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Biochar and Ammonium Nitrate Synergies: Enhancing Nitrogen Availability and Maize Growth in Oxisols

Igor de Oliveira Paiva , Everton Geraldo de Morais * and Carlos Alberto Silva

Department of Soil Science, Federal University of Lavras, University Campus, P.O. Box 3037, Lavras 37203-202, Minas Gerais, Brazil
* Correspondence: everton.morais2@ufla.br

Abstract: Effective nitrogen (N) management and the development of novel N fertilizers are essential for enhancing maize growth in tropical soils. One strategy to increase N use efficiency is the use of organic matrices as a source of N or their combination with the application of mineral N sources. Among these organic matrices, biochar emerges as a highly promising option for optimizing N use efficiency. Thus, the aim of this study was to evaluate the effects of different feedstocks, their respective biochars, and their combination with N on the dynamics and uptake of N by maize plants in two contrasting Oxisols. A 30-day greenhouse experiment was conducted using maize grown under treatments with four feedstocks (bamboo, sunflower cake, chicken manure, and shrimp carcass) and their respective biochars. The biochars were applied with or without ammonium nitrate (AN), alongside negative (no N) and positive (AN-only) controls. Ammonium and nitrate levels were analyzed in the soil solution at 1 and 15 days and in the whole soil before and after cultivation. Maize biomass production and shoot N accumulation were also evaluated at the end of the experiment. Among the main results, it was observed that soil type played a key role in available N, maize nutrition, and growth. In the medium-textured Oxisol studied, native soil organic matter partially met maize N requirements due to high content of available N observed. Biochars influenced N availability by increasing nitrate-N prevalence in the soil solution. Although whole-soil N levels were sufficient for robust maize growth, post-cultivation residual N remained low (<75 mg kg^{-1}), indicating the need for supplemental N fertilization for plants grown in pots. In the medium-textured Oxisol, bamboo or sunflower cake biochar combined with AN increased biomass production by ~12% compared with AN alone. Similarly, in the clayey Oxisol, maize fertilized with sunflower cake or shrimp carcass biochar—regardless of AN addition—outperformed AN-fertilized plants by 19–30%. Thus, this study highlights the potential of integrating biochar with N fertilization to improve soil and solution N availability and increase N use efficiency by maize plants.

Keywords: mineral nitrogen forms; nitrification; nitrogen in soil solution; biochar nitrogen chemical species; soil nitrogen immobilization; nitrogen from soil organic matter

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Academic Editor: Huashou Li

Received: 8 February 2025
Revised: 27 February 2025
Accepted: 28 February 2025
Published: 2 March 2025

Citation: Paiva, I.d.O.; Morais, E.G.d.; Silva, C.A. Biochar and Ammonium Nitrate Synergies: Enhancing Nitrogen Availability and Maize Growth in Oxisols. *Agronomy* **2025**, *15*, 633. https://doi.org/10.3390/agronomy15030633

1. Introduction

In 2019, Brazil generated approximately 73 million tons of solid waste, with around 45% originating from agricultural, industrial, and urban activities with potential for use as fertilizers [1]. Many organic residues (ORs), rich in proteins, amino acids, and labile nitrogen (N) forms, can serve as valuable N sources for crops [2,3]. Recycling and the use of N from postharvest waste, fishing industry byproducts, and animal manures are essential steps to reduce Brazil's reliance on imported N fertilizers [4]. However, organic waste must undergo processing for chemical stabilization and sanitation before adding it to agricultural soils. Pyrolysis is an efficient and fast process that stabilizes N in the final biochar, changes the waste chemical composition, and enhances carbon (C) persistence in the soil–plant system [4,5]. However, depending on the intensity of charring conditions, a portion of the N in feedstocks is lost during the pyrolysis process [4,6,7]. During pyrolysis, N is retained in aromatic, ammonium-N forms, or within the sorptive complex or micropores of the biochar, potentially reducing N losses through leaching and volatilization. However, biochar can also increase soil nitrification rates and pH, which may lead to increased soil nitrate leaching [8–12].

Biochar contains both mineral and organic N; although, pyrolysis typically reduces the overall N retention in the final product [13]. The N content, N chemical species, and aromatic character of biochar strongly depend on the pyrolysis temperature [4,10]. Biochars produced at temperatures above 450 °C contain chemically stable N forms resistant to soil mineralization due to the high energy required by soil microbes to decompose aromatic N structures [14–17]. Conversely, feedstocks high in N and pyrolyzed at temperatures below 350 °C yield biochars with more readily mineralizable N than those formulated at higher temperatures [4]. Nonetheless, higher pyrolysis temperatures result in biochars with fewer labile N forms, and their high C/N ratio can lead to increased soil N immobilization rather than the release of N for crop nutrition [13,14,17].

Maize is one of the primary crops cultivated in Brazil's Cerrado region, where the soils are characterized by high exchangeable aluminum (Al), a strong capacity to fix phosphate, and low to moderate soil organic matter (SOM) levels [18,19]. Urea, monoammonium phosphate (MAP), and ammonium sulfate are the primary N fertilizers used in Brazil for maize cultivation. Nitrogen from mineral soluble fertilizers is prone to losses through runoff, leaching, ammonia volatilization, denitrification, and immobilization by soil biota or within SOM [20–22]. Ammonium nitrate, increasingly used as a topdressing N source for maize, positively impacts grain yield by supplying both ammonium and nitrate in balanced levels, which enhance maize nutrition and growth [9]. The relative proportion of nitrate (NO_3^-) and ammonium (NH_4^+) supplied to maize plants depends on factors such as soil type, pH, plant growth stage, soil nitrification rates, and N sources used to nourish crops [9,23]. In Oxisols, N availability is governed by SOM content and mineralization rates, which regulate plant N acquisition [20,24]. Due to the low residual N levels in tropical soils, annual applications of mineral N fertilizers are crucial for increasing maize yields [25,26]. Therefore, the N rate, source, and use efficiency are critical for nourishing and promoting maximum maize growth while minimizing N losses through leaching, volatilization, and denitrification [27].

Biochar influences the dynamics and proportions of N forms in soil, affecting soil pH, organic matter decomposition, nitrification, denitrification, and volatilization process rates [10]. The C/N ratio of biochar directly affects its decomposition rates as C:N ratios exceeding 30:1 promote temporary N immobilization [28,29]. Supplementary mineral N fertilizers may be required where biochar-induced N immobilization outweighs mineralization. According to Mota and Silva [30], biochar–N composites, particularly those formulated with DAP, were as effective as urea in promoting plentiful maize growth. Conversely, the maize dry matter reduced when plants were only fertilized with raw biochars, showing that N from some biochars was insufficient to meet maize's N requirement. In the study of Castejon-del Pino et al. [31], biochar N-doping with urea increased the water-soluble fraction of N up to 14.5% of the total N, indicating that biochar N-based fertilizers can progressively supply N to plants, acting as true slow-release fertilizers. In tropical soils, the increase (12%) of N use efficiency and corn yield (26%) of plants fertilized with

N-doped biochars were attributed to the gradual release of N from the biochar N-enriched fertilizers [32].

In addition, many studies on the interaction between N and biochar have focused on its interaction with urea and/or sources containing the nutrient in only one form (nitrate or ammonium), with few addressing its application as ammonium nitrate, which provides both nitrate and ammonium forms [33–36]. Due to differences in charge, molecular size, and soil interactions, the simultaneous application of both N forms may interact differently compared to the application of a single N form [8,10,12]. Therefore, it is crucial to determine the dynamics of these N sources when combined with biochar, which is an effect that is also highly dependent on the soil type used.

Preliminary studies have shown that sources such as sunflower cake, chicken manure, and shrimp carcass have high potential as nitrogen sources for plants [4,37]. However, biochars derived from bamboo have a high C:N ratio and contain more recalcitrant carbon, which can immobilize nitrogen in the soil, affecting both native soil N and that from mineral fertilizers [4]. Additionally, due to differences in the properties of these biochars, they may exhibit distinct mechanisms influencing nitrogen mineralization or immobilization in the soil.

In this context, this study aimed to: (i) assess the capacity of raw feedstocks and their derived biochars, with or without ammonium nitrate, to supply N to maize plants; (ii) evaluate the interaction of soil type and N sources on N availability in solution and whole Oxisols; (iii) investigate the need for supplementary N from ammonium nitrate when tropical soils are treated with contrasting biochars; and (iv) determine residual soluble N in Oxisols following maize cultivation. We hypothesize that biochars may act synergistically with mineral N fertilizers or, depending on the biochar type, conversely, immobilize N, potentially limiting maize growth when readily available N is not added to Oxisol. Therefore, it is critical to investigate whether the N supplied by organic residues, biochars (alone or in combination with ammonium nitrate), and native SOM N can sufficiently support maize growth under greenhouse conditions in tropical soils with varying textures and organic matter content.

2. Materials and Methods

2.1. Pyrolysis and Biochar Production

All phases of this study, including biochar production, were conducted at the Federal University of Lavras, Department of Soil Science, in the Laboratory for the Study of Soil Organic Matter (LEMOS). The biochar production was carried out between July 2021 and November 2021. Four organic residues (ORs) with contrasting total nitrogen levels and elemental compositions were selected based on previous studies [38]. These ORs included woody, lignified, and nitrogen-poor feedstock (bamboo) and feedstocks enriched in labile nitrogen, such as chicken manure, shrimp carcass, and sunflower cake. The selected feedstocks were subjected to pyrolysis in a stainless-steel chamber at 300 °C, resulting in four biochars with distinct chemical and physicochemical properties, as well as varied mineral and total nitrogen contents (Table 1). Prior to pyrolysis, the feedstocks were dried in a circular oven at 70 °C until they reached a constant weight. The pyrolysis process was conducted in a muffle furnace equipped with a gas condenser, enabling carbonization of the organic residues under minimal or no oxygen conditions. The heating rate was set at 10 °C per minute until the target temperature (300 °C) was reached and maintained for 60 min. After pyrolysis, the process was terminated, and the samples were allowed to cool to room temperature. The resulting biochars were then ground with a marble pestle and sieved through a 0.5 mm mesh for subsequent analyses and soil applications.

Table 1. Values of pH, electrical conductivity (EC), total carbon (C) and nitrogen (N) content, and soluble mineral nitrogen (ammonium and nitrate) in biochars pyrolyzed at 300 °C and their precursor feedstocks.

N Source	pH	EC ($mS\ cm^{-1}$)	Total C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	$N\text{-}NH_4^+$ ($mg\ kg^{-1}$)	$N\text{-}NO_3^-$ ($mg\ kg^{-1}$)
Bam	6.6	1.1	479	4	78.7	65.0
Bam300	7.2	0.5	772	5	78.7	34.2
SC	5.3	25.6	336	41	160.7	44.5
SC300	8.3	31.3	430	49	2889.9	136.8
CM	7.5	7.5	250	33	1607.4	2384.7
CM300	9.6	6.6	309	37	253.1	147.1
SCa	7.9	7.8	435	89	745.6	547.2
SCa300	9.4	8.3	472	75	242.8	218.9

The pH was determined in a ratio of biochar/biomass:water of 1:10 (w/v). Total N was determined by the Kjeldahl method; and total C was determined by dry combustion in a TOC automatic analyzer. $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ were extracted with a 1 mol L^{-1} KCl solution at a 1:10 (w/v) ratio, following the analytical protocol proposed by Bremner & Keeney [39]. The different precursors are their biochars are abbreviated as follows: Bam, bamboo; Bam300, bamboo biochar pyrolyzed at 300 °C; SC, sunflower cake; SC300, sunflower cake biochar pyrolyzed at 300 °C; CM, chicken manure; CM300, chicken manure biochar pyrolyzed at 300 °C; SCa, shrimp carcass; SCa300, shrimp carcass biochar pyrolyzed at 300 °C.

2.2. Soils and Experimental Conditions

The maize cultivation experiment was conducted under greenhouse conditions from November 2021 to February 2022, with plants grown in two Oxisols characterized by the chemical and physicochemical properties shown in Table 2. The maize used was the DK390PRO hybrid (DEKALP®, DeKalb County, IL, USA), as it is a hybrid with high yield potential and a strong response to fertilization. During maize cultivation in the greenhouse, the temperature was maintained at 32 °C for 12 h (daytime) and at 20 °C for 12 h (nighttime). The soil samples were classified according to Soil Taxonomy (Soil Survey Staff, 2022) as Oxisols and under the Brazilian Soil Classification System as Dystroferric Clayey Red Latosol (LVd) and Red-Yellow Medium-Textured Latosol (LVa) [40]. Bamboo, sunflower cake, chicken manure, and shrimp carcass feedstocks, along with their respective biochars produced at 300 °C, were incorporated into the two Oxisols. The biochars, combined or not with ammonium nitrate (reagent grade, Synth), were added to Oxisols to supply to maize plants with 300 mg kg^{-1} of N. In the LVd soil, liming was performed to increase the availability of calcium (Ca) and magnesium (Mg) to optimize maize growth, targeting a soil pH of 6.0. The limed soil was incubated for 30 days with calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) (reagent grade, Synth), while maintaining soil moisture at approximately 70% of the maximum water-holding capacity (MWHC). In contrast, the LVa already had an ideal pH, sufficient Ca, and Mg levels for optimal maize growth, so liming was not performed. Prior to the liming and fertilization practices, the soil samples were air-dried, sieved (2 mm), and analyzed in the laboratory to determine the main chemical and physicochemical properties of the Oxisols (Table 2).

The experimental unit consisted of plastic pots filled with approximately 0.8 kg of soil. Pots with a height of 14 cm and a diameter of 16 cm were used for plant cultivation. The experiment was conducted using a randomized block design (RBD) with three replicates, encompassing 14 treatments. The treatments were as follows: four feedstocks (Bam, SC, CM, SCa) and their respective biochars (Bam300, SC300, CM300, SCa300), each added to the soil at a single dose of 2.7 g per pot. The tested biochar dose was based on the amount required to reach 300 mg kg^{-1}, using the minimum necessary quantity for the source with the highest N content (shrimp carcass) as a reference. From this, the amount of biochar and feedstock applied was standardized. These were tested either alone or combined with 300 mg kg^{-1} N as ammonium nitrate (Bam300 + N, SC300 + N, CM300 + N, SCa300 + N). Additionally, the experiment included a positive control (300 mg kg^{-1} N supplied exclusively as ammonium nitrate) and a negative control (no nitrogen added to the soil). All tested treatments are summarized in Table 3. The raw feedstocks, biochars, biochars combined with ammonium nitrate, and pure ammonium nitrate were homogeneously mixed with the entire soil mass (0.8 kg) before sowing. According to the amounts of materials applied and their nitrogen content (Table 1), the N input for each treatment was calculated per pot, as shown in Table 3.

Table 2. Chemical, physicochemical, and soil particle size distribution of the soil used.

Parameters	LVd	LVa
pH (1 g of soil: 2.5 mL of water)	4.3	5.8
EC (mS cm^{-1})	0.16	0.25
Total carbon (g kg^{-1})	46	11
Total nitrogen (g kg^{-1})	4.5	1.3
Clay (g kg^{-1})	750	230
Silt (g kg^{-1})	110	25
Sand (g kg^{-1})	140	745

The soil pH was determined in deionized water at a ratio of 1:2.5 (*w/v*). Silt, clay and sand were determined by the Boyoucos method. Soil C content was determined using the dry combustion method in an automatic TOC analyzer, Elementar, model Vario Cube. EC denotes electrical conductivity. The Dystroferric Red Latosol (LVd) is defined as clayey Oxisol and the Yellow Latosol (LVa) is defined as a middle texture Oxisol by the Brazilian Soil Classification System.

Table 3. Tested treatments in the greenhouse experiment.

Acronym of Treatment	Description of Treatments Applied	N Input (mg pot^{-1})
Bam	Bamboo (feedstock) (2.7 g pot^{-1})	10.8
Bam300	Bamboo-derived biochar (2.7 g pot^{-1})	13.5
Bam300 + N	Bamboo-derived biochar (2.7 g pot^{-1}) plus ammonium nitrate (300 mg kg^{-1} of N)	253.5
SC	Sunflower cake (feedstock) (2.7 g pot^{-1})	110.7
SC300	Sunflower cake-derived biochar (2.7 g pot^{-1})	132.3
SC300 + N	Sunflower cake-derived biochar (2.7 g pot^{-1}) plus ammonium nitrate (300 mg kg^{-1} of N)	372.3
CM	Chicken manure (feedstock) (2.7 g pot^{-1})	89.1
CM300	Chicken manure-derived biochar (2.7 g pot^{-1})	99.9
CM300 + N	Chicken manure-derived biochar (2.7 g pot^{-1}) plus ammonium nitrate (300 mg kg^{-1} of N)	339.9
SCa	Shrimp carcass (feedstock) (2.7 g pot^{-1})	240.0
SCa300	Shrimp carcass-derived biochar (2.7 g pot^{-1})	202.5
SCa300 + N	Shrimp carcass-derived biochar (2.7 g pot^{-1}) plus ammonium nitrate (300 mg kg^{-1} of N)	442.5
OS	Without the application of ammonium nitrate, biochar, and/or feedstock.	0
NAM	Only application of ammonium nitrate (300 mg kg^{-1} of N)	240

At sowing, nutrients were supplied at the following concentrations: 150, 150, 100, 40, 0.81, 1.33, 3.66, 0.15, 4, and 1.55 mg kg^{-1} of N (when applicable), P, K, S, B, Cu, Mn, Mo, Zn, and Fe, respectively. These nutrients were provided using the following sources: $NH_4H_2PO_4$, K_2SO_4, H_3BO_3, $CuSO_4{\cdot}5H_2O$, $MnCl_2{\cdot}4H_2O$, $(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$, $ZnSO_4{\cdot}7H_2O$, and $FeCl_3{\cdot}6H_2O$ (reagent grade, Synth) [41].

Water was added to maintain the soil moisture at approximately 70% of its maximum water-holding capacity (MWHC), and five maize seeds were sown per pot. Ten days after sowing, thinning was performed to leave two plants per pot. Topdressing fertilization was applied 15 days after planting, adding 150 mg kg^{-1} of N and K to the soil, supplied by NH_4NO_3 and K_2SO_4 (reagent grade, Synth). The topdressing fertilization was carried out to supplement the required amount of N and K, highlighting that ammonium nitrate was applied half at planting and half during topdressing fertilization. The maize plants were cultivated under greenhouse conditions for 30 days.

2.3. Soil and Solution Sampling

At the start of maize cultivation, 12 h after the application of nitrogen (N) and potassium (K) to the soil samples, the soil moisture was adjusted to approximately 70% of the maximum water holding capacity (MWHC). Subsequently, a 20 mL aliquot of the soil solution was collected. For this purpose, the Suolo Acqua® (Lavras, Brazil) soil solution sampler [42] was used. The sampler was placed in the center of the pot during its filling with soil, and the soil solution was extracted through a vacuum tube. The samples were filtered using a 0.45 µm pore-diameter cellulose membrane, and the pH of the soil solution was measured with a Hanna Instruments bench pH meter (HI2221 model) as showed in Tables A1 and A2. Fifteen days after sowing, during maize cultivation, soil solution samples were collected again following the same procedure.

The concentrations of N-NO_3^- and N-NH_4^+ in the soil solution were quantified through a process involving extraction, distillation, and titration of the nitrogen evolved from the samples as ammonium borate, according to the method described by Bremner and Keeney [39]. For the analysis, a 5 mL aliquot of the extracted solution was pipetted into a distillation tube. Ten milliliters of deionized water and 0.2 g of magnesium oxide (MgO) were added to create an alkaline medium, facilitating the conversion of NH_4^+ into ammonia (NH_3). For the determination of N-NO_3^-, after quantifying NH_4^+-N, 0.2 g of Devarda's alloy was added to the same distillation tube, generating a reducing environment to convert N-NO_3^- into NH_3. In both cases, the ammonia evolved from the distillation was collected at the condenser outlet into an Erlenmeyer flask containing 10 mL of boric acid-based indicator solution. The collected ammonia was then titrated with a 0.07143 mol L^{-1} HCl solution.

Eighteen hours after planting, and again at the end of the maize cultivation period, a 30 g soil sample was collected from each experimental unit. These samples were dried, macerated, and sieved (0.5 mm) for further analysis. The contents of N-NH_4^+ and N-NO_3^- in the whole Oxisols were determined following adaptations of the method proposed by Bremner and Keeney [39]. In this procedure, 2.5 g of soil was placed into a 50 mL Falcon tube and mixed with 25 mL of a 1 mol L^{-1} KCl solution. The mixture was shaken for one hour on a pendulum shaker at 100 rpm and allowed to settle for at least 12 h to separate the solid phase from the liquid extract. A 15 mL aliquot of the extract was transferred to a distillation tube, and the nitrogen content was determined using the previously described analytical method. The pH of the soil samples was measured in a soil–water suspension at a 1:2.5 ratio.

2.4. Maize Growth and N Nutritional Status

At the end of maize cultivation, the SPAD index was measured using the SPAD-502 Plus chlorophyll meter. The plants were then harvested and separated into shoots and roots, which were dried in an oven with air circulation at 60 °C until a constant weight was achieved. The maize biomass was weighed, and the shoot dry matter (SDM) was added to the root dry matter to calculate the total dry matter of the maize. To quantify nitrogen (N) accumulation in the maize shoots, the total N content was first determined using the Kjeldahl method [43]. The N accumulation in the shoots was then calculated by multiplying the total N content of the samples by the respective shoot dry matter for each experimental unit.

2.5. Statistical Analysis

All statistical analyses were conducted using R software version 4.3.1 [44] with the tidyverse, corrplot, and ExpDes.pt packages [45,46]. Fourteen treatments were tested as shown in Table 3. Therefore, the analysis of variance was conducted accordingly, such that for each variable analyzed, the 14 treatments were compared with each other. Initially, the data were subjected to analysis of variance (ANOVA) to verify compliance with the basic assumptions of the test. For significant differences among treatments identified during the ANOVA ($p < 0.05$), the treatment means were grouped using Scott–Knott's test ($p < 0.05$).

3. Results

3.1. Soil Available Nitrogen

The mineral N contents in Oxisols treated with feedstocks, biochars, and biochars combined with ammonium nitrate (AN) are shown in Figure 1. At the start (Figure 1a,b) and the end of maize cultivation (Figure 1c,d), ammonium-N levels exceed nitrate-N levels. In the Dystroferric Red Oxisol (LVd), the availability of mineral N (ammonium + nitrate) is the highest in experimental units receiving N in the form of ammonium nitrate and biochars derived from bamboo + AN and shrimp carcass + AN. Conversely, soils treated with the feedstocks used to produce the biochars in this study displayed the lowest levels of readily available N. In the LVd, the mineral N availability in the unfertilized soil is like that in soils treated with sunflower cake and chicken manure biochars (Figure 1a). In the soil with lower organic matter content, the Red Yellow Oxisol (LVa), more N is available to maize with the exclusive use of AN, followed by treatments combining biochars and AN. In this sandier soil, ammonium-N predominates; although, nitrate-N levels vary across treatments (Figure 1b). The addition of biochars to the soil without N supplementation results in reduced N availability, with N levels falling below the optimal range (150–250 mg kg^{-1}) for maize cultivation in pots. Supplying N via non-pyrolysed feedstocks does not ensure sufficient N for full maize growth. Interestingly, the available N levels in samples without added N (negative control) exceed those in some soils treated with biochars or their feedstocks, indicating potential N immobilization while also demonstrating the natural capacity of both Oxisols to supply soluble N for maize (Figure 1a,b).

The residual available mineral N in the Oxisols after maize cultivation was lower compared to the levels observed at the start of maize cultivation (Figure 1c,d). In the LVd, the highest residual ammonium levels were found in the SC300 treatment, followed by Bam, SC300 + N, SCa, and SCa300 + N, compared to the exclusive use of ammonium nitrate as a N source to maize (Figure 1c). Similarly, the highest residual nitrate levels in the LVd were observed in the Bam, Bam300 + N, SC, SC300, and CM300 treatments, over soils treated with ammonium nitrate (Figure 1c). In the LVa, the highest residual ammonium levels were verified in the SC treatment, exceeding those found in soil samples treated with ammonium nitrate (Figure 1d). Regarding nitrate-N levels in the LVa, use of AN accounted for the highest levels of nitric N, with reductions observed only in the Bam300, CM300, and negative control (no N addition) treatments (Figure 1d). Overall, residual mineral N levels varied across treatments but remained below the optimal range for maize cultivation in pots. In both Oxisols, residual mineral N levels were below 75 mg kg^{-1}, with ammonium-N consistently prevailing over nitrate-N. Despite the reduced availability, residual mineral N levels were higher in the high-OM clayey Oxisol (LVd) than in the medium-textured Red Yellow Oxisol (Figure 1c,d).

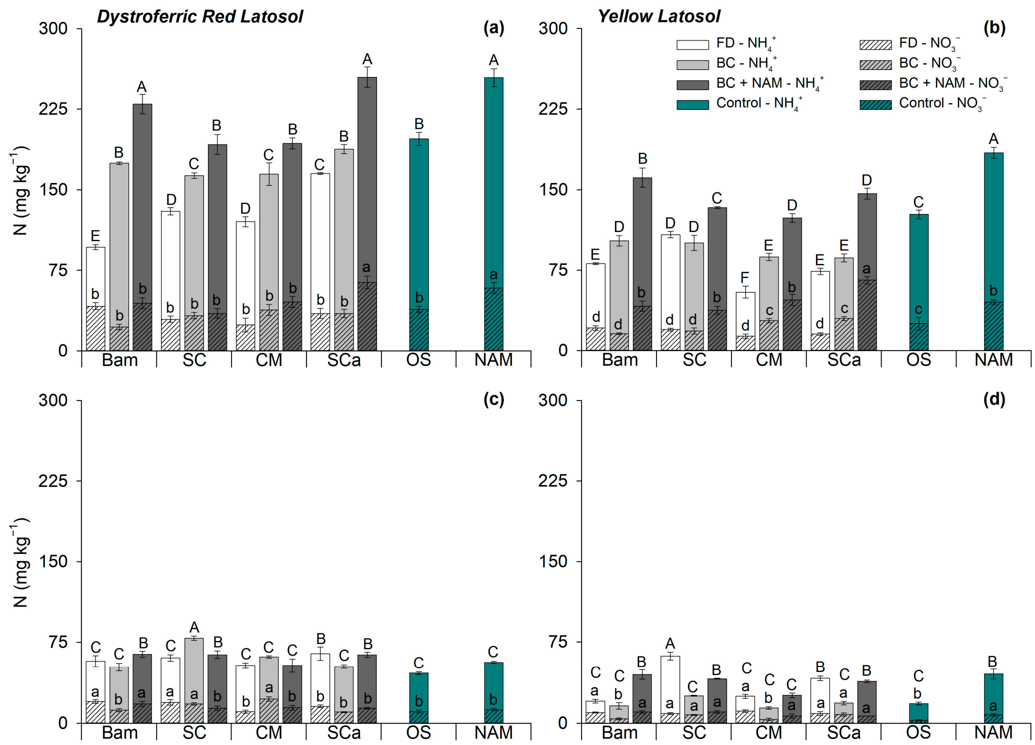

Figure 1. Initial (**a**,**b**) and residual (**c**,**d**) contents of mineral N in Oxisols (Dystroferric Red Latosol and Yellow Latosol) as related to the feedstocks (FD) and their derived biochars (BC), combined or not with ammonium nitrate (NAM). Treatment means with standard errors followed by the same uppercase or lowercase letters do not differ in ammonium and nitrate contents, respectively, according to the Scott–Knott test ($p < 0.05$). Bam, bamboo; SC, sunflower cake; CM, chicken manure; SCa, shrimp carcass; OS, only soil, without N addition (negative control); and NAM, ammonium nitrate (positive control).

3.2. Nitrogen in Soil Solution

The levels of nitrate-N, ammonium-N, and mineral N (ammonium + nitrate) in the solution of the clayey Oxisol are shown in Figure 2. The N levels in the solution exceed those measured in the whole soil. As maize cultivation progresses, ammonium-N and nitrate-N levels in the soil decrease significantly (Figure 2). At the start of maize cultivation, nitrate-N levels in soils treated with SCa + AN and AN alone exceeded 1100 mg L^{-1}, surpassing those levels of ammonium-N (Figure 2c,d). Overall, the combined use of biochar and AN promoted the prevalence and high levels of nitrate-N in the LVd solution. The availability of mineral N varied according to the treatment (N source) and solution sampling time, with lower N levels observed in soils treated with feedstocks or with their derived biochars over the combined use of biochar + AN. At the beginning of maize cultivation, mineral N levels were elevated in soils where biochar was combined with AN. After 15 days of maize sowing, there was a marked reduction in N level, which was less pronounced in soils treated with biochar + AN or AN alone (Figure 2e,f). Conversely, the absence of N application (negative control) resulted in the lowest levels of ammonium-N, nitrate-N, and mineral N in the LVd over soil samples fertilized with the other N sources.

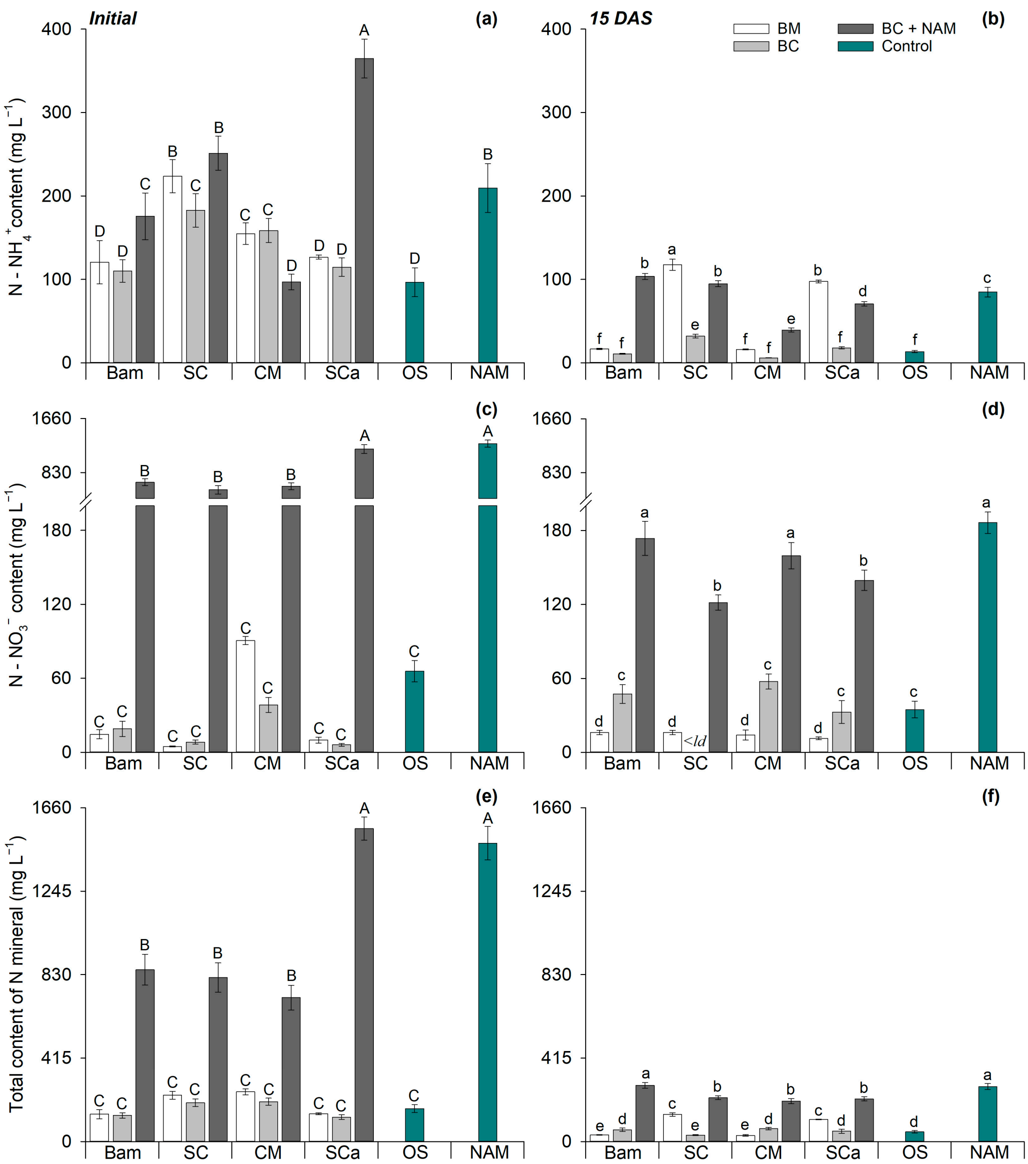

Figure 2. Initial and 15-day-after-maize-sowing (DAS) contents of N-NH_4^+ (**a**,**b**), N-NO_3^- (**c**,**d**), and total content of mineral N (**e**,**f**) in the soil solution collected from a Dystroferric Red Latosol cultivated with maize as related to feedstocks (FD) and their derived biochars (BC), combined or not with ammonium nitrate (NAM). Treatment means with standard errors followed by the same letters do not differ according to the Scott–Knott test ($p < 0.05$). Bam, bamboo; SC, sunflower cake; CM, chicken manure; SCa, shrimp carcass; OS, only soil; NAM, Ammonium nitrate; BM, biomass; BC, biochar; BC + NAM, biochar + ammonium nitrate; and <*ld*, values below the detection limit.

Compared to LVd, there was a predominance of N-NH_4^+ over N-NO_3^- in the medium-textured Oxisol (LVa). In the LVa, ammonium levels in the solution were the highest for the Bam300 + N and SC300 + N treatments, followed by the exclusive use of ammonium nitrate and samples under the influence of the CM300 + N treatment (Figure 3a). At 15 DAS, the highest ammonium levels were observed in the SC300 + N and ammonium nitrate treatments (Figure 3b). Nitrate levels in the solution were higher with the simultaneous application of biochar and ammonium nitrate, compared to the exclusive application of ammonium nitrate (Figure 3c). Over time, ammonium-N decreases, while nitrate-N increases in treatments where biochars were simultaneously added to the soil with ammonium nitrate. Regardless of the solution sampling time, the combined use of biochar + AN or AN alone provides maize plants with more mineral N (ammonium + nitrate) than feedstocks and their raw biochars. The supply of nitrate-N to plants becomes limited after 15 DAS in treatments in which feedstocks and biochars without AN were used as N sources to the plants (Figure 3d).

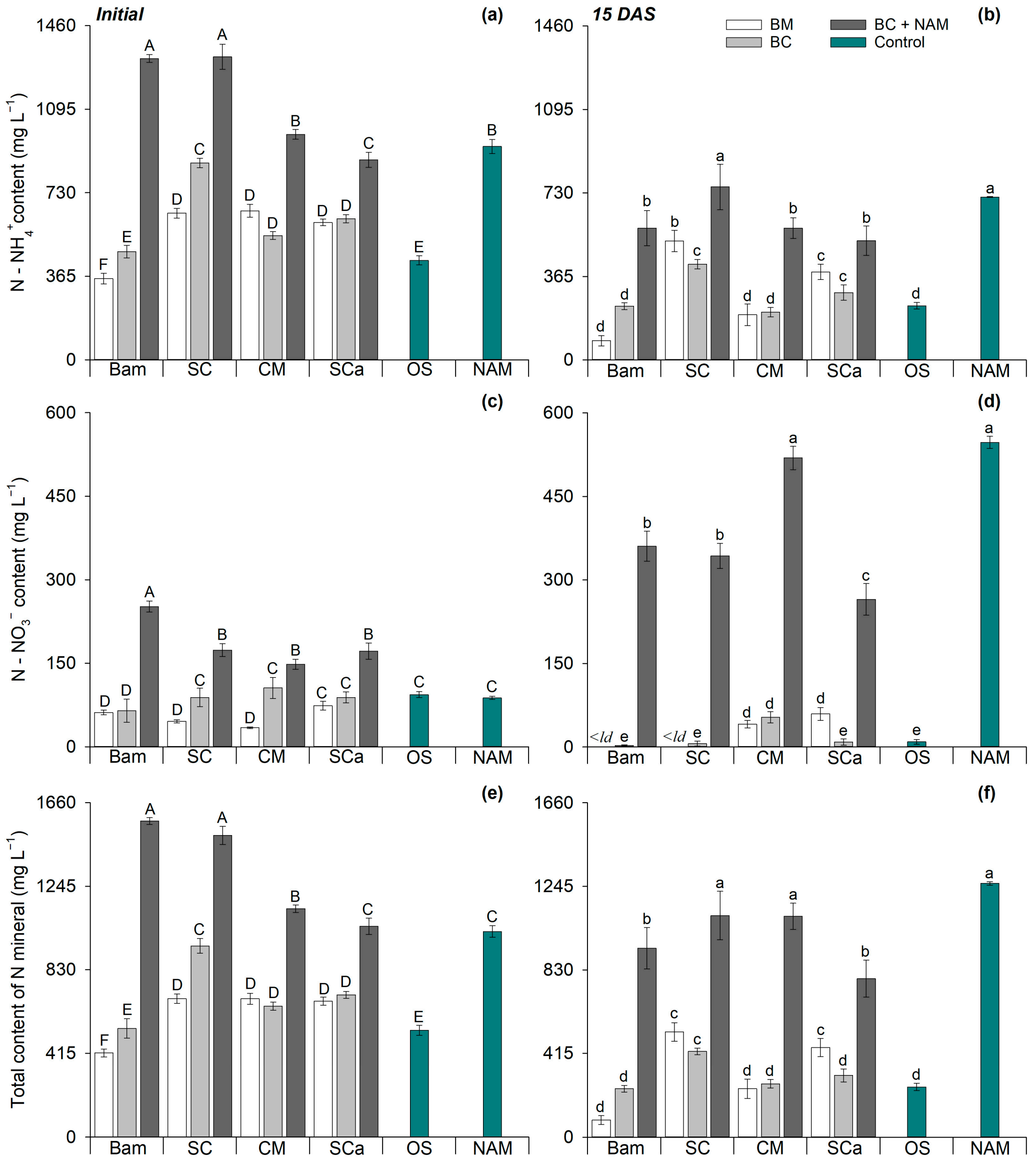

Figure 3. Initial (**a**,**c**) and 15-day-after-maize-sowing (**b**,**d**) contents of N-NH_4^+ (**a**,**b**), N-NO_3^- (**c**,**d**), and total content of mineral N (**e**,**f**) in the soil solution collected from the Yellow Latosol (medium-textured Oxisol) cultivated with maize and treated with feedstocks (FD) and their derived biochars (BC), combined or not with ammonium nitrate (NAM). Treatment means with standard errors followed by the same letters do not differ according to the Scott–Knott test ($p < 0.05$). Bam, bamboo; SC, sunflower cake; CM, chicken manure; SCa, shrimp carcass; OS, only soil, without N addition; NAM, ammonium nitrate; and <*ld*, values below the detection limit.

3.3. Maize Nutrition and Growth

The SPAD index varies depending on the nitrogen (N) sources supplied to the maize, particularly in plants fertilized with ammonium nitrate alone or in combination with biochars in both Oxisols. However, the SPAD index patterns do not correspond to N accumulation in maize shoots (Figure 4a,b). Although plants exposed to shrimp carcass and sunflower cake biomasses exhibit high SPAD values, suggesting an optimal N nutritional status, this does not align with actual N accumulation in maize shoots across these treatments. Regardless of the N source, maize grown in the clayey Oxisol accumulates more N in its shoots than plants grown in the medium-textured Oxisol. In the clayey Oxisol, maize fertilized with ammonium nitrate (AN) or AN combined with sunflower cake (AN + SCa) accumulates more N in its shoots than plants under the effect of other N sources. In contrast, the lowest shoot N levels occur in plants fertilized with N derived from non-pyrolyzed biomass. Overall, shoot N accumulation does not account for variations in dry matter production in response to different N sources (Figure 4c,d). On the contrary, excess N leads to reduced dry matter production in soils amended with shrimp carcass and chicken manure biochars combined with AN.

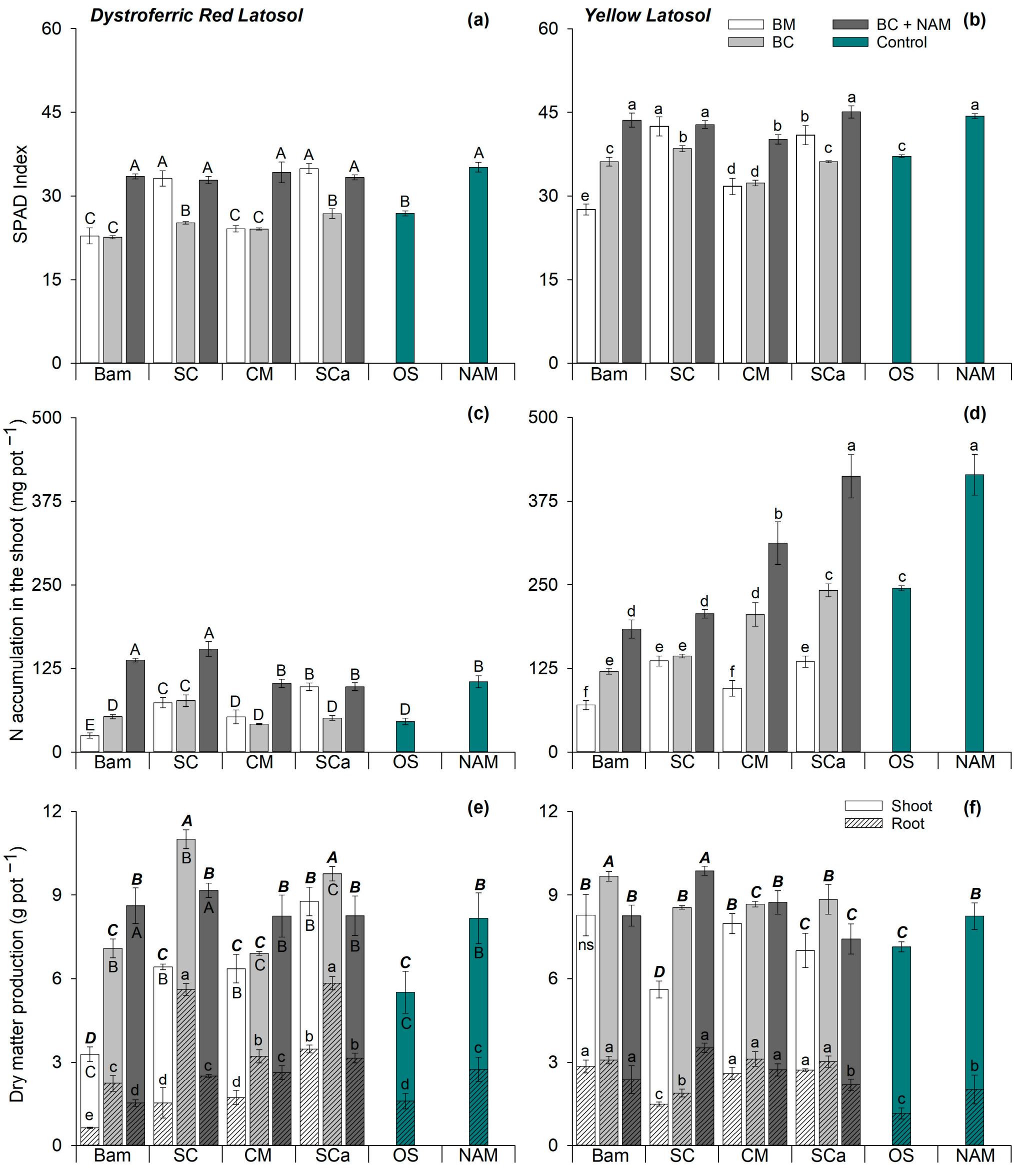

Figure 4. SPAD index (**a**,**b**), N accumulated (**c**,**d**) in the shoots, and total dry matter (DM = shoot + root) (**e**,**f**) of maize grown in contrasting Latosols, under the influence of different feedstocks and their respective biochars, combined or not with ammonium nitrate. Treatment means with standard errors followed by the same letters do not differ according to the Scott–Knott test ($p < 0.05$) for SPAD index and N accumulation in the shoots (**a**–**d**). Treatment means with standard errors followed by the same italic bold-uppercase, uppercase, or lowercase letters do not differ in total (full bar), shoot, or root dry matter production (**e**,**f**), respectively, according to the Scott–Knott's test ($p < 0.05$). Bam, bamboo; SC, sunflower cake; CM, chicken manure; SCa, shrimp carcass; OS, only soil; NAM, ammonium nitrate; and <*ld*, values below the detection limit.

Results shown in Figure 4e,f illustrate root and shoot dry matter production as affected by N sources. The highest total dry matter production (root + shoot) is observed in the clayey Oxisol, where maize fertilized with sunflower cake biochar (+19%) and shrimp carcass biochar (+30.2%) outperforms that fertilized exclusively with AN. Soil type influences maize growth depending on the supplied N source. In clayey Oxisol, supplemental mineral N is unnecessary in soils amended with shrimp carcass and sunflower cake biochars. Overall, non-pyrolyzed biomass immobilizes soil N to the extent that plants produce less biomass than the control, which received no additional N. However, combining chicken manure and bamboo biochars with AN sustains maize biomass production at levels comparable to those fertilized exclusively with AN. Shrimp carcass biochar promotes proportionally greater root growth relative to shoot growth. In the medium-textured Oxisol, plants fertilized with bamboo biochar or sunflower cake biochar combined with AN produce ~12% more biomass than those fertilized exclusively with AN. The natural N supply from organic matter supports average maize biomass production and potentially reduces N immobilization in soils amended with only with feedstocks low in N and their derived biochars. N supplementation with AN is necessary only for plants fertilized with sunflower cake biochar (Figure 4f).

4. Discussion

The use of biochars combined with ammonium nitrate altered soil nitrogen (N) dynamics by influencing its availability in the whole soil and soil solution, as well as N uptake by plants, in a soil type-dependent manner. The availability of mineral N in the soil varies depending on the N source, with higher mineral N levels observed in soils treated with biochars compared to those in which plants were nourished with N from the biochar precursor feedstock. The addition of 300 mg kg^{-1} N as ammonium nitrate significantly increases available N in the soil compared to other treatments.

In mineral soluble fertilizers, N is readily available, whereas the N chemical species in biochar depend on the feedstock N content and the intensity of charring conditions [4,31]. In this study, only a few N sources exhibited mineral N availability in the whole soil comparable to that of ammonium nitrate (AN). In the whole soil, ammonium-N predominates over nitrate-N, particularly in biochar and biochar mixed with AN. Mixing AN with biochar results in lower mineral N availability than the exclusive use of AN, suggesting that part of the mineral N may be immobilized within the biochar matrix, native soil organic matter, or soil biota. This interaction between applied nitrogen and biochar has also been demonstrated in a study using biochars derived from coffee husk and chicken manure, indicating that the main mechanisms involved in this interaction and N retention include adsorption through electrostatic bonds at the CEC, the formation of N precipitates such as struvite, and physical adsorption of ammonium-N in biochar pores [37]. In addition to low N content, biochars exhibit a high C/N ratio. Consequently, depending on the application rate and water-soluble C content, these materials are prone to immobilizing mineral N in soils [9,10]. Over time, the combined use of some biochars with AN increases nitrate-N availability in Oxisol solutions, with nitrate-N levels from AN exceeding those found in soils treated with most biochars and their pristine feedstocks.

Biochar is believed to increase soil nitrification rates, particularly in low-fertility soils, which is partially explained by biochar's liming effect and its ability to influence the activity and structure of soil nitrifying bacteria [47]. In this study, ammonium-N prevailed over nitrate-N in whole Oxisols; although, nitrate-N levels in soils fertilized with biochar combined with AN were higher than in soils treated with other N sources, particularly in soil solution. Biochar can act as an electron shuttle, potentially promoting dissimilatory nitrate reduction to ammonium, thereby contributing to higher ammonium levels, as observed in our study [48].

The high levels of nitrate in soil solution in the beginning of maize cultivation are concerning, as nitrogen in the ammonium-N form is much less susceptible to loss than nitrate-N. The high levels of nitrate in the soil solution are probably explained by AN itself rather than the biochar effect on nitrification. While NH_4^+ can be adsorbed by soil colloids with minimal downward movement, NO_3^- is not easily adsorbed, remains in soil solution, and can be leached into deeper soil layers, potentially contaminating groundwater [49,50].

Native organic soil matter plays a crucial role in controlling the availability of N in the investigated Oxisols. Although N mineralization is greater in undisturbed than in disturbed soil samples [51], the mineral N content in disturbed soil—possibly due to an increased OM mineralization rate—is equal or even exceeds the amounts of mineral N released into the soil by the feedstocks and their derived biochars, despite no additional N being supplied to nourish maize plants. In a study involving the application of biochar-based fertilizers derived from the composting process, effects similar to those found in this study were observed, where, due to soil disturbance, there was an increase in and high levels of mineral nitrogen in the soil solution [52].

Regardless of the evaluated N source, mineral N content is higher in the clayey Oxisol than in medium-textured Oxisol. Soil N availability depends on the organic matter content and the turnover of organic N into mineral N through mineralization [53]. Overall, available N levels in the whole Oxisol samples vary; but, in most treatments, they fall within the range considered optimal for full maize growth. The amount of N required in the soil for adequate plant growth varies among crops and is also influenced by root depth. Overall, in field trials, N levels in whole soil samples should not fall below 10 mg kg^{-1}; and should not exceed 50 mg kg^{-1}. For a set of Brazilian soils, maize N uptake was strongly correlated with potentially mineralized soil N, with 130 mg kg^{-1} N identified as sufficient for optimal N uptake in plants grown under greenhouse conditions [54].

In whole soil samples, the NH_4^+:NO_3^- ratio varied according to soil type and the N source added to the evaluated Oxisols. Nitrate and ammonium are the primary forms of nitrogen taken up by plants; although, some plants can also absorb amino acids. Maize growth and yield are favored by an ammonium-N:nitrate-N ratio close to 50%:50%. A NO_3^-:NH_4^+ ratio of 1:1 at two weeks after planting resulted in higher maize grain yields (6097 kg ha^{-1}) compared to a 1:0 (5415 kg ha^{-1}) or a 0:1 (5328 kg ha^{-1}) ratio. A NO_3^--N:NH_4^+-N ratio of 1:0 does not adequately meet plant N requirements, whereas a 0:1 ratio led to ammonium toxicity effects [55]. The ammonium:nitrate ratio affects gene expression, plant growth, and development, as the exclusive presence of ammonium induces anthocyanin accumulation, while reducing biomass, chlorophyll, and flavonoid accumulation [56]. Ammonium and nitrate have distinct effects on plant physiology. Compared to nitrate, ammonium reduces root growth and leaf surface area, limiting CO_2 fixation and thereby restricting plant growth. However, due to energy savings and easier metabolism in ammonium-treated plants, the CO_2 assimilation rate is higher than in crops exclusively nourished with nitrate-N [57].

Regardless of the N source supplied to plants, at the end of maize cultivation, the remaining levels of mineral N in the soil (residual N) are relatively low and insufficient to meet the N requirements of most crops. Such reduced levels of available N are common for mineral fertilizers such as ammonium nitrate, and the results of this study indicate that additional N fertilizer is required for plants grown in succession to maize. Conversely, according to Carvalho et al. [58], biochar-based N fertilizer (BBF), formulated with urea and derived from coal processing fines for steel production, exhibited a greater residual effect compared to the exclusive use of urea for oat nutrition. This effect was attributed to the slow N release from BBF. In agreement with Carvalho et al. [58], the combined use of mineral N and biochar improves N use efficiency in crops and enhances residual N levels in soils after corn harvest. This approach is promising for the development of novel fertilizers with improved agronomic efficiency to supply N to crops.

Biochar supplies more N in available forms for crops than its precursor feedstock [15,59], which aligns with the results reported in this study. Soil type is a key factor influencing N availability in response to the different N sources tested. The use of biochars derived from chicken manure and shrimp carcass increased the availability of nitrate-N in the soil to levels even higher than those observed in treatments where N was supplied as ammonium nitrate. The two Oxisols examined in this study have different capacities to supply N for maize. The LVd (clayey Oxisol) was able to provide greater amounts of N than most feedstocks and their derived biochars when added to the medium-textured Oxisol (LVa). According to Morais et al. [60], N availability in soils was initially higher in BBF-treated soils compared to soils treated with mineral N fertilizers. However, the effects of BBFs on N availability, both in whole soil and in soil solution, did not significantly influence N uptake by maize shoots or overall plant N accumulation. These findings suggest that the similarity in plant N uptake between BBFs and NPK mineral fertilizers cannot be solely explained by the amount of N added through fertilization. N in biochar exists in various organic forms, with its mineralization rate controlled by decomposer activity and abiotic factors, such as soil type [61]. Since a significant portion of N in BBFs is in organic forms, biochar N-doped matrices are more prone to gradual mineralization over time, leading to increased residual soil N levels in the long term, for crops cultivated in succession after maize [60]. However, regardless of the N source, after maize is cultivated in pots, the residual N in the whole Oxisol reduced and was insufficient for plants in succession, even in soils treated with readily available N from urea [30]. Therefore, further sequential field experiments should be conducted under real field conditions to assess the potential of biochar-based N fertilizers to supply and sustain crop nutrition over the medium and long term in soil types with different organic matter contents.

The soil–biochar interaction exerts a strong influence on the prevalence of the nitric-N form in solution over N in the NH_4^+ form. In the clay Oxisol, nitrate-N prevails over N-ammonium, mainly in the samples treated with biochar + ammonium nitrate. In addition, the ammoniacal-N form predominates in the clayey Oxisol at levels exceeding 1000 mg kg^{-1}, which far exceeds the threshold content range recommended for plentiful maize growth in nutritive solutions. Availability of N-nitrate or N-ammonium in the solution is regulated by the soil type–N source interaction [10,62]. Nitrogen is available in the soil solution at greater levels than those determined in whole soil. In fact, N was found in the soil solution at levels that exceeded the optimal range of mineral N (80–160 mg L^{-1}) for the full growth of plants in nutrient solutions, e.g., hydroponic solutions [63]. This prevalence of N-ammonium over N-nitrate in treatments where biochar was combined with ammonium nitrate is thought to hinder maize growth due to excess available N, and an imbalance in the ammonium ratio decreases maize growth, which is favored when the NH_4^+:NO_3^- ratio is found in soils in a balanced proportion, ideally at a ratio greater than 1:1 [64].

When added to the two Oxisols, biochars favor the nitrification process; although, this effect is restricted to the weathered soil with the highest clay and OM contents (clayey Oxisol). In fact, the nitrification process is enhanced by the presence of biochar in the soil, but it takes time for the biochar matrix to play a role in the conversion of ammonium into nitrate [8–10]. In the medium-textured Oxisol (LVa), there is only a greater availability of nitrate-N in soil samples after 15 days of maize cultivation. The role played by N sources in soil available N depends on their interaction with soil constituents; thus, the prevalent form of N in the soil requires further study. In addition, it is necessary to verify the main features and biochar properties that influence the nitrification rate, which is specific for each soil type. The levels of mineral N in the solution of both Oxisols exceeded the levels of mineral N in the whole soil. It is necessary to investigate if the high levels of ammonium and, mainly, nitrate, are detrimental to maize nutrition and growth.

Equally important is the need to evaluate the positive priming effect of soil structure disruption on increasing the decomposition rate of native soil organic matter and soil nutrient availability. In soil, the use of biochar—depending on its application rate and composition—can either enhance or hinder the supply of N to crops due to increased N immobilization by soil biota and within the biochar structure itself [10,65]. Beyond its high N content, an imbalance in the forms of N supplied to maize exists within the soil solution. To date, this is the first study to evaluate ammonium and nitrate levels, as well as their ratios, in whole soil and soil solution for maize biomass production in response to biochar, organic residues, and ammonium nitrate as N sources. To the best of our knowledge, this is also the first time that mineral N contents have been analyzed in the soil solution of highly weathered Brazilian soils. Our findings indicate that native soil organic matter plays a key role in the exceptionally high mineral N content observed in the Oxisol solutions. At least in pot experiments, organic matter can effectively contribute to increasing readily available N in the solution for maize grown in disrupted cultivated Oxisols. Surprisingly, the mineral N levels in the soil solution exceed the critical thresholds recommended for plant growth in nutrient solutions and hydroponic media. For instance, some crops, such as lettuce and leafy greens, typically require 150–200 mg L^{-1}, while fruiting crops like tomatoes and peppers may require 200–300 mg L^{-1} at peak growth stages [63,66].

The effects of N dynamics modified by the addition of biochars and their conjugated use with ammonium nitrate demonstrate a direct impact on variables such as dry mass, N accumulation, and the SPAD index, which is used indirectly to assess the N nutritional status [67,68]. In this study, the SPAD index did not reflect the availability of N in the soil and does not anticipate the N accumulated by maize, nor can it predict the effects that the soil types and treatments studied have on the production of maize biomass. This indicates that maize leaf greenness reflects higher levels of N uptake by maize when fertilized with organic residues, biochars, and biochar + ammonium nitrate, mirroring the photosynthesis rate and chlorophyll content in maize leaves. Thus, it is possible to infer the N nutritional status of maize plants through a quick reading with a chlorophyll meter (SPAD index). Furthermore, it is evident that, in general, the maize growth indices (SDM, NAc, SPAD) are positively correlated with the levels of mineral N (N-NH_4^+ and N-NO_3^-), both in whole soil and soil solution; although, the variability of maize biomass is better explained by the availability of N in the soil solution. Therefore, the uptake and accumulation of N by maize plants are partially controlled by the availability of N in the Oxisol solution rather than by the N in the whole Oxisol.

Overall, the accumulation of N in maize plants is greater in the medium-textured Oxisol (LVa), without implying a greater production of maize dry matter. N uptake without a corresponding increase in plant growth is classified as N luxury consumption. Maize shoot N accumulation is enhanced by the combined use of ammonium nitrate and biochar, particularly when ammonium nitrate is combined with chicken manure and shrimp carcass biochars. The use of bamboo and sunflower cake biochars + AN ensured the highest dry matter production in the sandy Oxisol (LVa), while in the clayey Oxisol (LVd), maize dry matter increased mainly due to the application of sunflower cake-derived biochar.

Nitrogen is essential for plants and is a highly reactive element that interacts with and influences the cycles, forms, and dynamics of carbon (C), sulfur (S), oxygen (O), and other elements in the soil–plant system [69,70]. The availability of N in soil is regulated by inputs from fertilizers, organic residues, soil organic matter (SOM), biochar, and the activity and diversity of soil biota [10]. The supply of N to crops depends on several factors, including the biochar C/N ratio, N content, recalcitrance of N forms, and water-soluble carbon content. These factors ultimately determine net N immobilization or mineralization and, consequently, the soil's capacity to supply N to crops [8,10,71–73]. Soil dissolved organic carbon (DOC) undergoes rapid turnover, while relatively stable pyrogenic carbon (PyC) and aromatic hydrocarbons present in biochar decompose much more slowly [38]. In biochar-treated soils, bioavailable N (NH_4^+ and NO_3^-) initially decreases but gradually increases over time. Soil microbes preferentially decompose fresh plant litter over recalcitrant N pools found in SOM [9,50], thereby slowing the overall SOM turnover rate [38]. In other words, compared to fresh organic matter, older SOM and N in biochar with high aromatic characteristics form more stable and persistent N sources for plant uptake, reducing N losses, especially in the presence of biochar; although, this also limits their immediate availability as N sources for crops [9]. Although the aging process of biochar may indirectly affect the nitrogen cycle, detailed investigations into the coupling of soil/biochar carbon and nitrogen cycles remain limited. The interactive mechanisms involved are not yet fully understood, and the regulatory role of biochar in this process—whether in the presence or absence of plants—has yet to be fully elucidated.

Biochar effectively retains soil nutrients and enhances nutrient uptake by crops by stimulating microbial and enzymatic activity. It possesses a well-developed pore structure and high biochemical stability, along with strong sorption and redox capacities due to multiple organic functional groups and its large specific surface area and pores, which allows it to compete for mineral surface sites [74,75]. Additionally, biochar plays a regulatory role in activating or inactivating soil biota and soil processes involved in the release of nutrients, hormones, and toxins by influencing alkaline functional groups [76,77]. Its indirect effects on soil amendment and nutrient cycling are often more significant than its direct effects; this is similar to soil organic matter (SOM), which acts as a microdomain framework, maintaining balance among the solid, liquid, and gaseous phases in soil [38,71].

This study, due to the high number of treatments tested, demonstrated the potential of biochar as a nitrogen source and its interaction with nitrogen sources. Despite the high potential of this study, further research under field conditions is necessary to validate the technology, confirming in commercial cultivation conditions the increase in nitrogen use efficiency resulting from the use of biochar. The complex interaction of plant traits regulating crop yield in the dynamic environments experienced by field-grown plants [78] should be considered when designing controlled experiments to effectively improve wheat growth and grain yield [79]. According to Sales et al. [79], when breeding plants for specific environments, a better alignment between phenotypes in field and greenhouse conditions can be achieved by designing experiments in which key conditions match the cropping cycle of the target breeding environment. While controlled environment studies (e.g., greenhouse conditions) are valuable for large-scale assessments of soil types, nutrient closed systems, and testing of a full range of nutrient and fertilizer sources on nitrogen availability and plant growth, it is essential to validate these findings under field conditions. Genotypic traits that contribute to crop growth and grain yield may behave differently in the field due to environmental factors, plant–genotype interactions, and stress conditions. These factors can significantly influence plant growth and yield in ways that differ from greenhouse experiments.

5. Conclusions

In general, sunflower cake or shrimp carcass biochar were the most promising materials for providing N and improving its dynamics for maize cultivation. However, this study demonstrates that biochar and feedstock amendments significantly affect soil nitrogen (N) availability, maize nutrition, and biomass production in contrasting Oxisols. While biochars alone reduce plant-available N due to microbial immobilization, their combination with ammonium nitrate (AN) restores soil-available N levels. In the clayey Oxisol, shrimp carcass and sunflower cake biochars improve maize biomass production without additional mineral N inputs, whereas non-pyrolyzed feedstocks consistently limit N availability and reduce plant growth. Residual soil N after maize cultivation remains low (<75 mg kg^{-1}), highlighting the need for N fertilization in successive crops. Nitrate-N dominates the soil solution, with mineral (ammonium + nitrate) levels exceeding those found in whole soils. However, despite high soil solution N concentrations, maize uptake efficiency varies, and excessive N supply can reduce dry matter production. The SPAD index does not consistently reflect plant N status in biochar-amended soils, emphasizing the need for complementary diagnostic tools. In the medium-textured Oxisol, plants fertilized with bamboo or sunflower cake biochar combined with ammonium nitrate produce ~12% more biomass than those receiving AN alone. Similarly, in the clayey Oxisol, maize fertilized with sunflower cake or shrimp carcass biochar—regardless of AN addition—outperforms ammonium nitrate-fertilized plants by 19–30%. Overall, supplemental mineral N is only necessary in the sandy Oxisol when using sunflower cake biochar. These findings highlight the importance of soil type, organic matter content, and site-specific N management when integrating biochar and ammonium nitrate into agricultural systems. The strategic combination of biochar with soluble N fertilizers can enhance maize growth, particularly in low-organic-matter soils. Future research should explore long-term biochar effects, optimize biochar-N composites, and refine biochar N fertilization strategies through field trials.

Author Contributions: Conceptualization I.d.O.P., E.G.d.M., and C.A.S.; methodology, I.d.O.P. and E.G.d.M.; software, I.d.O.P.; validation, I.d.O.P., E.G.d.M., and C.A.S.; formal analysis, I.d.O.P.; investigation, I.d.O.P., E.G.d.M., and C.A.S.; resources, E.G.d.M. and C.A.S.; data curation, I.d.O.P.; writing—original draft preparation, I.d.O.P., E.G.d.M., and C.A.S.; writing—review and editing, I.d.O.P., E.G.d.M., and C.A.S.; visualization, I.d.O.P.; supervision, E.G.d.M. and C.A.S.; project administration, C.A.S.; and funding acquisition, C.A.S. All authors have read and agreed to the published version of the manuscript.

Funding: The authors thank the Coordination for the Improvement of Higher Education Personnel (CAPES-PROEX/AUXPE 593/2018), the National Council for Scientific and Technological Development (CNPq) for the grants 307447/2019-7 and 311212/2023-9, and the Foundation for Research Support of the State of Minas Gerais (FAPEMIG) for their financial support and scholarships. A scientific initiation research scholarship was awarded to the first author of this study by CNPq.

Data Availability Statement: The data supporting this study's findings are available on request from the corresponding author.

Acknowledgments: The authors acknowledge the Coordination for the Improvement of Higher Education Personnel (CAPES), the National Council for Scientific and Technological Development (CNPq), and the Minas Gerais State Research Foundation (FAPEMIG) for financial support and scholarships.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the study's design, data collection, analysis or interpretation, manuscript writing, or decision to publish the results.

Appendix A

Table A1. Initial and residual pH in the whole soil of the Oxisols cultivated with maize as a function of different feedstocks (FD) and their respective biochars (BC), combined or not with ammonium nitrate (NAM).

	Feedstock	Dystroferric Clayey Red Latosol			Red-Yellow Medium-Textured Latosol		
		FD	**BC**	**BC + NAM**	**FD**	**BC**	**BC + NAM**
Initial	Bam	6.18 ± 0.06	6.23 ± 0.05	6.27 ± 0.04	6.13 ± 0.05	6.29 ± 0.04	6.12 ± 0.03
	SC	6.16 ± 0.07	6.15 ± 0.07	6.06 ± 0.03	6.24 ± 0.03	6.23 ± 0.05	6.20 ± 0.03
	CM	6.51 ± 0.05	6.22 ± 0.04	6.26 ± 0.03	6.73 ± 0.06	6.52 ± 0.05	6.43 ± 0.02
	SCa	6.45 ± 0.05	6.42 ± 0.01	6.36 ± 0.06	6.48 ± 0.05	6.58 ± 0.02	6.44 ± 0.03
	OS	6.19 ± 0.06			6.54 ± 0.03		
	NAM	6.02 ± 0.01			6.12 ± 0.02		
	Feedstock	**Dystroferric clayey Red Latosol**			**Red-Yellow medium-texture Latosol**		
		FD	**BC**	**BC + NAM**	**FD**	**BC**	**BC + NAM**
Residual	Bam	6.13 ± 0.05	6.02 ± 0.04	5.84 ± 0.04	6.02 ± 0.04	6.15 ± 0.04	6.23 ± 0.02
	SC	5.96 ± 0.03	5.88 ± 0.02	5.99 ± 0.06	6.43 ± 0.03	6.37 ± 0.06	6.35 ± 0.03
	CM	6.58 ± 0.04	6.22 ± 0.06	6.18 ± 0.02	7.14 ± 0.05	6.70 ± 0.05	6.79 ± 0.02
	SCa	6.19 ± 0.05	6.13 ± 0.04	6.11 ± 0.07	6.74 ± 0.05	6.69 ± 0.03	6.62 ± 0.01
	OS	5.99 ± 0.06			6.13 ± 0.03		
	NAM	5.86 ± 0.06			6.25 ± 0.04		

The soil pH was determined in deionized water at a ratio of biochar:water of 1:2.5 (w/v). FD, feedstock; BC, biochar. Bam, bamboo; SC, sunflower cake; CM, chicken manure; SCa, shrimp carcass; OS, only soil; and NAM, ammonium nitrate. All values are presented as the mean ± standard error.

Table A2. Initial and 15-days-after-sowing pH in the soil solution of the Oxisols cultivated with maize as a function of different feedstocks (FD) and their respective biochars (BC), combined or not with ammonium nitrate (NAM).

	Feedstock	Dystroferric Clayey Red Latosol			Red-Yellow Medium-Textured Latosol		
		FD	**BC**	**BC + NAM**	**FD**	**BC**	**BC + NAM**
Initial	Bam	6.42 ± 0.07	6.49 ± 0.05	6.69 ± 0.10	5.63 ± 0.06	5.78 ± 0.04	5.44 ± 0.03
	SC	6.01 ± 0.11	6.27 ± 0.10	6.58 ± 0.18	5.24 ± 0.03	5.60 ± 0.02	5.48 ± 0.03
	CM	7.32 ± 0.02	7.00 ± 0.05	7.21 ± 0.06	7.12 ± 0.06	6.40 ± 0.06	6.63 ± 0.03
	SCa	6.80 ± 0.07	6.88 ± 0.07	7.11 ± 0.03	6.99 ± 0.08	7.12 ± 0.03	6.86 ± 0.03
	OS	6.49 ± 0.07			5.77 ± 0.07		
	NAM	6.65 ± 0.05			5.40 ± 0.02		
	Feedstock	**Dystroferric clayey Red Latosol**			**Red-Yellow medium-textured Latosol**		
		FD	**BC**	**BC + NAM**	**FD**	**BC**	**BC + NAM**
15 days after sowing	Bam	6.62 ± 0.11	6.34 ± 0.17	6.69 ± 0.05	6.69 ± 0.15	7.10 ± 0.09	7.13 ± 0.10
	SC	7.26 ± 0.15	6.54 ± 0.19	6.34 ± 0.06	7.19 ± 0.05	7.06 ± 0.08	6.92 ± 0.02
	CM	7.86 ± 0.08	6.53 ± 0.16	6.58 ± 0.02	7.50 ± 0.08	7.40 ± 0.08	7.16 ± 0.13
	SCa	7.95 ± 0.10	6.43 ± 0.13	6.59 ± 0.13	7.73 ± 0.13	7.46 ± 0.10	7.79 ± 0.14
	OS	6.14 ± 0.01			7.05 ± 0.12		
	NAM	6.08 ± 0.07			7.12 ± 0.02		

The soil pH was determined directly in soil solution. FD, feedstock; BC, biochar. Bam, bamboo; SC, sunflower cake; CM, chicken manure; SCa, shrimp carcass; OS, only soil; and NAM, ammonium nitrate. All values are presented as the mean ± standard error.

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