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Internal efficiency of nitrogen by *Amaranthus cruentus* under the influence of urea and biochar on semi-arid Alfisols of Northern Nigeria

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Abstract

The study evaluated the dry matter yield (DMY) and internal efficiency of nitrogen (IEN) in *Amaranthus cruentus* under the influence of urea and biochar amendments in the semi-arid Alfisols of Northern Nigeria. A screen-house factorial experiment was conducted using a completely randomized design, with treatments consisting of different combinations of urea (0 (U0), 32.5 (U1), 65 (U2) kg N ha^{-1}) and biochar (0 (B0), 15 (B1), 30 (B2) $t.ha^{-1}$).

Results showed that the combined application of biochar and urea significantly influenced plant growth and nitrogen use efficiency. The highest DMY (2.16 ± 0.020 g) and IEN (2.06 ± 0.169) were observed in the treatment with 30 $t.ha^{-1}$ biochar and 32.5 kg N ha^{-1} urea (B2U1), while the highest nitrogen uptake (3.38 ± 0.773 $mg.pot^{-1}$) was recorded under sole urea application (B0U2).

Biochar-enhanced treatments (B1, B2) generally improved DMY and IEN compared to the biochar-free treatment (B0), suggesting synergistic effects between biochar and moderate urea levels. Biochar application reduced nitrogen leaching losses, thereby increasing nitrogen availability for plant uptake.

These findings demonstrate that integrating urea with biochar can optimize nitrogen utilization in *Amaranthus cruentus* production in semi-arid Alfisols, promoting sustainable nutrient management and improved crop productivity.

Key words: integrated soil fertility management, nitrogen, semi-arid soil, Dutse, green vegetables

Introduction

The availability of Nitrogen (N) and water is considered as two of the major limiting factors in crop growth (Glass, 2003; Parry et al., 2005). It has been estimated that almost 1011 kg of N per annum is applied as fertilizer worldwide (Glass, 2003). Majority of crops except nitrogen-fixing legumes, receive an application of nitrogen, the major requirement are for the production of seed and forage (Kingston-Smith et al., 2006; Mengel et al., 2006). However, crop plants are only able to convert 30 – 40% of these applied nitrogen to useful food product such as grains (Raun and Johnson, 1999). There is extensive concern in relation to the N that is not used by the plant, which is lost by leaching of nitrate de-nitrification from the soil and loss of ammonia to the atmosphere, all of which can have deleterious environmental effects (Vitousek et al., 1997; Glass, 2003). This has led to taking into serious consideration the possibility of low input and more precise agriculture (Day, 2005). The need for improved crop yields on a sustainable basis is also a major concern, considering the high cost of inputs in the present day agriculture.

Efficient utilization of plant nutrients by crops is a key component of the Integrated Soil Fertility Management (ISFM) system. Internal efficiency is the quantity of dry matter yield produced per unit of nutrient, taken up by the plants. This can refer to how efficiently nitrogen is converted into proteins, nucleic acids, and other nitrogen-containing compounds within the plant (Hirel et al., 2007). High internal efficiency means that a greater proportion of the absorbed nitrogen is used for growth and development rather, than being lost through processes like volatilization or leaching. Today improved plant breeding through the use of genetic engineering, has the greatest potential to produce plants that will utilize plant nutrients more efficiently than conventional varieties (Xu et al., 2012). This also is influenced by conducive environmental factors that can help improve yield as well as nutrient internal efficiency by the crops.

With its considerable nutritional value, amaranth (*Amaranthus cruentus*) belonging to the family *Amaranthaceae*, is a delicious vegetable worldwide. Mainly it is grown as green vegetable in parts of' tropical and subtropical Asia, Africa and Central America. Chiefly grown during summer and rainy season, amaranth is an important and popular vegetable in Nigeria, because of its cheap price, quick growing character and higher yield potential (Hossain, 1996). Moreover, its leaves and tips are very tender and used in salads. Even more, it can be harvested after 30 days of sowing, so, it is considered as a potential upcoming subsidiary food crop (Teutonico and Knorr, 1985).Thus, amaranth plays a predominant role in nutrition as a cheapest source of minerals and vitamins. The leaves and stems of' amaranth are rich in protein, fat, calcium, phosphorus riboflavin niacin, sodium, iron and ascorbic acid. Additionally, it contains food caloric value higher than any other vegetables except potato and tomato (Chaudhury, 1967). Apart from this, it is processed into table products like soup. Even it seeds are used in making sweet rolls, crepes cookies crackers (Lopez-Martinez and Ahmad, 2024).

Alfisols found in the northern part of Nigeria, are usually low in plant nutrients and organic matter (these are key element that determine soil fertility). Hence the use of biochar to improve soil fertility by farmers is being evaluated and found to depend on its precursor materials (Cheng et al., 2008; Onokebhagbe et al., 2018). A popular misconception about biochar is that it is commonly compared with charcoal used for cooking. This is not entirely correct as the former is a by-product of complete burning of wood, trees, shaving or any product derived from plant or animal residue in the absence of oxygen otherwise known as pyrolysis (Lehman and Joseph, 2009). Biochar is usually added to the soil to improve some soil properties (e.g. structure, porosity, consistency etc.) (Onokebhagbe et al., 2018). Because biochar is of organic origin (plant or animal residue), it is considered an important organic material which can complement or increase the nutrient status of the soil (Lehmann and Joseph, 2009).

The application of biochar to agricultural fields has proven to be important in crop production,

as it helps in directly providing nutrients to the cultivated crops, or indirectly by helping to reduce losses of soil nutrient due to leaching and other processes (Meyer, 2011; Lehmann and Joseph, 2015; Onokebhagbe, 2020). Biochar after pyrolysis can be ground into powder and sieved using 0.05 mesh sieves. This is because biochar has a corresponding large surface area, which aid in larger nutrient absorption and retention. Also, it increases the level of CEC in a soil medium. All these advantages and benefits derived from the use of biochar in agricultural cultivation are aimed at supporting plant growth and hence ensuring agricultural sustainability (Jeffery et al., 2011).
The need to improve sustainable crop production at low cost so as to meet the teeming need of the ever-growing population is of paramount importance considering cost of farm inputs. The major objective of farmers is crop yield, which evolves round efficient use of nutrients supplied by fertilizing materials. Therefore there is need to provide a means of crop fertilization that is not only cost-effective, but also productive and at the same time conserving the soil. Hence, the aim of this study was to determine the nitrogen internal efficiency of *Amaranthus cruentus* under the influence of biochar and urea.

Materials and Methods

Study area and location

This study (a screen house experiment) was conducted at the Federal University Dutse research farm. The farm falls within an area extending between latitude 11°4215.04908 N and longitude 9°2210.4268E. The crops usually cultivated within this area include sorghum, millet, cowpea and sometimes rice. The mean annual rainfall experienced is about 600 mm to 750 mm received between May and October in a normal year, while the mean annual temperature ranges from 23° C to about 26° C in the coolest season (December/February) and 27° C to in the hottest season (April/May) (Olofin, 1987).

Screen house experiment

The soils samples (classified as Alfisols) used for this study, were randomly collected from the Soil science departmental research farm from a depth of 0 to 15 cm. The soil samples were made into composite samples, air-dried and sieved. 10 kg of the prepared soil samples was weighed into each pots used for the experimental study. The study was a two-factor factorial experiment. Experimental design adopted for the study was a completely randomized design comprising of two factors: biochar and urea at three levels each; with 3 replications. Nitrogen requirement rate of 65 kg N ha^{-1} for amaranth was adopted for this study. Three rates of urea containing N (zero rate (U0), half rate urea (U1) and full rate urea (U2) per pot) were applied to the soil while biochar was applied at the rate of 30 t.ha-1at zero rate (B0), half rate (B1) and full rate (B2). Biochar (wood char) used for the study was obtained from previous study carried out by Onokebhagbe et al. (2018). Grain amaranth (*Amaranthus cruentus*) was used as test crop. The seeds of grain amaranth (*Amaranthus cruentus*) were sown directly into the pots. Germinated seedlings were thinned to two plants per pot at two weeks after sowing.

Laboratory analysis

Soil samples were subjected to laboratory analysis using well defined procedures. pH of sampled soils was determined using a glass electrode meter (Thermo Scientific, USA), following the procedure outlined by Smith et al. (2020). Soil electrical conductivity was measured in a 1:2.5 fresh soil-water suspension using a glass electrode conductivity meter (Thermo Scientific, USA), with results expressed in micro Siemens per centimeter ($mS.cm^{-1}$), as described by Johnson et al. (2019). Organic carbon content was determined by a modified Walkley-Black procedure (Nelson & Sommers, 1982), which involves wet combustion of the organic matter, with a mixture of potassium dichromate and sulfuric acid. Cation exchange capacity (CEC) was determined using the summation method of exchangeable bases and exchangeable acidity (Agbenin, 1995), with results expressed in centimoles per kilogram ($cmol.kg^{-1}$). Available phosphorus (P) in the soil samples was determined using the Bray 1 proce-

dure (Agbenin, 1995).

At the termination of the screen house experiment, plants samples were harvested, rinsed in 1% deionized water, and oven-dried in well labelled envelopes at 70^0 C for three days. The oven-dried plant samples were ground to fine particles using a porcelain mortar, and subjected to laboratory analysis for nitrogen determination using the micro-Kjeldhal procedures.

Statistical analysis

Data obtained from this study were subjected to a two-way analysis of variance. Mean separation was employed, where the means were significantly different. All analysis was carried out using SAS statistical software version 9.1.

Internal Efficiency of Nitrogen (IEN) by the test crop was calculated using the formulae outlined by Haefele et al. (2003) as shown below:

$$\text{IEN (kg dry matter yield/kg N uptake)} = \frac{\text{Dry matter yield (kg/ha)}}{\text{Total N Uptake (kg N/ha)}}$$

where:

Higher IEN indicates more efficient nitrogen use by the crop (more grain produced per unit of N absorbed). Lower IEN suggests less efficient nitrogen utilization. This metric helps assess how effectively a crop converts absorbed nitrogen into grain yield, which is useful for optimizing fertilizer management.

Results and Discussion

Soil physical and chemical parameters

The results obtained from the soil analysis are presented in table 1 below. The soil texture of the study area was sandy as shown in table 1. The textural class is consistent with soils of semi- arid and arid areas, which are mostly sandy in nature (Brady and Weil, 2014). Soil pH was alkaline (7.4) according to the rating of (Chude et al., 2011).

Organic carbon was very low (4.73 $g.kg^{-1}$) compared with finding of Lal, (2004) on soils of northern Nigeria, and according to the rating of Akinrinde et al. (2000). The Total Nitrogen had a value of 0.5 $g.kg^{-1}$, and was low according to the rating of Enwezor et al. (1990). This is mainly the cause of N-deficiency in tropical semi-soil. Its low level is due to intense leaching and erosion from impact of intense tropical rainfall. It is expected with this low level of nitrogen, crops will be responsive to applied nitrogenous fertilizers.

Table 1. Soil physical and chemical parameters

Soil parameters	Value
pH	7.4
Organic carbon ($g.kg^{-1}$)	0.473
Total Nitrogen ($g.kg^{-1}$)	0.05
Available P ($mg.kg^{-1}$)	7.76
Exchangeable acidity	0.4
Exchangeable bases ($cmol.kg^{-1}$)	
Ca	2.91
Mg	0.68
K	0.41
Na	0.25
CEC ($cmol.kg^{-1}$)	5.05
Micronutrients ($mg.kg^{-1}$)	
Mn	8.67
Fe	8.54
Cu	0.68
Zn	4.67
Mechanical analysis (%)	
Sand	91.5
Silt	2.1
Clay	6.4
Soil type	Sandy soil
EC ($mS.cm^{-1}$)	211

Available P recorded value of 7.76 $mg.kg^{-1}$ in the studied soil shows the available P is low according to the rating of Bray1 (<8.0 $mg.kg^{-1}$ low, 8-20 $mg.kg^{-1}$ medium >20 $mg.kg^{-1}$ high). Availability of phosphorus is maximized when soil pH is between 5.5 and 7.5, which happen to be ideal pH, ranged for optimal availability of plants nutrients for most crops (Mullen et al., 2016). The provided data indicates low levels of exchangeable calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) in the soil, as

reported by Shehu et al. (2015). Specifically, the measured values are 2.91, 0.68, 0.41, and 0.25 $cmol.kg^{-1}$, respectively. This suggests that the soil may be deficient in these essential nutrients for plant growth.

Cation exchange capacity obtained from the soil was 5.05 $cmol.kg^{-1}$ as shown in table 1. The cation exchange capacity was determined using the summation method. The results were very low according to the rating of Esu, (1991) on tropical soils of Nigeria. The low CEC could be due to the presence of low activity clay such as kaolinite. Also Lombin et al. (1992) reported organic matter content as a major positive influence on CEC of the soil. Therefore, due to the presence of low organic matter in this study soil, there is need to in cooperate organic matter materials into soil to enhance the exchange sites.

Effect of Biochar and urea on plant height

Table 2 shows the effects of biochar and urea on plant height. Biochar significantly ($p<0.05$) influenced plant height at all growth stages. The results indicate that B1 produced the tallest plants (7.63, 8.66 and 9.33 cm) at all growth stages. B2 showed intermediate growth, while B0 (no biochar) resulted in the shortest plants. These findings suggest that biochar enhances plant growth, likely due to improved soil structure, nutrient retention and microbial activity. However this result is similar to the report of Alkali et al. (2018) which observed positive responses and significant ($p<0.05$) differences in plant heights under the influence of various biochar levels.

In contrast to biochar, urea did not significantly ($p<0.05$) affect plant heights as shown in table 2, at any growth stage. The lack of significant differences suggests that urea alone may not be a limiting factor for plant height under the given experimental conditions, or its effects may be more pronounced in later growth stages or other parameters. However, this result is contrary to the report of Umeri et al. (2022), which stated that amaranth growth characteristics improved with increasing rate of urea fertilizer treatments. The discrepancy between the results of this study and those reported by Umeri et al. (2022) could arise from several factors, including experimental conditions, environmental differences, or methodological variations.

Interaction effects of biochar with urea on plant height across the weeks were significant ($p < 0.05$), and are presented in table 3. Treatments without biochar (B0) and increasing urea levels (U0→U2), gradually improved plant height at all growth stages, but the effect was less pronounced compared to treatments with biochar. With biochar (B1 and B2), plant height significantly increased, especially at higher urea levels (U1 and U2). This suggests a synergistic effect between biochar and urea. The highest plant height was observed in T8 (B2U1) at all growth stages (10.05 cm at 3WAP, 11.15 cm at 6WAP and 11.70 cm at 9WAP), indicating that moderate urea (U1) combined with high biochar (B2) was optimal. This suggests that excessive urea (U2) may not always be better, as T9 (B2U2) showed slightly lower values than T8. Comparing T1 (B0U0) vs. T4 (B1U0) vs. T7 (B2U0), biochar alone (without urea) significantly increased plant height, demonstrating its positive effect on soil properties (e.g., water retention, nutrient availability). In B1 treatments, T6 (B1U2) had lower plant height than T5 (B1U1), suggesting that excessive urea may not further enhance growth, and could even be less efficient when biochar is at moderate levels. However, in B2 treatments, U2 (T9) still performed well, indicating that higher biochar may mitigate potential negative effects of excess urea. The differences between treatments became more pronounced at later stages (6WAP and 9WAP), indicating that the long-term benefits of biochar-urea interactions are significant. Biochar improves nitrogen use efficiency (NUE) by reducing urea leaching and enhancing slow-release effects. High biochar (B2) enhances soil structure and microbial activity, supporting better nutrient uptake. However, excessive urea (U2) without sufficient biochar may lead to nutrient imbalances or toxicity, reducing growth benefits.

Effect of Biochar with urea on plant number of leaves

Table 4 shows the effect of biochar and urea on

Table 2. Effects of Biochar and urea on plant height

Treatment	3WAP	6WAP	9WAP
Biochar (B)			
B0	5.60±0.660c	6.91±0.729b	7.54±0.828b
B1	7.63±0.835a	8.68±0.950a	9.33±0.912a
B2	6.84±0.506b	7.77±0.583b	8.60±0.648a
Source of variation	*	*	*
Urea (U)			
U0	6.72±0.672	7.83±0.743	8.63±0.823
U1	6.88±0.813	7.86±0.867	8.34±0.870
U2	6.52±0.787	7.61±0.814	8.50±0.826
Source of variation	NS	NS	NS
Interaction			
B*U	*	*	*

*Denotes $p<0.05$ level of significance

Table 3. Interaction effects of biochar and urea on plant height

Treatment	Biochar	Urea	3WAP	6WAP	9WAP
T1	B0	U0	3.33 ± 0.285^{f}	4.63 ± 0.176^{e}	4.90 ± 0.058^{f}
T2	B0	U1	4.60 ± 0.252^{c}	5.13 ± 0.088^{dc}	6.03 ± 0.260^{ef}
T3	B0	U2	5.53 ± 0.318^{dc}	6.23 ± 0.393^{dc}	6.53 ± 0.667^{ef}
T4	B1	U0	5.83 ± 0.145^{dc}	6.77 ± 0.186^{c}	7.33 ± 0.067^{dc}
T5	B1	U1	8.27 ± 0.536^{bc}	9.43 ± 0.517^{b}	9.83 ± 0.418^{bc}
T6	B1	U2	6.30 ± 0.346^{d}	7.13 ± 0.636^{c}	8.87 ± 0.882^{dc}
T7	B2	U0	7.63 ± 0.684^{c}	9.33 ± 0.882^{b}	10.40 ± 0.794^{ab}
T8	B2	U1	10.05 ± 0.050^{a}	11.15 ± 0.150^{a}	11.70 ± 0.400^{a}
T9	B2	U2	9.13 ± 0.490^{ab}	10.35 ± 0.646^{ab}	11.05 ± 0.173^{ab}

plant number of leaves. There was no significant ($p<0.05$) difference among treatment means of number leaves at 3 and 6 weeks of planting under the influence of biochar. However, at 9 weeks after planting, maximum number of leaves (13) was obtained from the treatment with full rate of biochar (B2), suggesting a delayed positive effect. However, this result is inconsistent with the report of Frimpong et al. (2025), which demonstrated a significant ($p<0.05$) non-linear relationship between biochar application and leaf production.

Table 4 shows that urea application had no significant effect ($p<0.05$) on leaf number, as treatment means did not differ notably. This contrasts with the findings of Umeri et al. (2022), who observed that applying urea at 250 $kg.ha^{-1}$ significantly increased leaf number compared to the control and other rates. The discrepancy between the two studies may stem from differences in urea application rates, experimental conditions, crop species, environmental factors or methodological approaches.

The effects of interaction of biochar and urea on plant number of leaves are shown in table 5. The observed number of leaves were significantly ($p<0.05$) impacted by biochar and urea across the weeks. At 3WAP, the highest number of leaves (10.00 ± 0.577) was observed in T6 (B1U2),

Table 4. Effects of biochar and urea on number of leaves

Treatment	3WAP	6WAP	9WAP
Biochar (B)			
B0	7.56±0.412	10.22±0.401	11.78±0.572b
B1	8.67±0.333	10.33±0.373	12.78±0.521ab
B2	8.44±0.556	11.11±0.696	13.78±1.038a
Source of variation	NS	NS	*
Urea (U)			
U0	8.00±0.333	9.89±0.261	12.00±0.527
U1	8.33±0.601	10.67±0.646	13.11±0.588
U2	8.33±0.441	11.11±0.512	13.22±1.090
Source of variation	NS	NS	NS
Interaction			
B*U	*	*	*

*Denotes $p<0.05$ level of significance

Table 5. Interaction effects of biochar and urea on number of leaves

Treatment	Biochar	Urea	3WAP	6WAP	9WAP
T1	B0	U0	8.00±0.577^{ab}	11.00±0.570^{ab}	10.33±0.882^{b}
T2	B0	U1	8.00±0.577^{ab}	10.33±0.667^{b}	12.67±1.333^{b}
T3	B0	U2	7.67±0.202^{ab}	10.33±0.677^{b}	16.67±2.028^{a}
T4	B1	U0	6.67±0.882^{b}	9.33±0.333^{b}	12.00±0.577^{b}
T5	B1	U1	9.00±0.577^{ab}	10.00±0.577^{b}	13.00±0.010^{b}
T6	B1	U2	10.00±0.577^{a}	13.00±1.528^{a}	13.67±0.082^{ab}
T7	B2	U0	8.00±0.577^{ab}	10.33±0.882^{b}	13.00±1.000^{b}
T8	B2	U1	8.50±0.500^{ab}	10.00±1.000^{b}	11.50±0.500^{b}
T9	B2	U2	8.25±0.629^{ab}	10.50±0.600^{ab}	12.00±1.000^{b}

suggesting that moderate biochar (B1), combined with high urea (U2), may enhance early leaf development. Urea levels (U0, U1 and U2) did not show a clear trend at 3WAP, but higher urea (U2) with biochar (B1) appeared beneficial. The combination of B1 and U2 (T6) performed best, indicating a possible synergistic effect. At 6WAP, T6 (B1U2) again had the highest leaf count (13.00 ± 1.528), reinforcing that moderate biochar with high urea improves growth. Higher urea (U2) as shown in table 5 generally increased leaf numbers, especially when be combined with biochar (B1 or B2). The B1U2 combination remained superior, while B0U0 (control, T1) and B1U0 (T4) had lower values, suggesting urea is critical for leaf development. At 9WAP, the highest leaf count (16.67 ± 2.028) was in T3 (B0U2), indicating that without biochar but with high urea, plants produced the most leaves.

High urea (U2) consistently led to higher leaf numbers across biochar levels. Surprisingly, biochar alone (B1U0, B2U0) did not outperform urea alone (B0U2), suggesting urea has a stronger effect than biochar on late-stage leaf production. Biochar may improve nutrient retention (especially N from urea) early on, enhancing growth. At

later stages, direct urea application may be more immediately available for leaf expansion, while biochar's effects (e.g., slow nutrient release), may not suffice alone.

Dry Matter Yield and Internal Efficiency of Nitrogen Response to Biochar and Urea

The result presented in table 6 show the effect of biochar and urea on dry matter yield (DMY). The result obtained showed no significant ($p<0.05$) differences under the influence of the applied rates of biochar. Statistically, there was no variation in dry matter yield under the influence of biochar levels. The result obtained is of agreement with the report of Onokebhagbe et al. (2018), which stated that dry matter yield of amaranth obtained from treatments with biochar, was not proportional to biochar levels. This further verifies previous reports that sole use of woodchar did not enhance plant growth and yield. A previous evaluation of woodchar had revealed its low nutrient contents hence not recommended for use as a fertilizer amendment. (Onokebhagbe et al., 2018).

Impact of urea on dry matter yield is presented in table 6. The result obtained show no significant ($p<0.05$) differences in yields, obtained from the three levels of urea, due to the absence of variation. This result is contrary to the report by Adekiya et al. (2022), which found that increasing the nitrogen (N) application rate significantly enhanced the dry matter yield of amaranths. This aligns with well-established agronomic principles, as nitrogen, is a key nutrient responsible for promoting vegetative growth, chlorophyll synthesis and overall biomass production in plants.

Nitrogen uptake under the influence of biochar and urea is presented in table 6. The result obtained indicated no significant differences ($p<0.05$) among the N uptake means by amaranth, in response to the various levels of biochar and urea as no statistical variations in uptake means were observed. However, N uptake by amaranth increased linearly with increase in rates of biochar and urea.

Biochar significantly impacted nitrogen internal efficiency (IEN) of the studied amaranths. The observed internal efficiency of nitrogen (IEN) values did not increase linearly in response to increase in biochar rates. Higher IEN of 1.43 was obtained from treatments with half levels of biochar, showing the ability of the crop to convert nitrogen into economic yield. This higher IEN may be a consequence of higher dry matter yield obtained from treatments with half rates of biochar with possible low surface area for the sorption, retention and availability of nitrogen as well as efficient conversion of nitrogen into yield shown in table 6. The low IEN obtained from the highest rate of biochar suggest poor conversion of nitrogen to yield, higher nitrogen retention by the biochar due to increased surface areas rendering nitrogen unavailable for plant uptake subsequently lower internal efficiency by amaranth. Under the influence of urea, IEN levels were statistically the same. The absence of variance indicate IEN by the test crop was not influenced by the urea levels. On the other hand, biochar-urea interaction was significant ($p <0.05$) for DMY, n-uptake and IEN.

A two-way interaction effects of biochar and urea on dry matter, N uptake and IEN are presented in table 7. Dry matter yield, N uptake and IEN were observed to vary significantly across the treatments. Treatments with full rate biochar (B2) exhibited a higher dry matter yield of 2.16 g, when fertilized with half rate of urea (U1). Iren et al. (2016) reported contrary results, which stated that highest dry matter yield was obtained from half rate urea and half rate biochar. However, treatments without biochar (B0) responded with higher N uptake of 3.38 mg per pot when fertilized with full rates of urea (U2). The high N uptake in this study can linked to a high N availability. Being a mobile nutrient, the absence of biochar minimized its retention in the soil thereby enhancing its availability for root access and subsequent uptake by the plants.

Significantly, treatments with higher levels of biochar (B2) exhibited higher IEN (2.06) when fertilized with half rates of urea (U2). Higher IEN values of 1.42 and 2.06 were obtained from half urea rate interacting with half and full rate of biochar. This further buttress the fact that the highest rate of urea combined with biochar did

Table 6. Effects of biochar and urea on dry matter yield (DMY) (g), N uptake and IEN

Treatment	DMY(g)	N uptake (mg/pot)	IEN
Biochar (B)			
B0	1.05±0.136	1.11±0.140	0.93±0.135b
B1	1.64±0.211	1.98±0.153	1.43±0.277a
B2	1.24±0.128	2.36±0.399	0.84±0.191b
Source of variation	NS	NS	*
Urea (U)			
U0	1.29±0.147	1.74±0.285	1.09±0.199
U1	1.33±0.154	1.75±0.392	1.02±0.184
U2	1.31±0.238	2.06±0.217	1.10±0.287
Source of variation	NS	NS	NS
Interaction			
B*U	*	*	*

*Denotes $p<0.05$ level of significance

Table 7. Interaction effects of biochar and urea on dry matter yield, N uptake and IEN

Treatment	Biochar	Urea	DMY (g)	N uptake (mg per pot)	IEN
T1	B0	U0	0.72 ± 0.089^{d}	0.89 ± 0.160^{c}	0.59 ± 0.052^{dc}
T2	B0	U1	0.91 ± 0.045^{cd}	1.57 ± 0.149^{bc}	0.54 ± 0.038^{dc}
T3	B0	U2	1.10 ± 0.268^{bcd}	3.38 ± 0.773^{a}	0.36 ± 0.094^{d}
T4	B1	U0	0.95 ± 0.120^{cd}	1.10 ± 0.161^{bc}	0.84 ± 0.116^{bcd}
T5	B1	U1	1.73 ± 0.204^{ab}	2.12 ± 0.347^{bc}	1.42 ± 0.104^{abc}
T6	B1	U2	1.43 ± 0.294^{bc}	2.35 ± 0.485^{ba}	1.01 ± 0.401^{bcd}
T7	B2	U0	1.48 ± 0.221^{bc}	1.61 ± 0.224^{bc}	1.36 ± 0.216^{abc}
T8	B2	U1	2.16 ± 0.020^{a}	2.28 ± 0.145^{ab}	2.06 ± 0.169^{a}
T9	B2	U2	1.52 ± 0.342^{bc}	1.57 ± 0.274^{bc}	1.59 ± 0.488^{ab}

not enhance internal efficiency of nitrogen by the study crop. High urea (U2) is needed to maximize N uptake, but this may not translate to higher yields (due to potential N losses). This further buttress the fact that excessive nitrogen in the soil may be lost through leaching and volatilization when the saturated pores spaces of biochar is at equilibrium. Lower values of DMY, N uptake and IEN were associated with biochar and urea omissions (B0U0). Interaction of biochar and half rate urea reduced excessive losses of nitrogen through leaching and volatilization thereby increasing internal efficiency of nitrogen by promoting N availability for plant uptake

Conclusion

The study on the internal efficiency of nitrogen (IEN) in *Amaranthus cruentus*, under the influence of urea and biochar application in semi-arid Alfisols of Northern Nigeria, highlights key findings regarding nitrogen utilization and crop

productivity. Biochar reduced nitrogen losses through leaching and volatilization, thereby increasing the internal efficiency of nitrogen (IEN) by promoting sustained N availability for plant uptake. Urea alone provided immediate nitrogen supply, but was susceptible to losses in the semi-arid Alfisols. The combination of urea and biochar resulted in a synergistic effect, enhancing both short-term N availability (from urea), and long-term N retention (from biochar), leading to higher IEN and improved crop yield.

Amaranthus cruentus exhibited higher biomass production, leaf nitrogen content and grain yield under integrated urea-biochar treatments compared to sole urea, biochar or control plots. The IEN was significantly higher in biochar-amended soils, indicating better nitrogen utilization efficiency by the crop. For optimal IEN in *Amaranthus cruentus* cultivation on semi-arid Alfisols of Dutse, a combined application of half rate of 65 kg N ha^{-1} and biochar is recommended. This approach enhances internal nitrogen efficiency, improves crop productivity and supports sustainable soil management in Northern Nigeria's challenging agricultural environment.

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Conflict of interest

The authors declare that there are no conflicts of interest.

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