Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga
ISSN 1983-2125 (online)

http://dx.doi.org/10.1590/1983-21252025v3812689rc

Scientific Article

Effects of soil compaction and wood ash application on reproductive components of safflower

Efeitos da compactação do solo e aplicação de cinza vegetal sobre componentes reprodutivos do cártamo

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ABSTRACT - Increased mechanization favors subsurface soil compaction, and the addition of agro-industrial waste can improve its chemical and physical characteristics. The objective of this study was to evaluate the reproductive components of safflower cultivated in Brazilian Cerrado soil compacted and fertilized with wood ash. The experiment was conducted in a greenhouse with a randomized block design with five levels of compaction and fertilized with five doses of wood ash, with 4 replicates, totaling 100 experimental units. The data on the number of branches, days to flowering, number of capitula, capitulum dry mass and total shoot dry mass were collected 75 days after plant emergence at the time of harvest. The results were subjected to analysis of variance; when significant, regression was applied with a significance of up to 5%. All the variables analyzed were affected by compaction level and wood ash level. The dose of wood ash that provided the highest shoot dry weight was 25.25 g dm^{-3}. For the soil bulk density levels, the linear decreasing regression model was adjusted as the soil bulk density levels increased. Thus, the addition of wood ash is beneficial for the development of safflower crops up to a dose of 24 g dm^{-3}, and an increase in soil compaction from 1.2 Mg dm^{-3} is harmful to plant development.

Keywords: Physical attribute. Solid waste. Oilseed. Productive characteristics.

RESUMO - O aumento da mecanização favorece a compactação subterrânea do solo, e a adição de resíduos agroindustriais pode melhorar suas características químicas e físicas. O objetivo deste estudo foi avaliar os componentes reprodutivos do cártamo cultivado em solo de Cerrado brasileiro, compactado e adubado com cinza vegetal. O experimento foi conduzido em casa de vegetação em delineamento de blocos casualizados com cinco níveis de compactação e adubado com cinco doses de cinza vegetal, com 4 repetições, totalizando 100 unidades experimentais. Os dados de número de ramos, dias para floração, número de capítulos, massa seca de capítulos e massa seca total da parte aérea foram coletados 75 dias após a emergência das plantas, no momento da colheita. Os resultados foram submetidos à análise de variância, quando significativo, foi aplicada regressão com significância de até 5%. Todas as variáveis analisadas foram afetadas pelos níveis de compactação e níveis de cinza vegetal. A dose de cinza vegetal que proporcionou maior massa seca da parte aérea foi de 25,25 g dm^{-3}. Para os níveis de densidade do solo, houve ajuste no modelo de regressão linear decrescente à medida que os níveis de densidade do solo aumentaram. Assim, conclui-se que a adição de cinza vegetal é significativa para o desenvolvimento da cultura do cártamo até a dose de 24 g dm^{-3}, e o aumento dos níveis de compactação do solo a partir de 1,2 Mg m^{-3} são prejudiciais ao desenvolvimento das plantas.

Palavras-chave: Atributo físico. Resíduo sólido. Oleaginosas. Características produtivas.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

Received for publication in: May 13, 2024.
Accepted in: June 11, 2025.

Editor in Chief: Aurélio Paes Barros Júnior

Data Availability: The data that support the findings of this study can be made available, upon reasonable request, from the corresponding author.

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INTRODUCTION

In a world that faces constant challenges, we need to transform our agri-food systems and prepare our planet for the future (FAO, 2022). Given the growing demand for food for human and animal food, economic, environmental and agronomic factors are limiting the increase in agricultural production systems (ALMEIDA et al., 2017). Considering increasingly technified systems and with a greater number of interventions related to mechanization, productive areas are increasingly prone to soil compaction.

In compacted soils in the subsurface "foot-of-grid", there is a reduction in root growth and water movement in the soil, which ultimately leads the farmer to turn it over, physically and biologically disrupting it. To avoid mechanical interventions, the main strategy for the physical recovery of soils is based on the rotation of crops with a vigorous and aggressive root system, promoting long-term improvements in physical quality, especially in the total porosity, hydraulic conductivity and macroporosity of the soil. (DJIEMON; GASSER; GALLICHAND, 2019).

Considering methods for soil conservation and physical and chemical improvements, agro-industrial waste, such as wood ash, has been added because it has the ability to correct soil pH and provide nutrients, improving its conditions for cultivation. However, as with any other residue, studies are needed to evaluate the best doses and responses of plants regarding their use (ISLABÃO et al., 2016; SMOL et al., 2015).

In combination with wood ash fertilization, crop rotation is a management technique that changes biological, chemical and physical properties. In addition to performing nutrient cycling with the use of plants with a vigorous root system, crop rotation can be performed in the medium/long term, improve the physical characteristics of the soil, promote the water infiltration ratio and increase the carbon stock.

Currently, the most commonly used plants for this purpose are grasses and legumes; however, some Asteraceae have gained increasing importance because of their versatility and high protein and oil contents (SAUZET et al., 2021; SEDDAIU et al., 2016). Safflower (*Carthamus tinctorius* L.), belonging to the Asteraceae family, is an annual oilseed used in cultivation systems in several countries in the Middle East and North and South America. In Brazil, cultivation is still negligible, and research on culture is scarce. The crop is extremely versatile and adaptable to various cultivation conditions, with high dry matter performance, grain production and oil content (LEHNHOFF et al., 2017) when properly managed.

Considering the versatility of safflower, this plant has become an excellent alternative second crop plant for Cerrado vegetation in the state of Mato Grosso (QUEIROGA; GIRÃO; ALBUQUERQUE, 2021). With this in mind, the aim of this work was to evaluate the productive performance of safflower under different levels of soil bulk density, with the application of wood ash as a soil conditioner in subsurface layers.

MATERIAL AND METHODS

The experiment was conducted in a greenhouse located in the municipality of Rondonópolis-MT, with coordinates of latitude 16° 28 '150 "S, longitude 50° 38' 08" W and an altitude of 284 m. During the experiment, the daily temperature and relative humidity were checked, obtaining averages of 27 °C and 81%, respectively.

The experiment was conducted in a randomized block design with a 5 × 5 factorial scheme, with five doses of wood ash (0, 8, 16, 24 and 32 g dm^{-3}) and five levels of soil bulk density (1.0, 1, 2, 1.4, 1.6 and 1.8 Mg m^{-3}), with 4 replicates.

The soil was collected from a Cerrado area in the 0–0.2 m depth layer and classified as Oxisol soil (SANTOS et al., 2018).

The chemical and particle size characterization followed the methodology recommended by Embrapa (2011) (Table 1).

Table 1. Chemical and granulometric attributes of Oxisol soil in the 0–0.20 m depth layer in an area under Cerrado vegetation.

pH	OM	P	K	Ca	Mg	Al	H+Al	CEC	Zn	Cu	Fe	Mn	B	S	Sand	silt	clay
$CaCl_2$	g kg^{-1}	mg dm^{-3}		- - - - - - - - - - cmolcdm^{-3} - - - - - - - - - -					- - - - - - - - - - - mg dm^{-3} - - - - - - - -						- - - - - - g kg^{-1} - - - -		
4.0	20.6	1.1	43	0.5	0.3	1.2	7.4	8.3	0.3	1.2	152	7.4	0.2	8	425	100	475

P - Mehlich^{-1}.

The wood ash used was obtained from food industry furnaces, which, during the combustion process, had an average temperature of 800 °C, with combustion starting at 250 °C. The wood ash was analyzed as fertilizer, following the methods of Alcarde (2009), which presented the following characteristics (Table 2).

Table 2. Chemical attributes of wood ash.

pH	NP	N	P_2O_5	K_2O	Ca	Mg	Fe	Mn	B	SO_4	Si	Cr	As
$CaCl_2$	- % -											mg kg^{-1}	
10.7	28	0.3	0.9	3.4	3.3	2.1	1.03.	0.04	0.01	0.4	27.4	7.98	0.21

NP - neutralizing power; N - nitrogen; P2 O5 - phosphorus in neutral ammonium citrate and water (CNA + water); K2° - potassium; Ca - calcium; Mg - magnesium; Fe - iron; Mn - total manganese; B - total boron; Zn - total zinc; SO4 – sodium; Si – silicon; Cr – chromium; As– arsenic.

To complement the chemical analyses of the material, physical hydric analyses of the waste were also performed, following the methodology suggested by MAPA (2007). The following values were found: material density, 0.45 Mg m^{-3}; particle density, 1.65 g dm^{-3}; and water retention capacity, 0.71 cm³ cm^{-3}.

After collection, 10 dm^3 of soil was added to 12.0 dm³ plastic bags, and the respective doses of wood ash were added plus 0.2 L of water, which remained sealed for approximately 30 days to allow the residue to react.

Each experimental unit had 9.4 dm³ of soil, composed of three isometric rings of PVC (Vanila polycride) 0.2 m in diameter and 0.1 m in height, joined by silver tape. Previous soil compaction tests performed by Fagundes, Silva and Bonfim-Silva (2014) in soil collected in the same area of the present experiment identified an optimal compaction moisture of 16%, which was used for compaction. Within each ring of the 0–0.1 m layer, an Irrigas® was installed, a device used to measure soil moisture. This equipment consists of a porous capsule and a plunger, which indicates when the soil has a moisture content lower than 22% of the maximum water retention capacity in the soil. When the moisture content was lower than this value, irrigation was performed.

The soil of the 0.1–0.2 m layer was compacted with the aid of a P15ST hydraulic press, and the 0–0.1 m and 0.2–0.3 m layers were compacted with 3.14 dm³ of soil, equivalent to a density of 1.0 Mg m^{-3}. To estimate the volume of soil used in each layer, the volume of dry soil was first stipulated (Equation 1), and then the wet soil mass to be added to the compacted layers was calculated (Equation 2):

$$MSS=Va \times Ds \quad (1)$$

$$MSU=MSS\,(1 + \theta m) \quad (2)$$

where MSS is the dry soil mass (kg), Va is the ring volume (dm³), Ds is the soil bulk density (Mg m^{-3}), MSU is the wet soil mass (kg) andq m is the gravimetric moisture.

In the lower parts of the pots, a mesh with 0.001 m mesh was fixed, covering the entire base with the aid of a rubber strip, to drain the water and capture the contents of the pots. For the bottom of the container, plastic plates 0.3 m in diameter and 0.05 m in height were placed under each experimental unit.

After the pots were assembled, 10 seeds were distributed per experimental unit of the IMA 336 safflower accession at a depth of 0.02 m. Four days after sowing, the emergence process began. Two thinnings were performed to obtain a final population of three plants per pot.

The irrigation was initially performed daily by the surface of the pots. Fifteen days after sowing, irrigation was performed in the lower part of the experimental units, and water was added to the plastic dishes to stimulate the plants to break the compacted layer (0.1–0.2 m).

Owing to the chemical characteristics of wood ash, only nitrogen supplementation was performed. This mixture was provided in the form of urea at a dose of 150 mg dm^{-3}, which was divided into three applications at 15, 30 and 45 days after emergence at proportions of 26, 37 and 37%, respectively, and was diluted in aqueous solution to meet the needs of the culture according to Bonfim-Silva et al. (2015).

During the development of the crop, the number of days to flowering was measured, and before being cut at 75 days after emergence, the number of branches per plant and the number of capitula were counted. After being cut, the aerial parts of the plants were dried in a ventilation oven at 65 °C for 72 hours or until they reached a constant mass to obtain the dry mass of the capitula and the dry mass of the shoot.

Statistical analysis

After the data were collected, the results were subjected to statistical analysis via SISVAR software (FERREIRA, 2011) via analysis of variance (ANOVA) and regression tests, considering a significance level of up to 5%. When the effects of the factors were significant in isolation, the regression test was applied. In cases where interactions between the factors were identified, the data were analyzed via regression via SAS software (SAS INSTITUTE, 2002) to obtain the response surface equation.

RESULTS AND DISCUSSION

The treatments with the 0 g dm^{-3} dose of wood ash resulted in severe chlorosis and subsequent death at 15 days after emergence, making it impossible to determine the variables after this date. For the number of branches, days to flowering and number of capitula plants, interference was observed for both the soil bulk density and wood ash dose at different significance levels (Table 3).

Table 3. Summary of the analysis of variance for the variables number of branches plant no.$^{-1}$ (NRAM), days to flowering (DFLOR) and number of capitula (NCAP) no. Pot^{-1}.

FV	GL	p value		
		NRAM	DFLOR	NCAP
(cz)	3	< 0.001***	< 0.001***	< 0.001***
(ds)	4	< 0.001***	< 0.001***	< 0.001***
cz x ds	12	< 0.1 $^{\theta}$	< 0.1 $^{\theta}$	0.18^{ns}
Residue	57			
CV (%)		41.68	5.9	40.18
Mean		9.78	50.12	32.27

NRAM = Number of branches, DFLOR = Days to flowering, NCAP = Number of capitula, FV = Source of variation, GL = Degree of freedom, QM = Mean square, cz = wood ash, ds = soil density, CV = Coefficient of variation, $^{\theta}$, **, *** = Significant at 10, 1 and 0.1% probability test f.

There was a significant interaction effect between the wood ash dose and the soil bulk density. Thus, the response surface study indicated that the greatest number of total branches (17.1) was observed when the soil was fertilized with a dose of wood ash of 27.67 g dm^{-3} at a soil bulk density level of 0.98 Mg m^{-3} (Figure 1). The number of branches is a vegetative characteristic directly linked to reproductive aspects in safflower plants, as they are the branches that will descend new chapters and consequently more achenes.

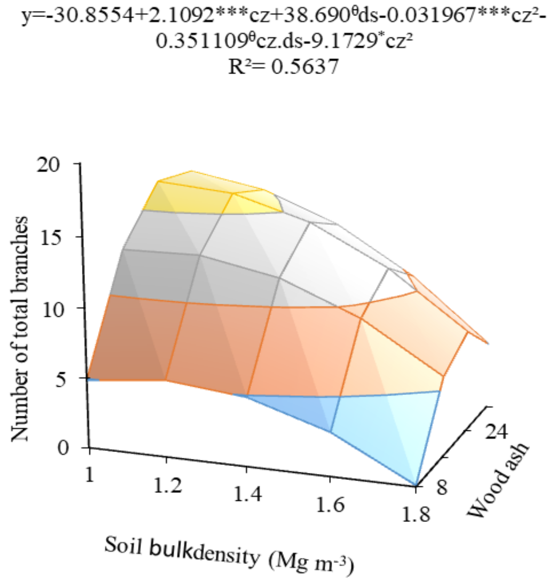

Figure 1. Total branches of safflower at 75 days after emergence as a function of the combination of wood ash dose and soil bulk density in the Oxisol. θ, *, **, *** = significant at 10, 5, 1 and 0.1% probability, respectively.

Neves et al. (2020) evaluated the development of peanuts under various soil bulk density levels and coinoculated them with microorganisms in soils under the same conditions as those used in the present study and under subsurface compaction and reported that the soil compaction level did not affect the number of branches of peanut plants. This result may be associated with the test being developed in pots, preventing the emission of new stolons in the soil. These findings indicate that studies addressing the emission of reproductive and vegetative branches should be conducted in greater detail, as plants can behave in different ways in response to the same type of stress (TAIZ et al., 2017).

The doses of wood ash and the soil bulk density levels together influenced the flowering season of the plants. The doses of wood ash provided a quadratic model for the number of days to flowering, with a shorter period when subjected to a dose of wood ash of 23.0 g dm^{-3} (Figure 2). However, for the soil bulk density levels, a decreasing linear behavior was observed with increasing soil bulk density, advancing the cycle by almost 10 days when the plants were grown at relatively high soil densities.

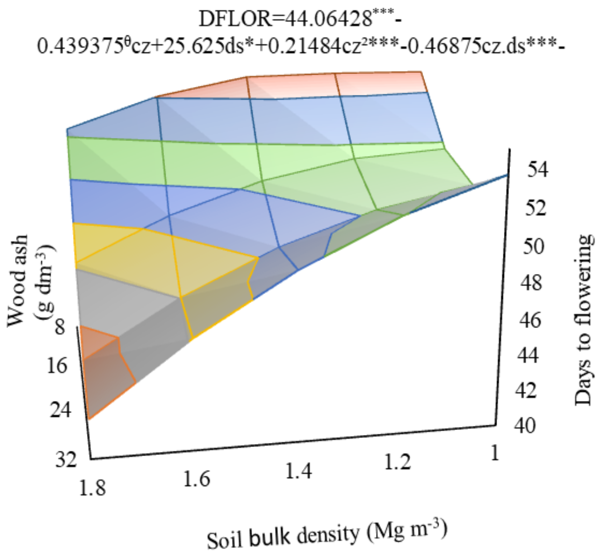

Figure 2. Days to flowering (DFLOR) of safflower as a function of ash level and soil compaction level. cz = Wood ash, ds = Soil bulk density, θ, *, ** = Significant at 10, 5 and 1% probability, respectively.

The plants in the treatments without the addition of wood ash did not flower because most plants died early in their development due to low base saturation and soil pH. Thus, plants subjected to a dose of wood ash of 8 g dm^{-3} flowered approximately ten days later than those subjected to higher doses.

Linhares et al. (2020) evaluated the development of sunflower under compaction and intercropping systems and reported that soil compaction directly affects the productive and reproductive characteristics of plants, demonstrating the probable sensitivity of sunflower and Asteraceae to soil compaction in general.

For the variable number of capitula, it was possible to observe a significant isolated interaction for the soil bulk density levels and wood ash doses. Both treatments tended to quadratically influence the number of capitula, and when grown with a dose of 26.81 g dm $^{-3}$ wood ash, a maximum of 41.93 capitula pot $^{-1}$ was obtained (Figure 3A). In contrast, at compaction levels of 1.11 Mg m $^{-3}$, a maximum number of capitulates of 39.7 pot $^{-1}$ capitula was observed (Figure 3B).

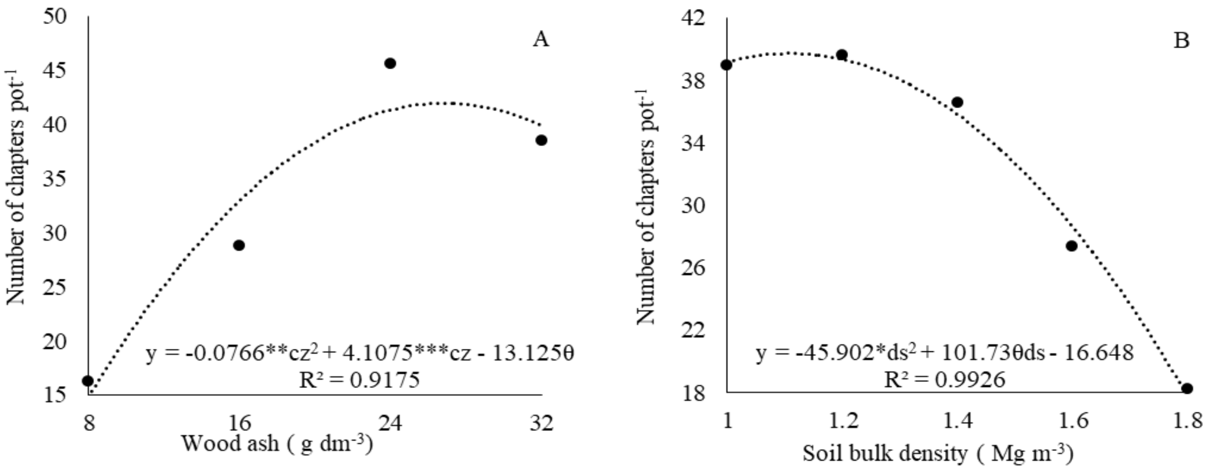

Figure 3. Number of chapters per pot as a function of the combination of wood ash dose (A) and soil bulk density (B) in the Oxisol. *, **, *** = significant at 5, 1 and 0.1% probability, respectively.

The number of chapters is directly related to crop yield and, consequently, plant production. The number of capitula per pot indicates that the plants were able to withstand compaction at a soil bulk density of up to 1.1 Mg m^{-3}, with insignificant losses compared with the soil without compaction.

The results of the present study correspond to those reported by Paludo et al. (2017), who studied safflower genotypes grown in the same soil and density levels and reported a decrease in the number of capitula when the plants were subjected to compactions greater than 1.4 Mg m^{-3}.

Bonfim-Silva et al. (2017b) verified the response of safflower to phosphorus fertilization and reported a positive linear trend in the number of capitula in response to phosphorus, with an increase of 54% in the number of capitula, indicating the need for fertilization for cultivation in Cerrado soils. Thus, the addition of wood ash, even when grown in soil with increased density, provides not only an alternative for waste disposal but also a source of nutrients such as phosphorus, potassium, calcium and magnesium to increase the capitulum production of safflower (BONFIM-SILVA et al., 2018).

Some characteristics of wood ash ensure that when grown in soils subjected to compaction, they promote improvements in their physical composition, such as macroporosity and soil water retention, facilitating plant development because the material has low density and granules, which improve aeration and water maintenance in the soil (ISLABÃO et al., 2016; PEREIRA; SILVA; BONFIM-SILVA, 2016).

The dry masses of the components of the aerial parts of the plants were influenced in isolation by the doses of wood ash and the soil bulk density levels (Table 4).

Table 4. Summary of the analysis of variance for the components of dry mass of capitulas g pot^{-1} (MASCAP) and total dry mass of shoots g pot^{-1} (SDM).

			MASCAP	MSPATOT
FV	GL1	GL2	QM	QM
Block	4	3	9.91	51.22$^{\theta}$
(cz)	4	3	173.22***	1667.40***
(ds)	4	4	136.06***	565.77***
cz x ds	16	12	18.26*	84.93***
Residue	72	57	8.60	23.46
CV (%)			32.6	32.76
Mean			8.97	14.78

MASCAP = Chapter dry mass, MSPATOT = shoot total dry mass, FV = source of variation, GL 1 and 2 = degrees of freedom for Chapters total dry mass and shoot total dry mass, respectively, QM = mean square, cz = wood ash, ds = soil bulk density, CV = coefficient of variation, $^{\theta}$, *, *, **, *** = significant at 10, 5, 1 and 0.1% probability.

The dry mass of the safflower capitula was significantly influenced by the wood ash dose and soil bulk density. Both treatments fit the quadratic regression model, with a maximum value of 11.28 g pot^{-1} when a wood ash dose of 24.80 g dm^{-3} was applied and 11.39 g pot^{-1} when the plants developed at the soil bulk density. of 1.07 Mg m^{-3}, corresponding to maximum production rates of 11.28 g pot^{-1} (Figure 4A) and 11.39 g pot^{-1} (Figure 4B), respectively.

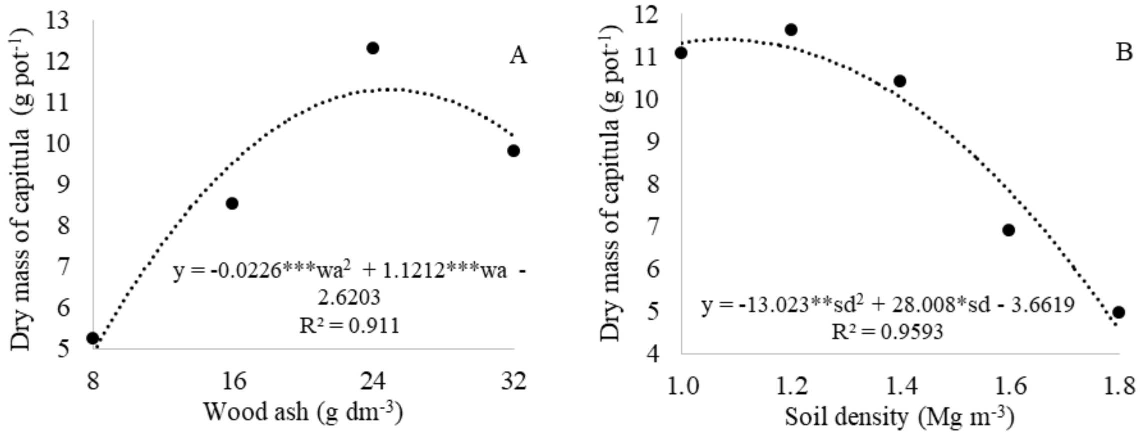

Figure 4. Dry weight of safflower plant capitula as a function of wood ash level (A) and soil bulk density level (B) in the Oxisol (Haplo-udoxis) ***, *** indicate significance at 5%, 1% and 0.1% probability, respectively.

The evaluation of the total dry mass of the shoots revealed a significant effect in isolation for the doses of wood ash and soil bulk density levels, represented significantly by the quadratic regression model for residue doses. The dose that provided the highest dry mass value was when the plants developed in soil fertilized with 25.25 g dm^{-3} wood ash (Figure 5A). For the soil bulk density levels, the linear regression model was adjusted as the soil density increased. (Figure 5B).

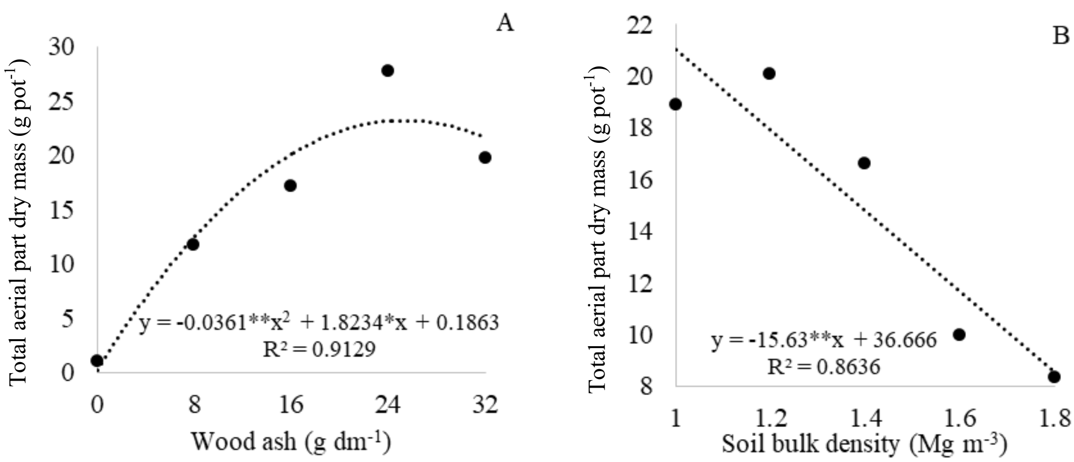

Figure 5. Total dry mass of the aerial part (g $pot^{-1)}$ as a function of the wood ash dose (A) and soil bulk density (B) in the Oxisol. ***, *** indicate significance at 5%, 1% and 0.1% probability, respectively.

The mean values of the shoot dry mass in the present study agree with those reported by Fontenelli et al. (2017), who evaluated the development of safflower using different irrigation methods, including Irrigas, and reported an average production of 7.7 g $plant^{-1}$ of total shoot dry mass, a value close to that reported in the present study when the soil was fertilized with the optimal dose of 25.25 g dm^{-3} wood ash, with a dry mass production of 7.3 g $plant^{-1}$. Thus, replacing or complementing crop fertilization with the use of wood ash is suggested.

The increase in dry matter production of the aerial part as a function of the wood ash dose was reported by Bonfim-Silva et al. (2017c, 2017a), who evaluated cowpea (Vigna unguiculata) and jack bean (*Canavalia ensiformis*) and reported an increase in shoot dry mass of 93% for Vigna unguiculata and 66% for *Canavalia ensiformis*. The increases are explained mainly by the regulation of soil pH, which favors the availability of nutrients such as P, K, Ca and Mg. The highest dry mass yields of the aforementioned studies were observed when the soil was fertilized with doses close to

20 g dm^{-3} wood ash.

Paludo et al. (2018) evaluated the performance of safflower genotypes subjected to the same soil bulk density levels and reported that plants that developed at soil bulk density levels of 1.1 Mg m^{-3} presented maximum shoot development. The increase in soil bulk density implies a direct decrease in the porous spaces of the soil. Consequently, root development is compromised, directly affecting the plant area, due to the restriction of nutrient and water absorption (NUNES; BONFIM-SILVA; SILVA, 2016).

CONCLUSIONS

The application of 24 to 27 g dm^{-3} wood ash improved the development of safflower crops.

Soil bulk density levels of up to 1.2 Mg cm^{-3} do not harm the development of safflower plants.

There was a significant interaction effect at the 10% probability level between soil compaction and wood ash dose on the day of flowering and the number of branches of safflower plants.

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