the leached biochar-amended soils contained infinitesimal amounts of exchangeable ammonium (0–7.3 $\mathrm{mg\,kg^{-1}}$) and nitrate (5.8–8.0 $\mathrm{mg\,kg^{-1}}$), which could negatively affect crop yield even though they did not grow any crops in their experiment. Indeed, in a four-year field experiment, Haider et al. [13] found that although biochar reduced nitrate leaching from the temperate soil, there was no positive effect on the yield of the grown maize. Contrary to this observation, Liu et al. [14] indicated that the concomitant reduction in N leaching caused by biochar applied to the sandy soil boosted N uptake and the dry weight of ryegrass in the first season of the experiment, although this positive effect was ephemeral and could not be reproduced in the second season. It is important to note that both experiments that involved the growing of crops were conducted in temperate soils and, to the best of our knowledge, there are no data that examined the effects of biochar on the leaching of N and subsequent effects on the uptake and yield of the crops grown in a tropical soil. Therefore, this experiment was conducted to assess the effects of biochar on N leaching from two different tropical sandy soils and to discern if the biochar's influence on N leaching affects N uptake and the growth of crops using maize as a test crop.

2. Materials and Methods

2.1. Descriptions of the Soils and Biochar Used in the Experient

The soils used belonged to the Keta (K) and Nyankpala (Ny) series whose samples were taken from Anloga in the Volta and Nyanpkala in Tolon-Kumbumgu district of the northern regions of Ghana, respectively. The Volta region is situated within the coastal savannah zone of Ghana with a mean temperature of 28 °C and an average annual rainfall of about 900 mm which is evenly spread over the year. On the other hand, Nyanpkala is situated within the guinea savannah zone of Ghana with a unimodal rainfall pattern of 1000–1300 mm per annum and a mean temperature of 32 °C. K series belongs to an Entisol order and Psamment suborder (*Quartzipsamment*) of the USDA soil taxonomy. Although the K series has little agricultural prospect due its low fertility status, with heavyfertilization the soil has been used for intensive maize and vegetable production over the years (Obeng, 2000). The Ny series soils are classified as Plinthic acrisols according to the FAO soil classification system. Both soil types were sampled at the depth of 0–20 cm, transported to the laboratory, air-dried, sieved through a 2 mm sieve, analyzed and used for the study. Biochar was produced at 500 °C in a kiln from three different feedstock biomasses and these were rice husk, saw dust and corn cob, following the pyrolysis method described by Lehmann et al. [15]. After pyrolysis, the biochar samples obtained were ground and the particles were homogenized by sieving through a 0.5 mm sieve.

2.2. Biochar and Soil Analysis

Biochar's pH measurement with a pH meter followed extraction of biochar with distilled water in ratios of 1:10, respectively. The total phosphorus and cations were extracted by wet ashing with concentrated nitric acid. The orthophosphate was then determined colorimetrically following a method espoused by Murphy and Rilley [16] after neutralization of the digest's pH with NaOH, while the cations were quantified with atomic absorption spectrometery (AAS). The total surface area was determined by following the Brunauer–Emmett–Teller (BET) method. The soil pH was measured both in water and calcium chloride. The mixing ratios adopted in the former method were 1:5, while 1:2.5 (soil: calcium chloride) was adopted for the latter. Particles size distributions were determined by using the Bouyoucos method [17], while the soil bulk densities were determined through strict adherence to the Blake and Hartge [18] method. The total organic carbon was determined by strictly adhering to the Walkley and Black [19] method, whilst the total nitrogen content was analyzed through the Kjeldahl method. The available phosphorus was determined by strictly adhering to the Bray P1 extraction procedure as outlined by Jones [20] and quantifying the orthophosphate colorimetrically at 880 nm by following the Murphy and Rilley [16] method. The basic cations were extracted from the soil samples with 1 M neutral ammonium acetate and analyzed by the AAS. The selected properties of the two soils used in the experiment are shown in Table 1, while those of the biochars are exhibited in Table S1 in the Supplementary File.

Table 1. Properties of the soils used in the experiment.

Parameters Assessed		Soil Type	
		K	Ny
Particle size (%)	Sand	90.04 ± 0.44	68.01 ± 0.65
	Silt	7.01 ± 0.07	24.01 ± 0.19
	Clay	2.95 ± 0.05	7.98 ± 0.09
Bulk density (Kg/m^3)		1.63 ± 0.04	1.58 ± 0.06
pH	H_2O (1:5)	6.60 ± 0.22	5.35 ± 0.34
	$CaCl_2$ (1:2.5)	6.31 ± 0.16	5.10 ± 0.25
TOC (g kg^{-1})		3.77 ± 0.30	9.95 ± 0.69
TN (g kg^{-1})		0.20 ± 0.01	0.71 ± 0.05
Avail. P (mg kg^{-1})		1.71 ± 0.13	2.23 ± 0.28
CEC (cmol$_c$ kg^{-1})		3.03 ± 0.11	8.14 ± 0.59
Exchangeable bases (cmol$_c$ kg^{-1})	Ca	1.02 ± 0.07	1.10 ± 0.15
	Mg	0.50 ± 0.00	0.54 ± 0.03
	K	0.30 ± 0.05	0.40 ± 0.01
	Na	0.50 ± 0.09	0.23 ± 0.06

K: Keta series, Ny: Nyankpala series.

2.3. Assessment of the NH_4^+ and NO_3^- Retention Capacities of the Biochars

Before the leaching experiment, the biochars were tested for their potentials to retain both the ammonium and nitrate ions. To execute this objective, biochar was packed into acrylic cylinders, the bottoms of which were covered with Whatman No 42 filter paper followed by a 25 µm pore size nylon mesh. The filter paper and nylon mesh were secured at the mouth with circular metal clips to prevent biochar particles from falling. Then, 150 g of each of the biochar sample was weighed into the acrylic cylinders and packed to 200 cm^3 by gently tapping the sides of the cylinders. The set up was replicated three times for each biochar type. Subsequently, 2.1 g of $(NH_4)_2SO_4$ and 3.42 g of KNO_3 as sources of NH_4^+ and NO_3^-, respectively, were each dissolved in 500 mL of deionized water and allowed to pass through the biochar sample in the column. A constant head of 50 cm was maintained and the leachate was collected. The concentrations of NH_4^+-N and NO_3^--N in every 50 mL of the leachate collected were determined colorimetrically. The former was determined through the indophenol blue method after extraction with 2 M KCl following a method adopted by Hood-Nowotny et al. [21], while the latter was extracted with 2M

KCl and determined following the chromotropic acid procedure espoused by West and Ramachandran [22]. The NH_4^+-N and NO_3^--N retention powers of the biochar were determined according to the equation below:

$$A = M_1 - M_2/W,$$

where A = amount of NH_4^+-N or NO_3^--N retained by the biochar, M_1 = mass of NH_4^+-N or NO_3^--N applied, M_2 = mass of NH_4^+-N or NO_3^--N in leachate, W = weight of biochar in the column. Apart from fertilizers that supplied single forms of ionic N, a retention experiment with a fertilizer source that supplied both NH_4^+ and NO_3^-, i.e., NH_4NO_3 was also conducted with NH_4NO_3 used in such quantities as to maintain the amounts of NH_4^+ and NO_3^- employed in the above-mentioned cases. Two biochars with superior retention capabilities of both NH_4^+ and NO_3^- were selected out of the three biochars tested for the leaching and used for the maize growing experiments in the greenhouse. The quantities of the different ionic forms of N retained by the different biochar types are shown in Table S2 in the supplementary file. The biochar impregnated with ammonium sulfate was dried and used as a nitrogen-enriched biochar-based fertilizer, denoted as ASS.

2.4. Greenhouse Experiment

The greenhouse experiment was conducted to assess the effects of biochar amendments on leaching of nitrogen from two distinctly different sandy soils and elucidating whether the biochar-induced effects on leaching has any bearing on N uptake and dry matter accumulation by maize. The two soils used for the experiment were the K series soil (Quartzipsamment) and the Ny series soil (Plinthic Acrisol) collected from the Volta and northern regions of Ghana, respectively. Under heavy fertilization regimes, both soils have been used for intensive maize and vegetable production over the years. A 2.3 kg sample of each of the soils was weighed into experimental pots measuring 15 cm in height and 8 cm in diameter. Four holes were created at the bottom of the pots which were then plugged with cotton wool to prevent soil particles from falling. The moisture content of the soil was maintained at 80% field capacity except on the days of collecting the leachate when the soils were saturated. Each pot was placed in a bowl to allow easy collection of leachate. Each of the biochars was applied at rates of 20 and 40 tons per hectare, while N in form of ammonium sulfate (ASP) was applied at the recommended rate of 265 kg per hectare and each of the treatments was replicated thrice. Additionally, the two biochars were impregnated with ASP and applied as nutrient-enriched biochar-based fertilizers. The ASP embedded into the biochar was denoted as ASS. A treatment with cow dung (CD) as a nitrogen source instead of the mineral fertilizers was included and it was applied at a rate that satisfied the nitrogen requirement of maize. Another treatment, CDASS was constituted by combining ASS and CD in equal proportions in terms of their nitrogen contents. The experiment was organized in a completely randomized design. The sawdust biochar applied at 20 tons and 40 tons per hectare was denoted as SD20 and SD40, respectively. The rice husk biochar applied to the soil at 20 tons and 40 tons per hectare was denoted as RH20 and RH40, respectively. All the soil amendments, including N, were applied once at the beginning of the first growing season. Four seeds of maize were sown per pot and thinned to two plants per pot after germination. Maize was grown for two seasons and each season lasted for a period of 5 weeks. Each of the treatments was replicated thrice. The leachate was collected on the 14th and 28th days after planting (DAP) in both seasons. The harvested maize plants were separated into shoots and roots, and dried in an oven at a temperature of 68 °C for 48 h to determine dry matter weight and N content of the maize which was determined through the Kjeldhal method. In order to investigate whether biochar amendments could lead to the preservation of soil N, maize was grown for a second season without any additional amendments to the soil.

2.5. Statistical Analysis

The data collected were subjected to analysis of variance (ANOVA) using Genstats (9th edition) and the means were separated at a least significance level of 5%.

3. Results and Discussion

3.1. Nitrogen Retentions by Biochar and Leaching from the Soil

As shown in Table S2, the saw dust biochar retained the highest amounts of NH_4^+ from both the $(NH_4)_2SO_4$ and NH_4NO_3 fertilizers with the quantity adsorbed from the former totaling to 2273.40 mg kg^{-1} while that from the latter amounted to 2475.1 mg kg^{-1}. This was followed by the rice husk biochar which retained 1809.57 mg kg^{-1} and 1703.88 mg kg^{-1} of NH_4^+ from $(NH_4)_2SO_4$ and NH_4NO_3 fertilizers, respectively. The corncob biochar on the other hand adsorbed 1756.70 mg kg^{-1} of NH_4^+ from the $(NH_4)_2SO_4$ fertilizer whilst the quantity retained from NH_4NO_3 was a meagre 1022.38 mg kg^{-1}. This same trend was observed with the adsorption of NO_3^- from NH_4NO_3 where the sawdust biochar retained 2283.93 mg kg^{-1}, whereas rice husk and corncob biochars adsorbed 1860.32 mg kg^{-1} and 1569.08 mg kg^{-1} of NO_3^-, respectively. With regard to the adsorption of NO_3^- from KNO_3, the saw dust biochar adsorbed the highest quantity which totaled up to 2283.93 mg kg^{-1} and was followed in a descending order by the corn cob biochar at 1881.31 mg kg^{-1} and the rice husk biochar at 1743.33 mg kg^{-1}. Therefore, in the presence of both NH_4^+-N and NO_3^--N (when NH_4NO_3 was used), the sawdust biochar exhibited a preference for NH_4^+ while both the rice husk and corncob biochars showed more affinity for NO_3^- than NH_4^+. The differences in the affinity for different forms of N by biochar have been documented by Yao et al. [8] through a batch experiment, where they employed one hydrochar as well as twelve biochars produced from four different biomass feedstocks at three different temperatures of 300 °C, 450 °C and 600 °C. They found that only three biochars pyrolyzed at the highest temperature of 600 °C could adsorb 0.12% to 3.7% of NO_3^--N from NH_4NO_3 while nine out of the twelve biochars adsorbed 1.8% to 15.7% of NH_4^+-N. Fidel et al. [23] later supported these deductions by demonstrating that the sorption of NO_3^--N increased with the pyrolysis temperature and that differences in sorption existed between red oak and corn stover biochars at most pyrolysis temperatures. The relatively high amount of NH_4^+-N and NO_3^--N retained by the sawdust biochar when the biochar samples were loaded with the fertilizer solutions could be due to the relatively high surface area of the sawdust biochar in comparison with other biochar types (Table S2), which provided more surfaces for N adsorption. Indeed, Zhou et al. [24] elucidated that adsorptions of nitrate and phosphates by biochars were influenced by their surface areas and porosity characteristics.

Leachates collected from the K series soil contained significantly higher amounts of both NH_4^+-N and NO_3^--N ($p < 0.05$) than the leachates obtained from the Ny series soil on both the leaching events and in both maize growing seasons as shown in Tables 2 and 3. The differences in the quantities of inorganic N leached from the two soils might have ensued from the differences in their clay contents. Additionally, control treatments without any biochar amendments leached significantly higher quantities of both NH_4^+-N and NO_3^-N ($p < 0.05$) than the biochar-amended soils, implying that biochar greatly reduced leaching of the aforementioned ions from the soil. In comparison with the control experiment, the worst performing biochar amendments reduced NH_4^+-N leaching from the K series soils fertilized with ASP, ASS, CD and CDASS by 229.8%, 329.6%, 121.4% and 180.3%, respectively, in the first leaching event of the first season (see Table 2). In the second leaching event of the first season, the worst performing biochar amendments reduced NH_4^+-N leaching by 269.0%, 160.6%, 177.2% and 87.5% from the K series soils fertilized with ASP, ASS, CD and CDASS, respectively.

Table 2. Amount of NH_4^+-N leached from the soil.

Season	Soil Type	Biochar Amendment	Nitrogen Fertilizers							
			ASP		ASS		CD		CDASS	
			L1	L2	L1	L2	L1	L2	L1	L2
1st Season	K	Control	23.58 ± 2.12a	16.20 ± 1.08a	25.99 ± 1.85a	15.27 ± 2.39a	17.93 ± 1.05b	16.44 ± 0.90a	20.60 ± 1.85a	10.97 ± 3.10b
		RH20	7.15 ± 1.24d	4.03 ± 2.10d	4.89 ± 1.33e	3.87 ± 0.89d	6.45 ± 1.52d	3.48 ± 1.66d	5.94 ± 2.00de	5.85 ± 1.72c
		RH40	4.51 ± 0.79e	3.91 ± 1.05d	6.05 ± 0.68d	3.60 ± 1.09d	8.10 ± 1.11d	5.93 ± 0.95c	7.35 ± 0.88d	4.10 ± 1.05d
		SD20	6.56 ± 1.88d	3.68 ± 0.93d	5.67 ± 1.27de	5.86 ± 0.78c	6.76 ± 2.16d	4.24 ± 1.92d	5.51 ± 2.21de	3.69 ± 0.69d
		SD40	6.17 ± 2.22d	4.39 ± 1.76d	5.08 ± 0.85e	3.75 ± 0.73d	8.01 ± 1.66d	5.64 ± 1.99c	4.03 ± 0.78e	3.41 ± 1.62d
	Ny	Control	10.44 ± 3.10c	9.70 ± 2.07b	11.72 ± 0.97c	8.08 ± 1.54b	10.59 ± 1.39c	10.91 ± 1.07b	9.34 ± 1.59c	9.98 ± 0.85b
		RH20	2.10 ± 0.67f	3.98 ± 0.92d	1.74 ± 1.05f	4.12 ± 0.82d	3.96 ± 0.63e	4.14 ± 0.93d	2.75 ± 0.69f	1.95 ± 0.55e
		RH40	1.66 ± 0.23f	3.68 ± 0.87d	2.14 ± 0.64f	4.09 ± 0.73d	1.83 ± 0.87f	5.01 ± 0.91cd	1.78 ± 0.56f	3.33 ± 0.39d
		SD20	2.17 ± 0.86f	2.63 ± 0.75d	3.68 ± 0.58def	1.86 ± 0.63e	2.90 ± 0.97f	3.53 ± 0.81d	1.89 ± 0.55f	2.77 ± 0.36d
		SD40	1.98 ± 0.85f	1.85 ± 0.36e	2.24 ± 0.94f	2.79 ± 0.81d	1.76 ± 0.46f	2.56 ± 0.65d	1.66 ± 0.59f	2.04 ± 0.88de
2nd Season	K	Control	8.78 ± 0.69ab	3.99 ± 0.56b	9.24 ± 0.39a	4.65 ± 0.25a	10.50 ± 0.48a	3.81 ± 0.67b	6.05 ± 2.10b	4.51 ± 0.92ab
		RH20	1.75 ± 0.96d	0.56 ± 0.44d	2.00 ± 0.72d	0.37 ± 0.13d	3.03 ± 0.45d	0.55 ± 0.33d	4.67 ± 0.96c	0.64 ± 0.17d
		RH40	2.25 ± 0.13d	0.46 ± 0.18d	3.13 ± 0.43d	0.51 ± 0.11d	1.96 ± 0.52d	0.63 ± 0.30d	2.40 ± 0.33d	0.50 ± 0.46d
		SD20	3.00 ± 0.91d	0.72 ± 0.12d	4.05 ± 1.22c	0.65 ± 0.26d	2.21 ± 0.54d	0.51 ± 0.42d	2.47 ± 0.81d	0.48 ± 0.21d
		SD40	2.53 ± 0.54d	0.67 ± 0.31d	2.14 ± 0.72d	0.54 ± 0.39d	2.44 ± 0.42d	0.66 ± 0.11d	1.07 ± 0.65d	0.42 ± 0.36d
	Ny	Control	5.70 ± 1.06b	1.98 ± 0.73c	6.01 ± 0.98b	2.09 ± 0.56c	7.09 ± 2.10b	3.07 ± 0.91bc	10.02 ± 2.17a	1.52 ± 0.82c
		RH20	1.91 ± 0.33d	0.53 ± 0.23d	2.11 ± 0.68d	0.68 ± 0.16d	1.84 ± 0.18d	0.49 ± 0.29d	3.06 ± 0.76d	0.52 ± 0.13d
		RH40	2.31 ± 0.22d	0.48 ± 0.16d	1.87 ± 0.30d	0.53 ± 0.17d	2.11 ± 0.73d	0.62 ± 0.35d	2.01 ± 0.52d	0.40 ± 0.29d
		SD20	2.07 ± 0.28d	0.54 ± 0.16d	1.91 ± 0.26d	0.60 ± 0.24d	1.59 ± 0.22d	0.50 ± 0.18d	2.78 ± 0.36d	0.38 ± 0.34d
		SD40	1.85 ± 0.42d	0.66 ± 0.41d	1.64 ± 0.18d	0.46 ± 0.13d	2.88 ± 0.53d	0.39 ± 0.10d	1.77 ± 0.17d	0.47 ± 0.20d

K: Keta series, Ny: Nyankpala series, L1: leachate collected on the 14th day after planting, L2: leachate collected on the 28th day after planting, ASP: Ammonium sulfate fertilizer, ASS: Ammonium sulfate embedded into the biochar, CD: Cow dung, CDASS: Cow dung + Ammonium sulfate embedded into the biochar, RH20: 20 t ha^{-1} Rice husk biochar, SD20: 20 t ha^{-1} sawdust biochar, RH40: 40 t ha^{-1} rice husk biochar, SD40: 40 t ha^{-1} sawdust biochar. Values for leachate collected on the same day with the same letter are not significantly different $p = 0.05$.

Table 3. Amount of NO_3^--N leached from the soil.

Season	Soil Type	Biochar Amendment	Nitrogen Fertilizers							
			ASP		ASS		CD		CDASS	
			L1	L2	L1	L2	L1	L2	L1	L2
1st Season	K	Control	8.86 ± 0.75a	6.88 ± 1.09a	10.05 ± 1.73a	7.53 ± 0.66a	9.13 ± 0.87a	7.01 ± 1.39a	7.49 ± 0.84b	8.03 ± 0.55a
		RH20	2.01 ± 0.68d	0.79 ± 0.07c	2.35 ± 0.39d	0.83 ± 0.07c	3.02 ± 0.51d	0.71 ± 0.09c	2.64 ± 0.75d	0.66 ± 0.08c
		RH40	3.09 ± 0.79d	0.89 ± 0.09c	2.70 ± 0.51d	0.65 ± 0.03c	1.69 ± 0.91d	0.72 ± 0.06c	2.51 ± 0.94d	0.79 ± 0.07c
		SD20	2.17 ± 0.87d	0.67 ± 0.09c	2.69 ± 0.73d	0.75 ± 0.05c	2.87 ± 0.51d	0.69 ± 0.08c	1.97 ± 0.91d	0.80 ± 0.07c
		SD40	1.99 ± 0.90d	0.82 ± 0.06c	2.26 ± 0.33d	0.69 ± 0.08c	2.66 ± 0.72d	0.59 ± 0.08c	2.99 ± 0.51d	0.77 ± 0.03c
	Ny	Control	6.67 ± 0.62bc	3.13 ± 0.57b	5.10 ± 0.81c	4.57 ± 0.76b	5.02 ± 1.00c	3.33 ± 0.32b	7.46 ± 2.54b	2.98 ± 0.54b
		RH20	1.88 ± 0.74d	0.30 ± 0.08c	0.77 ± 0.19e	0.29 ± 0.06c	0.93 ± 0.04e	0.41 ± 0.09c	0.57 ± 0.08e	0.31 ± 0.09c
		RH40	1.05 ± 0.71d	0.27 ± 0.09c	3.23 ± 0.80d	0.32 ± 0.06c	1.56 ± 0.79d	0.35 ± 0.05c	2.23 ± 1.03d	0.49 ± 0.06c
		SD20	2.22 ± 0.43d	0.51 ± 0.04c	1.55 ± 0.61d	0.27 ± 0.05c	1.89 ± 0.18d	0.29 ± 0.08c	1.58 ± 0.35d	0.33 ± 0.07c
		SD40	1.54 ± 0.69d	0.39 ± 0.07c	1.91 ± 0.22d	0.39 ± 0.07c	3.89 ± 0.07d	0.27 ± 0.03c	2.22 ± 1.09d	0.32 ± 0.06c
2nd Season	K	Control	4.29 ± 0.81a	1.97 ± 0.90b	3.93 ± 1.07a	5.46 ± 1.13a	4.09 ± 1.67a	3.16 ± 1.89b	1.99 ± 0.98b	2.39 ± 1.07b
		RH20	1.04 ± 0.82c	0.50 ± 0.06c	0.87 ± 0.08cd	0.63 ± 0.07c	0.60 ± 0.09d	1.77 ± 0.06b	0.28 ± 0.04d	0.79 ± 0.07c
		RH40	0.73 ± 0.08d	0.80 ± 0.05c	0.97 ± 0.06cd	1.81 ± 0.06b	0.87 ± 0.10cd	0.63 ± 0.04c	1.19 ± 0.30c	0.75 ± 0.09c
		SD20	0.69 ± 0.11d	0.45 ± 0.03c	0.75 ± 0.08d	0.63 ± 0.07c	0.57 ± 0.05d	0.61 ± 0.04c	0.86 ± 0.04cd	0.50 ± 0.06c
		SD40	0.47 ± 0.17d	0.66 ± 0.05c	0.55 ± 0.05d	0.60 ± 0.04c	0.85 ± 0.03d	0.48 ± 0.07c	0.93 ± 0.05d	0.57 ± 0.05c
	Ny	Control	2.16 ± 0.90b	1.89 ± 0.69c	3.78 ± 1.07a	0.90 ± 0.07c	1.95 ± 0.66b	2.03 ± 0.11b	4.10 ± 2.10a	1.86 ± 0.71b
		RH20	0.66 ± 0.09d	0.57 ± 0.05c	0.52 ± 0.06d	0.47 ± 0.06c	0.53 ± 0.09d	0.71 ± 0.08c	0.65 ± 0.07d	0.48 ± 0.03c
		RH40	0.70 ± 0.05d	0.69 ± 0.09c	0.75 ± 0.09d	0.82 ± 0.04c	0.47 ± 0.07d	0.66 ± 0.09c	0.71 ± 0.08d	0.52 ± 0.06c
		SD20	0.54 ± 0.08d	0.46 ± 0.06c	0.69 ± 0.07d	0.40 ± 0.07c	0.73 ± 0.08d	0.54 ± 0.07c	0.55 ± 0.05d	1.03 ± 0.08c
		SD40	0.99 ± 0.16cd	0.55 ± 0.04c	0.44 ± 0.05d	0.56 ± 0.09c	0.60 ± 0.07d	0.39 ± 0.05c	0.73 ± 0.03d	0.77 ± 0.09c

K: Keta series, Ny: Nyankpala series, L1: leachate collected on the 14th day after planting, L2: leachate collected on the 28th day after planting, ASP: Ammonium sulfate fertilizer, ASS: Ammonium sulfate embedded into the biochar, CD: Cow dung, CDASS: Cow dung + Ammonium sulfate embedded into the biochar, RH20: 20 t ha^{-1} Rice husk biochar, SD20: 20 t ha^{-1} sawdust biochar, RH40: 40 t ha^{-1} rice husk biochar, SD40: 40 t ha^{-1} sawdust biochar. Values for leachate collected on the same day with same letter are not significantly different $p = 0.05$.

In the Ny series soils, the worst performing biochar amendments abated NH_4^+-N leaching by 381.1%, 218.5%, 167.4% and 239.6% from pots fertilized with ASP, ASS, CD and CDASS, respectively, in the first leaching event of the first season (see Table 2). In the second leaching event, NH_4^+-N leaching reduced by 143.7%, 96.1%, 117.8% and 199.7% in the ASP, ASS, CD and CDASS fertilized pots, respectively. In the first leaching event of the second season, the worst performing biochar amendments reduced NH_4^+-N leaching from the ASP, ASS, CD and CDASS fertilized K series soil by 192.7%, 128.1%, 246.5% and 29.5%, respectively, while in the second leaching event, the reductions stood at 454.2%, 615.4%, 477.3% and 604.7%, respectively. The worst performing biochar amendments reduced NH_4^+-N leaching from the Ny series soil fertilized with ASP, ASS, CD and CDASS by 146.8%, 184.8%, 146.2% and 227.5%, respectively, in the first leaching event, whereas in the second leaching event, the reductions amounted to 200.0%, 207.4%, 395.2% and 192.3%, respectively. This observation accorded with the results obtained by Yao et al. [8], Sika and Hardie [10] and Haider et al. [13], who reported decrements in the amounts of nitrates and ammonium leached from biochar-amended soils.

The leachates generally contained more NO_3^--N than NH_4^+-N in all the leaching events in both soils, which was in agreement with the observation made by Liu et al. [14], who found that NO_3^--N accounted for more than 90% of the total amount of inorganic N leached from the soil. This can be attributed to the presence of negatively charged carboxylic and phenolic compounds on the biochar surface with limited ability to retain NO_3^- [25] and accelerated nitrification brought about by biochar which resulted in greater amounts of leachable NO_3^--N [14]. However, the amount of leached NO_3^--N were far less in biochar-amended soils than in the control. In comparison with the control, the worst performing biochar amendments on ASP, ASS, CD and CDASS fertilized K series soil reduced NO_3^--N leaching by 186.7%, 272.2%, 202.3% and 150.5%, respectively, in the first leaching event, and by 673.0%, 807.2%, 873.6% and 903.8%, respectively, in the second leaching event of the first season (see Table 3). In the Ny series soil, the worst performing biochar amendments waned NO_3^--N leaching by 200.5%, 57.9%, 29.0% and 234.5% in the first leaching event, and by 513.7%, 1071.8%, 7122.2% and 508.2%, respectively, in the second leaching event.

In the second season, the worst performing biochar amendments on K series soil fertilized with ASP, ASS, CD and CDASS lessened NO_3^--N leaching by 312.5%, 305.2%, 370.1% and 67.2%, respectively, in the first leaching event, and by 146.3%, 201.7%, 78.5% and 202.5%, respectively, in the second leaching event. In the N series, the worst performing biochar amendments lowered NO_3^--N leaching by 118.2%, 40.4%, 167.1% and 461.6% in the first leaching event, and by 173.9%, 9.8%, 185.9% and 8.1%, respectively, in the second leaching event. This is because biochar also has positive surface charges which aid in its attraction of the negatively charged ions including NO_3^- and phosphate ions, as Chintala et al. [26] noted. Great statistical differences existed both between the biochar types and application rates in the first leaching event as far as the amounts of NO_3^--N leached were concerned. In this regard, the sawdust biochar exhibited the highest leaching attenuation power and the leached quantities of NO_3^--N decreased with increasing application rates of either biochars. These statistical differences, however, diminished with subsequent leaching events to the extent that there were hardly any statistical differences in the amounts of NO_3^--N leached from the biochar-amended soils by the last leaching event, as seen in Table 3. On the other hand, the amount of NH_4^+-N leached from both soils in similar leaching events did not exhibit statistical variations. The amount of N retained in the soil at the end of the experiment was at least three times more in the biochar-amended soils than in the control, as shown in Table S3 which confirms the great N retention power of the biochar.

3.2. Dry Matter Accumulation and Nitrogen Uptake by Maize

The shoot and root dry matter (DM) accumulations in maize grown in the various amended soils are shown in Figures 1 and 2, respectively. The accumulated shoot dry matter of maize grown in the first and second seasons are shown in Figure 1a,b, respectively, while Figure 2a,b exhibits the root dry matter accumulated in the first and second seasons, respectively. The shoot and root dry weights produced by the control treatments in both soils were not significantly ($p > 0.05$) different from each other. This could be attributed to the inherent inability of the soils used to retain applied plant nutrients especially N as a result of their low CEC (Table 1). Amending the two soils with biochar significantly ($p < 0.05$) increased the dry matter yield. In comparison with the control experiment, the worst performing biochar amendments on ASP, ASS, CD and CDASS fertilized K series soil boosted shoot dry matter accumulation by 127.8%, 240.9%, 119.4% and 110.5%, respectively, in the first season. In the Ny series, the dry matter enhancement amounted to 101.8%, 128.5%, 220.0% and 162.7%, respectively. In the second season, the worst performing biochar amendments on ASP, ASS, CD and CDASS fertilized pots increased shoot dry matter accumulation by 928.9%, 534.7%, 488.9% and 378.8%, respectively, in the K series soil, and by 1629.6%, 1209.7%, 661.5% and 741.6%, respectively, in the Ny series soil.

The root dry matter increased by a minimum of 495.8%, 752.8%, 452.8% and 415.8% in the ASP, ASS, CD and CDASS fertilized K series soils, respectively, in the first season, and by 819.2%, 529.4%, 445.0% and 375.6%, respectively, in the second season in comparison to the control. On the other hand, the worst performing biochar amendments on the Ny series increased root dry matter accumulation by 498.0%, 555.3%, 700.0% and 590.7% in the first season, and by 1025.8%, 1050.0%, 311.0% and 691.5% in the second season when applied together with ASP, ASS, CD and CDASS nitrogen sources, respectively. The observations made as far as dry matter accumulations are concerned contradict the one made by Haider et al. [13] who indicated that while biochar was able to reduce leaching from temperate soils in a four-year field trial, the effects on dry matter accumulation and yield were null. Additionally, Liu et al. [14] showed that biochar increased the dry matter accumulation in ryegrass grown on a sandy soil only in the first season of a two-season experiment, while the effects in the second season were null in comparison to the control.

The observed increment in the dry matter accumulation observed in the current study could be ascribed to the increased availability of the applied N brought about by biochar’s high adsorption power for the ionic forms of the N fertilizer. According to Taghizadeh-Toosi et al. [27], recent evidence has indicated that N adsorbed by biochar is eventually made available for plant uptake. Ma and Matsunaka [28] reported that when biochar is applied as a sole amendment or together with N fertilizer, it significantly improved the dry matter of shoots and roots of lettuce. A similar trend was also observed during the second planting, as shown in Figure 2a,b. In both seasons, maize grown on the Ny series accumulated higher shoot and root dry matter than the one grown on the K series. It is worth noting, however, that the differences in the shoot dry matter of the maize grown on the amended soils were not statistically significantly different in the first season while the differences in the root dry matter in both seasons were not significantly different. The differences in the dry matter accumulated in the maize grown on the K and Ny series can be attributed to the differences in the clay contents of the two soils, whereby the Ny series soil contained almost thrice as much clay as did the K series (see Table 1). This observation concurs with the one made by Chintala et al. [26] who observed differences in dry matter accumulations in maize grown on two different soils and with different biochar types. However, they attributed the observed differences to the differing biochar properties rather than the differences in soil properties. Therefore, the reasons behind the observed differences require further investigations.

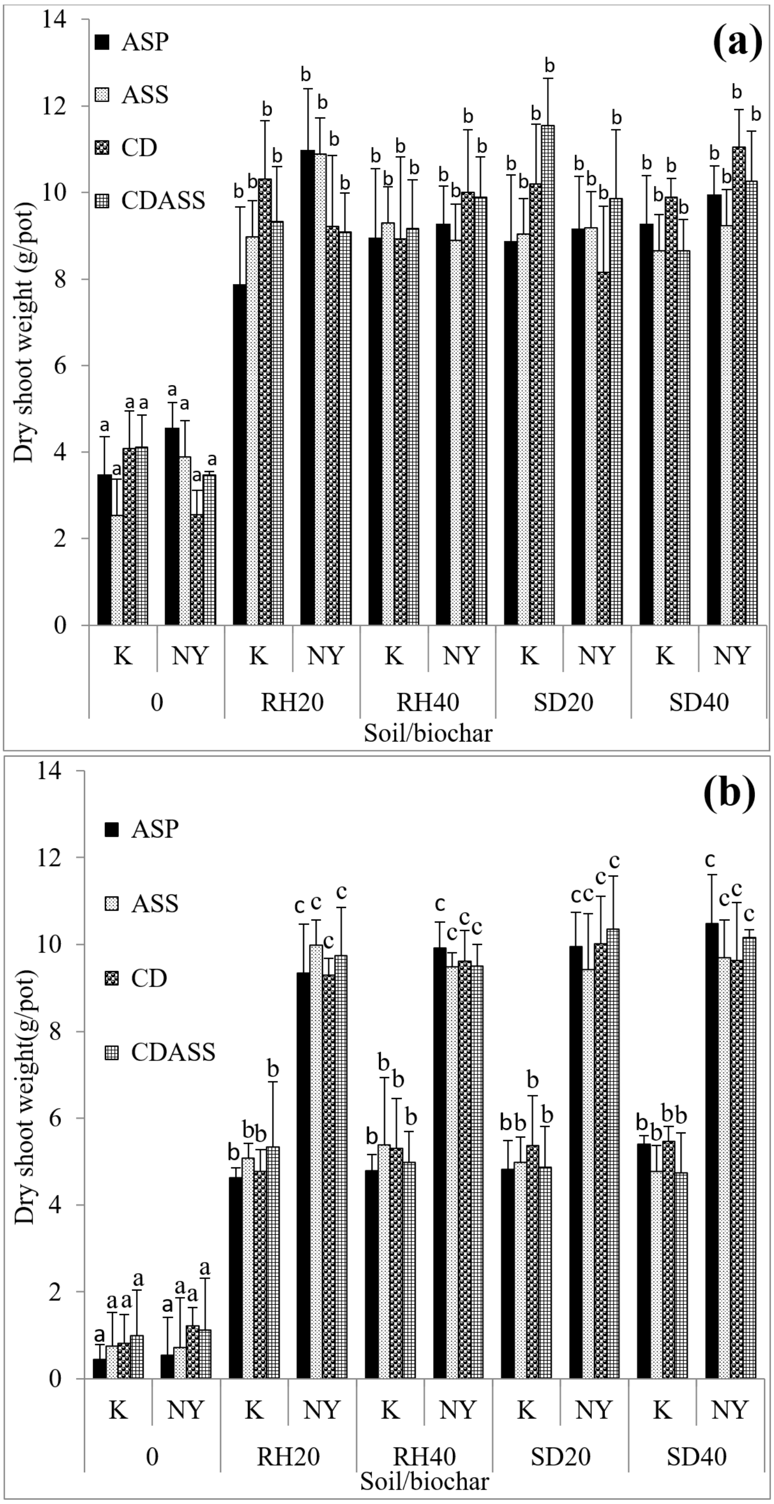

Figure 1. Dry shoot weight of the maize grown with the different amendments in the (**a**) first and (**b**) second growing seasons. K: Keta series, Ny: Nyankpala series, ASP: Ammonium sulfate fertilizer, ASS: Ammonium sulfate embedded into the biochar, CD: Cow dung, CDASS: Cow dung + Ammonium sulfate embedded into the biochar, RH20: 20 t ha^{-1} Rice husk biochar, SD20: 20 t ha^{-1} sawdust biochar, RH40: 40 t ha^{-1} rice husk biochar, SD40: 40 t ha^{-1} sawdust biochar. Values for dry shoot weight with same letter(s) under the same planting season were not significantly different at p =0.05.

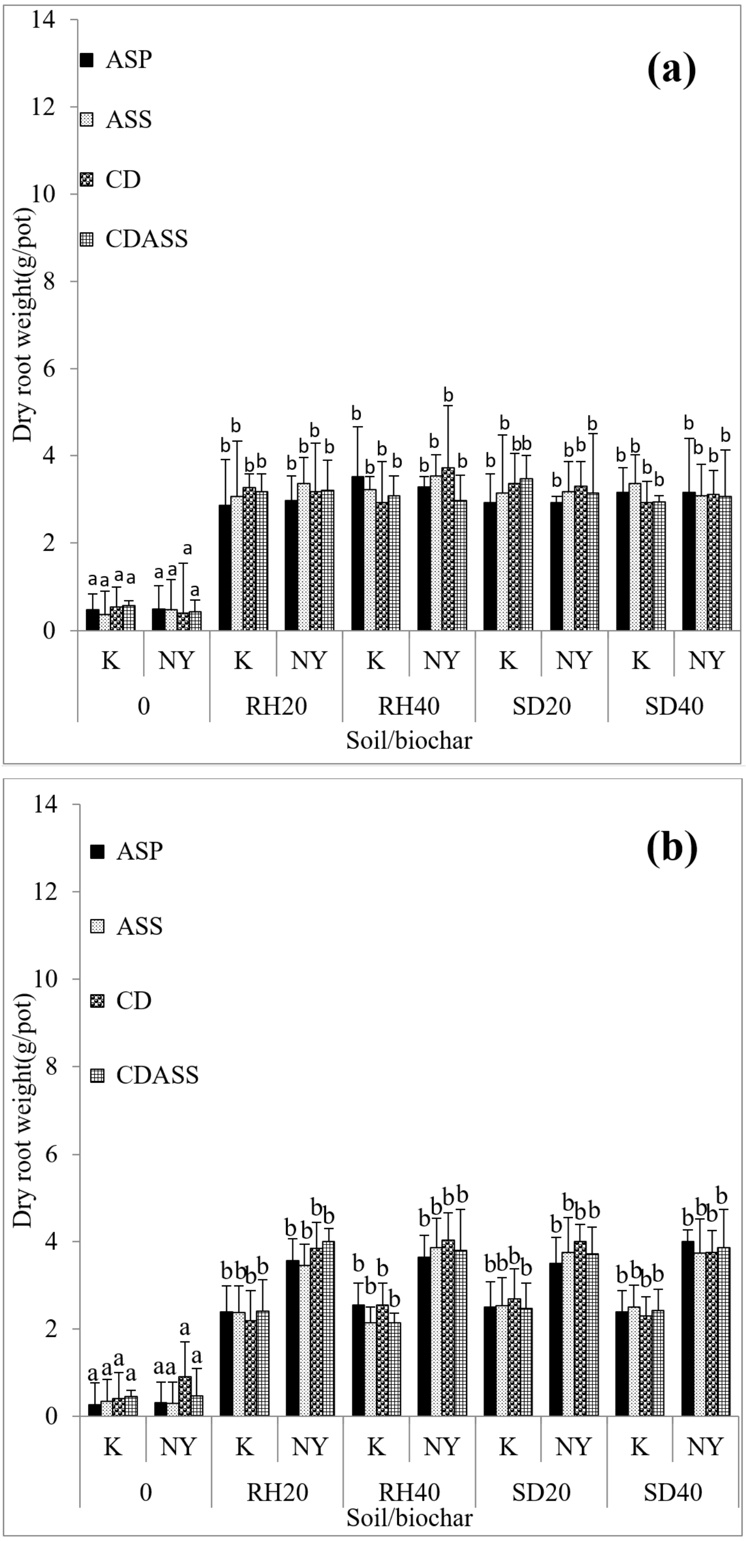

Figure 2. Dry root weights of the maize grown with the different amendments in the (**a**) first and (**b**) second growing seasons. K: Keta series, Ny: Nyankpala series, ASP: Ammonium sulfate fertilizer, ASS: Ammonium sulfate embedded into the biochar, CD: Cow dung, CDASS: Cow dung + Ammonium sulfate embedded into the biochar, RH20: 20 t ha^{-1} Rice husk biochar, SD20: 20 t ha^{-1} sawdust biochar, RH40: 40 t ha^{-1} rice husk biochar, SD40: 40 t ha^{-1} sawdust biochar. Values for dry root weight with same letter(s) under the same planting season were not significantly different at p =0.05.

Enriching biochar with nitrogen before application did not have any impact on the dry matter accumulation in maize as the shoot and root dry weights obtained with ASS were not significantly different from the rest of the treatments. This observation is in contrast to the one made by Dietrich et al. [29] and Luyima et al. [30]. The former found that biochar enriched with biogas digestates produced heavier dry shoot and root weights of maize than the normal biochar without any enrichment, while the latter indicated that sorbing urea into co-pyrolyzed cow dung and bone meal produced leaf lettuce with heavier shoots and roots than the control. Unlike the dry shoot weight, which exhibited significant statistical differences in the second season across the amended soils, there were no significant statistical differences in the dry root weights obtained from the biochar-amended soils in both seasons, even though the roots obtained from the K series were lighter than those from the Ny series.

Concerning N uptake by maize, the uptake was higher in the maize grown in the Ny series than in the K series in both seasons, as shown in Table 4. This may still be attributed to the fact that the clay content in the K series was lower than that in the Ny series, as shown in Table 1. Indeed, differences in N uptake ensuing from variations in soil properties have been well documented by Liu et al. [14], who found an increased N uptake by ryegrass grown on a sandy soil amended with biochar but failed to observe any improvement in N uptake when biochar was applied to a loam soil. Amending the soils with biochar significantly ($p < 0.05$) enhanced N uptake, as shown in Table 4. The addition of biochar to the two soils enhanced N retention in the soils, which might have helped in making the retained N available for possible uptake by maize. In contrast to the observation made by Liu et al. [14], who indicated that the ability of biochar to increase N uptake by ryegrass diminished in the second season, the capacity of biochar amendments to increase N uptake by maize remained strong even in the second season in the present study. This observation indicates that biochar is capable of enhancing soil retention of N for extended periods. There are several pathways through which biochar improves N retention in the soil including reductions in gaseous emissions, adsorptions of both NO_3^- and NH_4^+ ions, abatement of denitrification of NO_2, etc., as Rashid et al. [31], Luyima et al. [2,32,33] and others have elaborated. Taghizadeh-Toosi et al. [27] indicated that N adsorbed by biochar is bioavailable and is easily released for plant uptake.

Table 4. Nitrogen uptake in maize.

Soil Type	Biochar Amendment	Nitrogen Fertilizers							
		ASP		ASS		CD		CDASS	
		N1	N2	N1	N2	N1	N2	N1	N2
K	Control	8.97 ± 0.69a	9.64 ± 0.95a	9.54 ± 0.52a	7.94 ± 0.72a	8.89 ± 0.44a	6.56 ± 0.67a	9.02 ± 0.29a	7.46 ± 0.18a
	RH20	51.47 ± 4.17b	43.80 ± 3.10b	59.37 ± 4.98b	51.38 ± 2.10b	52.01 ± 3.21b	40.64 ± 5.01b	60.10 ± 3.97b	48.05 ± 2.87b
	RH40	51.60 ± 3.96b	50.49 ± 3.89b	47.87 ± 2.67b	52.71 ± 4.17b	56.37 ± 3.88b	43.36 ± 2.98b	54.12 ± 5.11b	50.66 ± 3.07b
	SD20	51.29 ± 2.86b	47.37 ± 2.77b	54.53 ± 2.85b	54.64 ± 3.62b	50.52 ± 2.99b	45.02 ± 5.40b	47.85 ± 2.84b	50.31 ± 3.52b
	SD40	52.36 ± 3.18b	44.19 ± 1.98b	55.77 ± 3.17b	51.71 ± 2.73b	53.62 ± 3.77b	42.87 ± 1.98b	52.70 ± 5.06b	50.42 ± 4.37b
Ny	Control	9.47 ± 0.71a	8.04 ± 0.45a	8.29 ± 0.32a	6.69 ± 0.51a	11.60 ± 0.62a	6.68 ± 0.39a	13.58 ± 0.83a	8.38 ± 0.28a
	RH20	84.13 ± 5.78c	77.09 ± 4.89c	78.70 ± 5.67c	66.36 ± 6.19c	81.77 ± 5.89c	69.89 ± 4.90c	73.34 ± 5.19c	74.11 ± 3.49c
	RH40	78.43 ± 4.13c	76.21 ± 6.67c	86.91 ± 5.81c	67.55 ± 4.96c	87.88 ± 5.33c	72.57 ± 6.13c	86.37 ± 5.76c	68.93 ± 4.88c
	SD20	81.09 ± 6.89c	65.46 ± 5.93c	75.99 ± 4.88c	73.68 ± 5.73c	84.78 ± 7.24c	68.93 ± 6.85c	83.29 ± 5.12c	71.48 ± 5.33c
	SD40	79.79 ± 5.88c	74.31 ± 4.89c	64.66 ± 6.02c	67.26 ± 3.94c	81.41 ± 6.88c	66.50 ± 3.99c	71.65 ± 6.03c	73.09 ± 6.42c

K: Keta series, Ny: Nyankpala series, N1: Nitrogen uptake by maize in the first season, N2: Nitrogen uptake by maize in the second season, ASP: Ammonium sulfate fertilizer, ASS: Ammonium sulfate embedded into the biochar, CD: Cow dung, CDASS: Cow dung + Ammonium sulfate embedded into the biochar, RH20: 20 t ha^{-1} Rice husk biochar, SD20: 20 t ha^{-1} sawdust biochar, RH40: 40 t ha^{-1} rice husk biochar, SD40: 40 t ha^{-1} sawdust biochar. Values for nitrogen uptake by maize obtained in the same season with same letter are not significantly different $p = 0.05$.

4. Conclusions

Although biochar exhibited significant differences in the sorption of ionic forms of N from solution during the column experiment, no such differences were observed in their capacities to reduce leaching of N from the soil. This means that even biochars that have been found to be inferior in sorbing ionic forms of N in batch experiments can be helpful in attenuating N leaching from the soil. Secondly, the ability of biochar to reduce N leaching from the tropical sandy soils is long-lived and, hence, biochar can result in a prolonged conservation of N in the soil. The abatement in the amounts of N leached out of the soil in biochar-amended sandy soils consequently resulted in more N being available to the growing maize crop which increased both N uptake and dry matter accumulations. From the observations made in this study, therefore, biochar amendments are recommended for sustainable maize production on tropical sandy soils since they result in the conservation of N and higher maize yields than the conventional fertilizer amendments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/c9010034/s1, Table S1: Some physico-chemical properties of the biochar used; Table S2: Amount of NH_4^+–N and NO_3^-–N retained by biochar; Table S3: Residual soil available N.

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Data Availability Statement: The data to support the conclusions made in the study are included in the manuscript while small amounts of the produced biochars can be provided to anyone upon request.

Conflicts of Interest: The authors declare that they have no conflict of interest.

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