Nativa, Sinop, v. 10, n. 2, p. 184-190, 2022.
Pesquisas Agrárias e Ambientais
DOI: https://doi.org/10.31413/nativa.v10i2.13529
ISSN: 2318-7670

The use of biochar-urea pellet formulations to reduced nitrogen losses

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Recebido em 08/03/2022; Aceito em 02/05/2022; Publicado em 03/06/2022.

ABSTRACT: This study aimed to evaluate the effects of soil texture, fertilizer formulation and nitrogen dose on the characteristics of upland rice production, and to compare the Agronomic Efficiency Index (AEI) of formulations of biochar-urea pellets (BUPs). The treatments comprised four fertilizers (three formulations of BUP and urea) and five nitrogen doses (0, 75, 150, 300 and 600 mg dm^{-3}), analyzed in two soil (sandy and clay). For each soil texture, a greenhouse experiment was established as a randomized block design with a 5 x 4 factorial arrangement and four replicates. Chlorophyll index, plant height, number of tillers and panicles, dry mass of aerial parts and of grains were all affected significantly by soil texture, fertilizer formulation and nitrogen dose and/or by the interactions between these sources of variation. The results demonstrated that the performances of BUPs are highly dependent on soil texture. Under sandy soil, application of BUP-based fertilizers contributed to the increase or maintenance of grain production compared to that of urea alone. Whereas under clayey soil the performance of BUPs exceeded that of urea only at low nitrogen doses. Compared to urea, BUPs were more efficient under sandy soil, with potential to increase AEI.

KEYWORDS: organomineral fertilizers; wood sawdust; pyrolysis; N-leaching.

Uso de pellets de biochar-ureia para reduzir as perdas de nitrogênio

RESUMO: Este trabalho objetivou avaliar os efeitos da textura do solo, formulações e doses de nitrogênio em características do arroz de terras altas, e comparar o Índice de Eficiência Agronômica (AEI) das formulações de pellets de biochar-ureia (BUP's). Os tratamentos foram: quatro fertilizantes (três formulações de BUP e ureia) e cinco doses de nitrogênio (0, 75, 150, 300 and 600 mg dm^{-3}), avaliados em dois solos de textura distinta. Para cada solo (arenoso e argiloso), foi conduzido um experimento em casa-de-vegetação em blocos casualizados em um arranjo fatorial 5 (doses) x 4 (fertilizantes), com quatro repetições. O índice de clorofila, altura de plantas, número de perfilhos, número de panículas, massa seca de parte aérea, massa seca de grãos tiveram diferenças significativas em função da textura do solo, fertilizantes e doses de N e/ou pelas interações entre esses fatores. Os resultados demonstraram que o desempenho dos BUP's foi dependente da textura do solo, com melhores respostas no solo arenoso em relação à ureia, com potencial de elevar a eficiência agronômica da adubação nitrogenada.

PALAVRAS-CHAVE: fertilizantes organominerais, pó de serra, pirólise, lixiviação de N.

1. INTRODUCTION

The search for intensive but sustainable production systems involves the use of practices that contribute to increase the efficiency of nutrient use while reducing nutrient pollution. Nitrogen fertilizers are among the most important inputs for food production but nitrogen efficient use remains challenging (REETZ, 2017). Nitrogen fertilizers management is considered complex because a significant proportion of nitrogen applied to the soil is lost through leaching, volatilization or denitrification (FAGERIA; BALIGAR, 2005), and such losses can be as high as 50% (KLUTHCOUSKI et al., 2006). Depending on the amount applied and the environmental conditions, nitrogen lost can contribute to surface or ground water pollution as well as to increase greenhouse gas emissions (CANTARELLA, 2007).

Nitrogen losses through leaching represents the mainly pathway of nitrogen losses in tropical soils, especially because its form that exhibit high mobility in soil water and have less chance of attaching to charged soil particles. The extent of leaching is influenced by soil texture and structure, characteristics of the fertilizer and application management practices (ERNANI et al., 2002; SANGOI et al., 2003; FEY et al., 2010). Although urea is one of the most common agricultural fertilizers (IPNI, 2019), its rapid hydrolysis by urease to volatile ammonia or its oxidation to nitrate by microbial nitrifiers may lead to poor crop responses and greater environmental damage. Thus, considerable research effort has been expended in recent years with aim of improving nitrogen use efficiency (NUE), particularly through the design of enhanced efficiency fertilizers that attempt to minimize nutrient losses. Such fertilizers may incorporate nitrogen stabilizers such as urease and nitrification inhibitors to delay processes of nitrogen losses such as the volatilization of NH_3, the leaching of nitrate (NO^{3-}) and the reduction of N_2O emissions, but also to control nitrogen release and meet crop demand. (FRAZÃO et al., 2014; TIMILSENA et al., 2015; GUELFI, 2017; RECH et al., 2017). An alternative strategy involves the use of organomineral fertilizers (OMFs) comprising a synthetic fertilizer such as urea combined with an organic matrix. However, this approach has been little explored, likely due to the challenge of finding stable formulations that inhibit interactions between the nitrogen source and the organic matrix from generating even greater nitrogen losses after mixing. Nevertheless, the adoption of a highly stable organic source could be essential for creating OMFs that are more efficient than conventional nitrogen fertilizers.

Biochar is a chemically stable form of charcoal produced by the pyrolysis of biomass in the presence of little or no oxygen (LENG; HUANG, 2018). Direct application of biochar to soil improves the physical, chemical and biological characteristics of the substrate and has been reported as a contributor to increase NUE (PETTER et al., 2016). In this sense, biochar is not only a practical solution for the disposal of harmful agro-industrial waste (LEHMANN; JOSEPH, 2009) but also has great potential as an organic matrix (MANIKANDAN; SUBRAMANIAN, 2013; ZHENG et al., 2013; AGEGNEHU et al., 2016) and as a long-term sink for atmospheric carbon dioxide (FAWZY et al., 2021).

The aim of the present study was to determine the viability of using biochar-urea pellets (BUPs) in agricultural systems in order to reduce nitrogen losses and environmental nitrogen pollution. For this purpose, we have: (i) evaluated the effects of soil texture, fertilizer type and nitrogen dose on the characteristics of upland rice production, and (ii) compared the Agronomic Efficiency Index values and plant yields fertilized with different BUPs formulations or with urea alone.

2. MATERIAL AND METHODS

2.1. Preparation and characterization of fertilizers

Activated biochar was produced from sawmill waste in slow pyrolysis reactor (horizontal tubular furnace) operating with water steam injection at 650°C. The chemical composition of the activated biochar corresponded to 49% of phenolics, 21% of lactose and 30% of carboxylic acids groups. Real density and apparent density corresponded to 1.27 and 0.31 g cm^{-3}, respectively, and 75% of porosity. Commercial grade urea was ground into fine particles (< 1 mm mesh) using a rotor mill and combined with the organic matrix to produce biochar-urea mixtures with proportions 2:1, 1:2 and 1:4 ($BUP_{2:1}$, $BUP_{1:2}$ and $BUP_{1:4}$, respectively). The mixtures were pelletized and the nitrogen contents determined by automated dry combustion analysis using a vario MACRO cube (Elementar Analysensysteme, Langenselbold, Germany) CNHS elemental analyzer. The total nitrogen contents of $BUP_{2:1}$, $BUP_{1:2}$, $BUP_{1:4}$ and pure urea were established as 16, 31, 36 and 45%, respectively. The mechanical hardness of the formulations were evaluated using a TA.HDplusC texture analyzer (Stable Micro Systems, Godalming, UK) and the forces required to break the pellets corresponded to 19, 10 and 2 kgf, respectively, for $BUP_{2:1}$, $BUP_{1:2}$ and $BUP_{1:4}$.

2.2. Soil preparation and analysis

Sandy and clay textured latosols were collected from the 10-20 cm soil layer under a native forest. Soils were air dried and sieved through a 2-mm mesh sieve. Table 1 shows the physicochemical characteristics of the two types of soils used in the experiments. Prior to the experiment establishment, soils of each texture were passed through 4 mm mesh sieves and their acidities corrected with limestone to raise the base saturation to 50%. Treated soils were transferred to separate plastic bags, homogenized with an appropriate BUP formulation or urea, transferred to 5 dm^3 plastic pots and finally allowed to equilibrate for 30 days under greenhouse conditions with soil moisture maintained at 70% of field capacity.

Table 1. Physicochemical characteristics of the forest soils used in the determination of the agronomic efficiency of biochar-urea pellets.
Tabela 1. Características físico-químicas dos solos utilizados na determinação da eficiência agronômica dos pellets de biochar-ureia.

Soil texture	pH_{H_2O}	P^a	K	Ca	Mg	Al	CEC^b	Organic C	Clay	Silt	Sand
		(mg dm^{-3})		($cmol_c$ dm^{-3})				(g kg^{-1})			
Clay	4.8	0.2	9	0.14	0.06	0.96	7.1	17.6	503	94	403
Sand	4.8	0.5	16	0.33	0.13	0.84	7.0	16.7	131	38	831

[a] Melich-1; [b] Cation exchange capacity.

2.3. Experimental design and measurements of agronomic variables

For each soil texture, completely randomized block design experiments were established with a 5 x 4 factorial arrangement comprising five nitrogen doses (0, 75, 150, 300 and 600 mg dm^{-3}) and four types of fertilizer ($BUP_{2:1}$, $BUP_{1:2}$, $BUP_{1:4}$ and pure urea) with four replicates of each combination. Each pot received four rice (*Oryza sativa* L.) seeds and thinning was performed 20 days after the emergence of seedlings leaving only two plants per pot. Soil moisture was maintained at 70% of the field capacity throughout the crop cycle. On the day before rice sowing, were applied 80 mg dm^{-3} of N, 250 mg dm^{-3} of P, 70 mg dm^{-3} of K, 420 mg dm^{-3} of CaO, 60 mg of dm^{-3} of S, 3.6 mg dm^{-3} Mn, 5.0 mg dm^{-3} Zn, 1.5 mg dm^{-3} Cu, 0.15 mg dm^{-3} Mo and 0.5 mg dm^{-3} B, diluted in water and inserted equally in each treatment plot. Falker chlorophyll indices were determined at the flowering stage using a Falker ClorofiLOG® 1030 (Falker, Porto Alegre, RS, Brazil) portable chlorophyll meter, and plant height (cm) and numbers of tillers and panicles per plant were recorded at the end of the culture cycle. Subsequently, grains were collected and the aerial parts of the plants were cut at 5 cm from the soil. Harvested plant material was dried in a forced-air oven at 60°C until constant weight, and the dry masses of aerial parts (DMA; g pot^{-1}) and grains (DMG; g pot^{-1}) were determined. To evaluate the agronomic efficiency of the organomineral fertilizer formulations, the Agronomic Efficiency Index (AEI) was calculated for grain dry matter (MSG) production, using the following:

$$\text{AEI } (\%) = \frac{(\text{DMG}_i - \text{DMG}_0)}{(\text{DMG}_u - \text{DMG}_0)} \times 100 \qquad (01)$$

where: DMG_i (g pot^{-1}) is the grain production in the experimental treatment, DMG_0 (g pot^{-1}) represents grain production without application of nitrogen, and DMG_u (g pot^{-1}) refers to grain production with application of urea at the same dose as in DMG_i.

2.4. Statistical analyses

Data obtained from sandy and clay soil conditions were submitted, individually and jointly, to analysis of variance (ANOVA) in order to analyze the effects of the independent variables (soil texture, fertilizer type, nitrogen dose) and their interactions on the dependent variables (chlorophyll index, tillers plant^{-1}, panicles plant^{-1}, plant height, DMA, DMG and AEI). When significant differences were found, mean values were compared using the Tukey test ($p < 0.05$). The best fit linear or quadratic regression models for the data sets were chosen on the basis of the nitrogen doses applied to the soil (FERREIRA, 2011).

3. RESULTS

The data on the effects of the independent variables (soil texture, fertilizer type and nitrogen dose) and their interactions on the characteristics of upland rice production are presented in Table 2. The chlorophyll index was affected significantly by nitrogen dose ($p < 0.0001$) with linear adjustment for both soil texture and fertilizer types (Fig. 1A). In contrast, plant height was influenced significantly ($p = 0.0017$) by soil texture regardless of nitrogen dose or fertilizer type. Plants grown in clay soil were taller at the end of the culture cycle than those grown in sandy soil (Fig. 1B).

Nitrogen dose affected significantly the number of tillers per plant ($p < 0.0001$) and the number of panicles per plant ($p < 0.0001$) The number of panicles per plant was also impacted significantly ($p = 0.0347$) by nitrogen doses X fertilizers interaction (Table 2). In both cases, the relationship between the independent and dependent variables could be modeled by quadratic functions. The highest number of tillers (8.5 per plant) was estimated at a nitrogen dose of 444 mg dm^{-3} regardless of fertilizer type (Fig. 1C). On the other hand, the highest number of panicles (7.7 per plant) was evaluated with a nitrogen dose of 469 mg dm^{-3} provided by BUPs, while a maximum of 7.7 panicles per plant were projected at a nitrogen dose of 358 mg dm^{-3} when urea was used as a fertilizer (Figure 1D).

DMA was affected significantly by nitrogen doses ($p < 0.0001$) and by the interaction soils texture X nitrogen doses X fertilizers ($p = 0.0118$; Table 2). In clay soil, only nitrogen dose impacted DMA values with a maximum production of 43.9 g pot^{-1} estimated at 527 mg dm^{-3} of nitrogen (Figure 2A). In sandy soils, the relationships between DMA and nitrogen doses for most types of fertilizers could be modeled by quadratic functions (Figure 2A). The highest levels of DMA were projected by fertilization with BUP$_{2:1}$ at a nitrogen dose of 523 mg dm^{-3}(45.0 g pot^{-1}), with BUP$_{1:4}$ at 483 mg dm^{-3} (45.2 g pot^{-1}), or with urea at 392 mg dm^{-3} (41.3 g pot^{-1}). For BUP$_{1:2}$, the DMA/nitrogen dose response was linear, thus it was not possible to estimate the maximum production under these conditions.

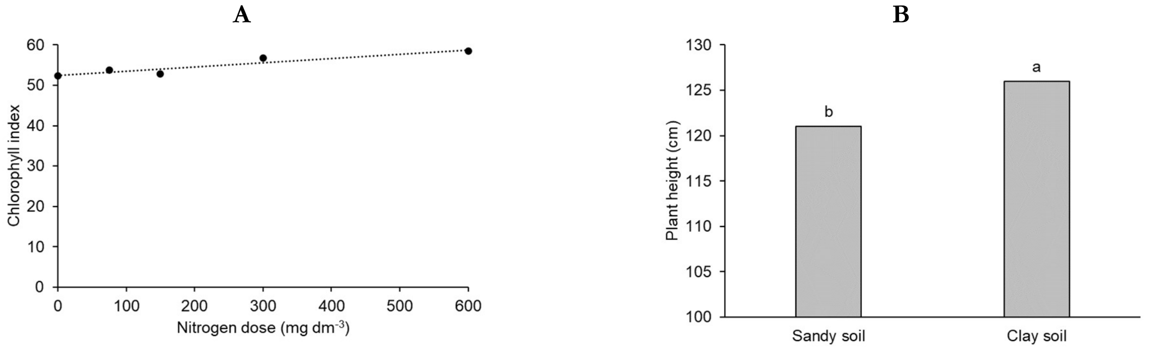
DMG was affected significantly by soil texture ($p = 0.0013$), nitrogen dose ($p < 0.0001$), and the interaction soils X fertilizers X nitrogen doses ($p = 0.0045$) (Table 2). In clay soil, there were no differences in DMG production between tested fertilizers, in which the highest level of 47.2 g pot^{-1} was evaluated at 594 mg dm^{-3} of nitrogen (Figure 2B). However, in sandy soils, the relationships between DMG and nitrogen doses could be modeled by quadratic functions for most types of fertilizers (Figure 2B). The highest levels of DMG were projected by fertilization with BUP$_{1:2}$ at 495 mg dm^{-3} of nitrogen (49.5 g pot^{-1}), with BUP$_{1:4}$ at 385 mg dm^{-3}(44.8 g pot^{-1}) or with urea at 541 mg dm^{-3} (41.4 g pot^{-1}). The DMG/nitrogen dose response for BUP$_{1:2}$ was linear, hence the maximum production under these conditions could not be estimated.

Table 2. Summary of the joint analysis of variance showing the effects of the three independent variables (soil texture, fertilizers and nitrogen doses) and their interactions on the characteristics of upland rice production.
Tabela 2. Resumo da análise de variância conjunta mostrando o efeito das variáveis independentes (textura do solo, fertilizantes e doses de nitrogênio) e suas interações nas características do arroz de terras altas.

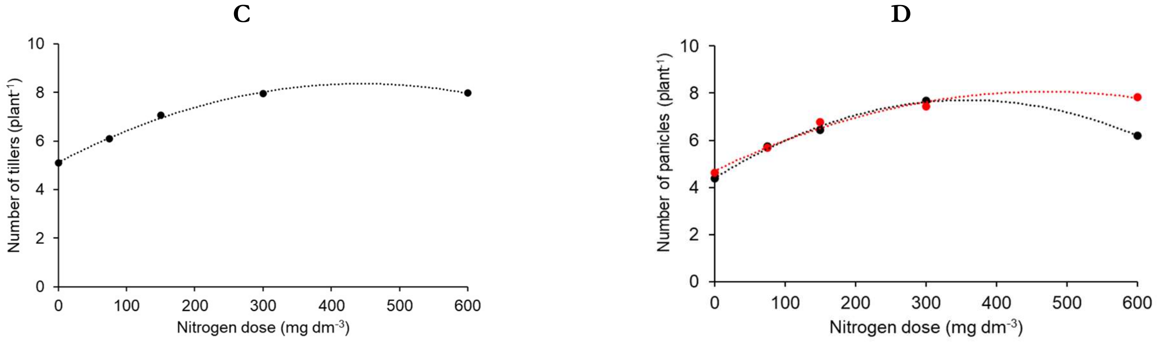
Sources of variation	Degrees of freedom	Chlorophyll index	Plant height (cm)	Tillers (plant^{-1})	Panicles (plant^{-1})	DMA (g plant^{-1})	DMG (g plant^{-1})
Replicates/Soils	6	40.2^{ns}	211.7^{*}	7.0^{**}	4.2^{**}	107.4^{**}	40.8^{ns}
Soils^{a}	1	13.4^{ns}	**870.9****	0.3^{ns}	2.6^{ns}	0.4^{ns}	**298.4****
Fertilizers^{b}	3	30.2^{ns}	37.1^{ns}	1.9^{ns}	1.8^{ns}	16.4^{ns}	19.9^{ns}
N doses^{c}	4	**224.2****	49.8^{ns}	**49.2****	**49.8****	**1866.8****	**2400.0****
Soils x Fertilizers	3	28.9^{ns}	194.9^{ns}	0.8^{ns}	1.0^{ns}	19.1^{ns}	**86.3***
Soils x N doses	4	49.2^{ns}	20.5^{ns}	0.7^{ns}	0.4^{ns}	11.5^{ns}	20.5^{ns}
Fertilizers x N doses	12	14.2^{ns}	42.6^{ns}	15.4^{ns}	**1.4***	23.5^{ns}	44.3^{ns}
Soils x Fertilizers x N doses	12	79.9^{ns}	148.6^{ns}	1.3^{ns}	0.6^{ns}	**53.5***	**70.7****
Residue	114	24.7	84.3	0.9	2.8	23.3	27.3
Mean		54.8	123.4	6.8	6.8	34.3	35.5
Coefficient of variation (%)		9.1	7.4	14.1	13.1	14.1	14.8

Abbreviations: DMA, dry mass of aerial parts; DMG, dry mass of grains; a - Soil: clay and sandy; b - Fertilizer: BUP2:1, BUP1:2 and BUP1:4 and pure urea; c - N dose: 0, 75, 150, 300 and 600 mg dm^{-3} soil; Statistical differences are denoted by * ($p < 0.05$), ** ($p < 0.01$) and ns (not significant).

In general, application of BUPs at the lowest nitrogen doses contributed to high AEI values, particularly BUP$_{2:1}$ at 150 mg dm^{-3} of nitrogen in sandy soil (Figure 3A) and BUP$_{1:2}$ and BUP$_{1:4}$ at 75 mg dm^{-3} in clay soil (Figure 3B). Considering nitrogen doses within the range 150 to 600 mg dm^{-3}, the mean values of AEI in sandy soil showed a direct relationship with the proportion of biochar in the formulation (i.e. highest with BUP$_{2:1}$ and lowest with BUP$_{1:4}$). These findings indicate that biochar improves nitrogen availability and utilization. However, in clay soil the application of BUPs did not contribute to increase AEI, which presented rates similar to those obtained with urea alone.



Sandy and clay soil; all fertilizers:
$y = 0.0105x + 52.491$; $R^2 = 0.879$



Sandy and clay soil; all fertilizers:
$y = -0.000016x^2 + 0.014595x + 5.124712$;
$R^2 = 0.997$

Sandy and clay soil:
(•) Urea: $y = -0.000026x^2 + 0.01853x + 4.3921$;
$R^2 = 0.993$
(•) Mean BUPs: $y = -0.000015x^2 + 0.01435x + 4.70157$;
$R^2 = 0.993$

Figure 1. Effects of independent variables (soil texture, nitrogen dose, fertilizer type) on the characteristics of upland rice production: (A) chlorophyll index; (B) plant height; (C) number of tillers; and (D) number of panicles. Data were obtained for plants grown in sandy and clay soils. Bars bearing dissimilar lower case letters represent mean values that are significantly different ($p = 0.0017$). Abbreviation: BUP, biochar-urea pellets.

Figura 1. Efeito das variáveis independentes (textura do solo, dose de nitrogênio e formulação de fertilizante organomineral) nas características do arroz de terras altas: (A) índice de clorofila; (B) altura de plantas; (C) número de perfilhos; (D) número de panículas. Os dados foram obtidos de plantas cultivadas em solo argiloso e arenoso. Letras minúsculas diferentes nas barras indicam diferenças significativas entre as médias (p = 0.0017). Abreviação: BUP, pellets biochar-ureia.

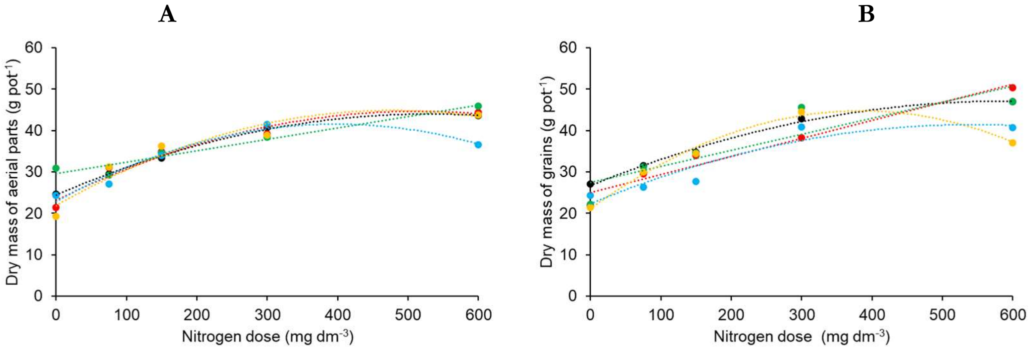
4. DISCUSSION

The results obtained in the present study showed that the effects of biochar-urea combinations is depending on the soil texture. In sandy soil the response of DMG to BUPs at different doses of nitrogen were similar, except for BUP$_{1:4}$ which, showed a marked reduction in grain production at the highest nitrogen dose of BUP, as well as urea. On the other hand, the effects of BUP$_{1:4}$ on panicle and DMA production were equivalent to those of BUP$_{2:1}$ and BUP$_{1:2}$. In contrast, urea alone contribute to reduce panicle and DMA production at 600 mg dm^{-3}. In clay soil, no differences were detected between the BUPs regarding production of DMG, DMA, tillers or panicles. According to Sangoi et al. (2003), clay-rich soils not only exhibit greater nitrogen retention capacity compared with sandy soils, but are also more effective in retaining moisture because of differences in water dynamics. Hence, leaching losses are lower in clay soils and plants can better exploit the nitrogen available, contrary to the effects in sandy soil where nitrogen percolates rapidly through the soil particles. Jia et al. (2021) state that urea coated with biochar had controlled nitrogen losses, mainly related to nitrate leaching, due to the slow release and also by the adsorption of nitrogen in the pores and functional groups of the surface of the biochar.

Along the period of the experiments, part of BUPs remained longer than the urea pellets on the surface of the soil. The mechanical durability of BUP$_{2:1}$ and BUP$_{1:2}$ (≥ 10 kgf) were considerably higher than that of BUP$_{1:4}$ (1.5 kgf), and the increased hardness likely contributed to the slow release of the nitrogen content of the pellets.

Dall'Orsoletta et al. (2017) reported that the loss of nitrogen through ammonia volatilization from urea ranged from 10.8 to 13.2% of the total nitrogen applied, regardless of soil moisture content, and no significant improvement was obtained when an organomineral fertilizer based on urea coated with poultry litter was used. Queiroz (2018) compared NUE values in maize cultivated in a 50% clay soil fertilized with 13 different OMFs containing biochar as organic matrix and found no significant differences regarding nitrogen use. However, the authors reported that, in comparison with other nitrogen sources, the release of nitrogen from biochar-urea formulations was slower suggesting that the organomineral fertilizer had the potential to improve NUE, especially in sandy soils. Zheng et al. (2013) demonstrated that, in addition to the physical protection offered by the biochar-urea pellet, the presence of the organomineral matrix itself improved NUE in maize by increasing nitrogen bioavailability in agricultural soils. Such effect is likely due to links formed between the nitrogen of the fertilizer source and the surface of the biochar matrix (Shi et al., 2020).

Considering treatment BUP1:4 with 600 mg dm^{-3} of nitrogen, the amount of biochar applied to the soil corresponded to 667 kg ha^{-1}, while for BUP2:1 the amount of biochar applied is 8-times greater (5,333 kg ha^{-1}).This comparison is important because the feasibility of using biochar must take into account the cost-benefit, since the BUP production must, at the least, be equivalent to the financial returns of its use. Despite evidence that biochar improves AEI, there are little information about the cost of production of the organomineral fertilizer, thus the economics concerning its use require careful assessment. In addition to the direct benefits of BUPs on crop yield, it is important to emphasize the environmental contribution of OMFs technology to the mitigation of N_2O emissions as well as the fixation of atmospheric CO_2. Further research in this field should be encouraged with particular emphasis on reducing the production costs of biochar.



Clay soil:
(⚫) All fertilizers:
$y = -0.00007{*}x^2 + 0.0738{**}x + 24.4$
$R^2 = 0.99$
Sandy soil:
(🔴) BUP$_{2:1}$: $y = -0.00008{*}x^2 + 0.0837{**}x + 23.1$
$R^2 = 0.96$
(🟢) BUP$_{1:2}$: $y = 0.02751{**}x + 29.6$
$R^2 = 0.95$
(🟡) BUP$_{1:4}$: $y = -0.0001{**}x^2 + 0.0966{**}x + 21.9$
$R^2 = 0.92$
(🔵) Urea: $y = -0.00012{**}x^2 + 0.094{**}x + 22.9$
$R^2 = 0.96$

Clay soil:
(⚫) All fertilizers:
$y = -0.000058{*}x^2 + 0.0689{*}x + 26.7$
$R^2 = 0.99$
Sandy soil:
(🔴) BUP$_{2:1}$: $y = 0.0437{**}x + 25.0$
$R^2 = 0.96$
(🟢) BUP$_{1:2}$: $y = -0.00011{**}x^2 + 0.109{**}x + 22.5$
$R^2 = 0.99$
(🟡) BUP$_{1:4}$: $y = -0.00016{**}x^2 + 0.1232{**}x + 21.1$
$R^2 = 0.99$
(🔵) Urea: $y = -0.000065{*}x^2 + 0.0704{**}x + 22.3$
$R^2 = 0.89$

Figure 2. Effects of independent variables (soil texture, nitrogen dose, fertilizer type) on the characteristics of upland rice production: (A) dry mass of aerial parts (DMA); (B) dry mass of grains (DMG). Data were obtained for plants grown in sandy and clay soils. Abbreviation: BUP, biochar-urea pellets; *, $p < 0.05$; **, $p < 0.01$.

Figura 2. Efeito das variáveis independentes (textura do solo, dose de nitrogênio, tipo de fertilizante) nas características do arroz de terras altas: (A) massa seca da parte aérea (DMA); (B) massa seca de grãos (DMG). Os dados foram obtidos de plantas cultivadas em solo argiloso e arenoso. Abreviação: BUP, pellets de biochar-ureia; *, $p < 0.05$; **, $p < 0.01$.

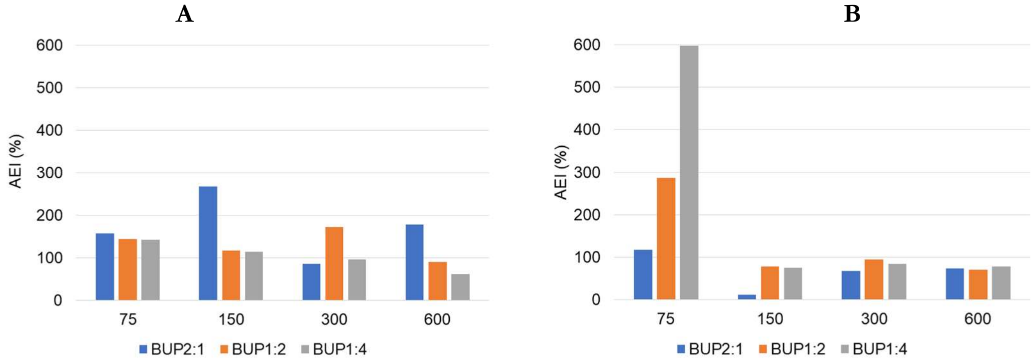


Figure 3. Agronomic efficiency index (AEI) of different formulations of biochar-urea pellets (BUPs) in (A) sandy soil and (B) clay soil. Bar designations: (🟦) BUP$_{2:1}$; (🟧) BUP$_{1:2}$; (⬜) BUP$_{1:4}$.

Figura 3. Índice de eficiência agronômica (AEI) de diferentes formulações de pellets biochar-ureia (BUPs) em (A) solo arenoso e (B) solo argiloso. Cores das barras: (🟦) BUP$_{2:1}$; (🟧) BUP$_{1:2}$; (⬜) BUP$_{1:4}$.

5. CONCLUSIONS

This study study demonstrated that soil texture plays a key role in the performance of biochar-urea pellets (BUPs). In sandy soil, the yields of rice obtained with BUPs were either equivalent to or greater than those obtained with urea alone. The best performance in sandy soil was observed with the application of $BUP_{2:1}$, showing that the biochar-urea ratio is relevant for improving the Agronomic Efficiency Index.

6. FUNDING

The study was partially funded by Fundação de Amparo à Pesquisa do Estado de Mato Grosso (FAPEMAT; grant no. 0585720/2016) and Conselho Nacional de Desenvolvimento Cientifico e Tecnológico (CNPq) third author research productivity grant PQ1D n.° 304621/2017-0.

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