ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.26, n.4, p.258-265, 2022
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v26n4p258-265

Wood ash as a vegetative-growth promoter in soils with subsurface compaction[1]

Cinza de madeira como promotor do crescimento vegetativo em solos com compactação subsuperficial

Edna M. Bonfim-Silva[2*], Tulio Martinez-Santos[3], Tonny J. A. da Silva[2], Rackel D. de S. Alves[2], Everton A. R. Pinheiro[2] & Thiago F. Duarte[2]

[1] Research developed at the Instituto de Ciências Agrárias e Tecnológicas, Universidade Federal de Rondonópolis, Rondonópolis, MT, Brazil
[2] Universidade Federal de Rondonópolis/Instituto de Ciências Agrárias e Tecnológicas, Rondonópolis, MT, Brazil
[3] Instituto Federal de Educação Ciência e Tecnologia de Mato Grosso, Campus Avançado Guarantã do Norte, Guarantã do Norte, MT, Brazil

HIGHLIGHTS:

Subsurface soil compaction did not affect the vegetative growth of safflower at the early stages of plant development.
Significant interactions between wood ash dose and subsurface compaction were partially regulated by the crop growth stage.
Regardless of wood ash dose, subsurface soil compaction was not alleviated for a single safflower growth cycle.

ABSTRACT: Subsurface soil compaction and nutritional stress are among the main factors that limit the yield of crops. Using forest residues, such as wood ash, is a viable option in the chemical recovery of soils and can promote vigorous root development in soils with subsurface compaction. The objective of this study was to indicate the most adequate dose of wood ash for efficient management of this residue applied in rotational crops cultivated in soils with subsurface compaction. Safflower plants (*Carthamus tinctorius*), a rotational crop with a deep taproot system, were grown in clay soil fertilized with different doses of ash and with induced levels of compaction in the subsurface layer. The experiment was conducted in a randomized block design, under a 4 × 5 factorial scheme, composed of four doses of wood ash (8.0, 16.0, 24.0, and 32.0 g dm^{-3}) and five levels of soil bulk density (1.0, 1.2, 1.4, 1.6, and 1.8 kg dm^{-3}), with four replicates. Crop growth variables (plant height, number of leaves, stem diameter, and SPAD chlorophyll index) were evaluated at 15, 45, and 75 days after emergence. The results indicated that soil compaction was the most limiting factor to the vegetative development of safflower, regardless of the ash dose. The interaction between the wood ash dose and bulk density, when present, showed that the best growth response occurred for ash dose of 25 g dm^{-3} for a soil bulk density of 1.2 kg dm^{-3}.

Key words: *Carthamus tinctorius*, soil management, bulk density

RESUMO: A compactação subsuperficial do solo e o estresse nutricional estão entre os principais fatores que limitam a produtividade dos cultivos agrícolas. A utilização de resíduos de origem florestal, como a cinza de madeira, é uma opção viável na recuperação química de solos, podendo proporcionar desenvolvimento radicular vigoroso em solos com compactação subsuperficial. Nesta pesquisa, objetivou-se indicar a dose de cinza vegetal mais adequada com vistas ao manejo eficiente desse resíduo aplicado em culturas rotacionais cultivadas em solos com compactação subsuperficial. Plantas de cártamo (*Carthamus tinctorius*), uma cultura de rotação com sistema radicular pivotante profundo, foram cultivadas em solo argiloso adubado com diferentes doses de cinza e com níveis de compactação induzida na camada subsuperficial. O experimento foi conduzido em delineamento experimental em blocos casualizados, sob esquema fatorial 4 × 5, composto por quatro doses de cinza vegetal (8,0; 16,0; 24,0 e 32,0 g dm^{-3}) e cinco níveis de densidade do solo (1,0; 1,2; 1,4; 1,6 e 1,8 kg dm^{-3}), com quatro repetições. As variáveis de crescimento da cultura (altura de plantas, número de folhas, diâmetro do caule e índice de clorofila SPAD) foram avaliadas aos 15, 45 e 75 dias após a emergência. Os resultados indicaram que a compactação foi o fator mais limitante ao desenvolvimento vegetativo do cártamo, independentemente da dose de cinza. A interação entre os fatores dose de cinza de madeira e densidade do solo, quando presente, mostrou que a melhor resposta de crescimento ocorreu para a dose de cinza na ordem de 25 g dm^{-3} para uma densidade de 1,2 kg dm^{-3}.

Palavras-chave: *Carthamus tinctorius*, manejo do solo, densidade do solo

• Ref. 252474 – Received 22 May, 2021
* Corresponding author - E-mail: embonfim@hotmail.com
• Accepted 17 Oct, 2021 • Published 29 Oct, 2021
Editors: Ítalo Herbet Lucena Cavalcante & Hans Raj Gheyi

Introduction

Factors that limit agricultural production include soil compaction, which in addition to causing a physical impediment to root penetration, reduces soil macroporosity, affecting dynamic processes related to water availability, water infiltration, and gas flow in the soil profile (Shah et al., 2017a; Stoessel et al., 2018; Correa et al., 2019).

The adoption of crop rotation, associated with the use of plant species with the potential to promote soil biological scarification, is a more sustainable option of decompaction when compared to mechanical methods for the recovery of compacted soils (Martinez-Santos et al., 2019).

The use of soil conditioners obtained from residues rich in nutrients that are essential to plants, such as wood ash, can accelerate the soil recovery process while preventing environmental impacts caused by the diffuse disposal of these residues by industries (Qin et al., 2017; Johansen et al., 2021).

The types and amounts of nutrients and organic matter present in wood ash depend on the source material, as well as on the conditions in the burning process, such as temperature, oxygen concentration in the system, and type of boiler used by the industry (Merino et al., 2017). Studies with wood ash have verified, to some degree, positive alterations in chemical, physical, and biological properties of agricultural and forested soils (Bonfim-Silva et al., 2015; Symanowicz et al., 2018; Bang-Andreasen et al., 2021). Studies investigating wood ash effects on compacted and acidic soils, as is the case of many degraded areas in the Brazilian Cerrado, are still scarce (Bonfim-Silva et al., 2018; Martinez-Santos et al., 2019).

The present study tested the hypothesis that the improvement of soil chemical aspects resulting from the application of wood ash doses promotes a more vigorous growth of safflower (rotational crop) plants cultivated in soil subjected to levels of compaction in the subsurface layer. The objective of the present study was to indicate the most adequate dose of wood ash for efficient management of this residue applied in rotational crops in soils with subsurface compaction.

Material and Methods

The experiment was carried out in a greenhouse covered with transparent polyethylene film and equipped with an air cooling system (evaporative cooling pad and fan) located at the Federal University of Rondonópolis, in Rondonópolis, MT, Brazil, at the coordinates 16º 28' 15" S and 50º 38' 08" W, with an altitude of 284 m.

According to the Köppen-Geiger classification, the region has an Aw climate, characterized by a rainy summer and a dry winter (Souza et al., 2013). During the experiment, the mean values of temperature and relative humidity of the air inside the greenhouse were 27 ºC and 81%, respectively.

The experimental design was randomized blocks, in a 4 × 5 factorial scheme, corresponding to four doses of wood ash (8.0, 16.0, 24.0, and 32.0 g dm^{-3}) and five levels of soil bulk density (1.0, 1.2, 1.4, 1.6, and 1.8 kg dm^{-3}), with four replicates, totaling 80 experimental units. Given the naturally low pH of soils from the Brazilian Cerrado (Table 1) and the wood ash capacity of neutralizing H^+ ions, it was verified that the safflower plants could not survive the early stages of development under the wood ash dose of 0 g dm^{-3}; for this reason, the safflower vegetative growth was not analyzed for this specific treatment.

The soil was collected in a preserved Cerrado area, in the 0-0.20 m layer, being classified as Oxisol. Table 1 presents the chemical and particle-size characterization of the soil according to the specific methodology (Teixeira et al., 2017).

After being collected, the soil was placed in 12 dm^3 plastic bags and the respective doses of wood ash were added (8, 16, 24, and 32 g dm^{-3}). Soil moisture was maintained at 60% of the maximum water retention capacity (monitored gravimetrically) for the reaction of the material, remaining sealed for approximately 30 days for the residue to react with the soil (Bonfim-Silva et al., 2018).

The eucalyptus wood ash used in this study was obtained from furnaces of the food industry, and the average temperature during the combustion process was 800 ºC. Wood ash was analyzed as fertilizer, following the analysis protocol of Darolt et al. (1993) (Table 2). Analyses of the material density, particle density, and total porosity were also performed according to the methodologies described by Teixeira et al. (2017) and MAPA (2017) (Table 2).

Each experimental unit contained a volume of 9.4 dm^3, composed of three isometric cylinders of 200 mm in diameter and 100 mm in height, joined by silver tape. The layers 0-0.10 m (upper cylinder) and 0.20-0.30 m (lower cylinder) were completed with approximately 3.14 dm^3 of soil, which

Table 1. Chemical and particle-size characterization of Latossolo Vermelho distrófico (Oxisol) collected in the 0-0.20 m layer, in an area under native Cerrado vegetation

pH-$CaCl_2$	P	S	Ca	Mg	K	Al	H + Al	SB	CEC	V	m
	(mg dm^{-3})		($cmol_c$ dm^{-3})							(%)	
4.0	1.1	8	0.5	0.3	0.1	1.2	7.4	0.9	8.3	10.8	57.1
Zn	Mn	Cu	Fe	B				OM	Clay	Silt	Sand
(mg dm^{-3})								(g kg^{-1})			
0.3	7.4	1.2	152	0.2				20.6	475	100	425

*OM= Organic matter; CEC = Cations Exchange Capacity at pH 7.0; V = Base saturation; m= Aluminum saturation

Table 2. Chemical and physical characterization of the wood ash used in the experiment

pH	NP[1] (%)	N	P_2O_5	K_2O	Ca	Mg	SO_4	Si	Mn	B	Fe
		(mg kg^{-1})									
10.7	28	3	9	34	33	21	0.4	274	0.4	0.1	10.3
Cr	As		Ash density			ρ_s[2]			Total porosity		
(mg kg^{-1})			(kg dm^{-3})						(cm^3 cm^{-3})		
7.98	0.21		0.45			2.61			0.71		

[1] NP - Neutralizing power; [2] ρ_s - Particle density

is equivalent to an approximate density of 1.0 kg dm^{-3}, while the 0.10-0.20 m layer (intermediate cylinder) was composed of soil which was compacted using a P15ST hydraulic press.

To estimate the soil mass to be used in each of the cylinders representing the layers in the soil column, the dry soil mass required to reach the desired density (Eq. 1) was first estimated and then the wet soil mass to be added to the layers referring to each cylinder was calculated by Eq. 2:

$$\rho = \frac{m_s}{V} \leftrightarrow m_s = \rho V \quad (1)$$

where:
- m_s - dry soil mass (g);
- V - cylinder volume (cm^3); and,
- ρ - soil bulk density (kg dm^{-3}).

$$m = m_s (1 + U) \quad (2)$$

where:
- m - wet soil mass (g); and,
- U - moisture based on mass (16%).

At the bottom of the pots, a 1-mm-mesh screen was fixed covering the entire base to allow the drainage of excess water and retain the soil within the experimental unit.

The rotational crop evaluated was safflower (*Carthamus tinctorius* L.), also known in Portuguese as "Açafrão-bastardo", a plant of the Asteraceae family, which has a robust and deep taproot system. Safflower has a short growth cycle and is an efficient crop in recycling nutrients from deeper soil layers, especially nitrogen. The positive benefits of safflower to the soil have increased its adoption as a cover crop in the Brazilian Cerrado, leading to more sustainable cash crops rotation systems (e.g., soybean and corn).

After the pots were prepared, 10 seeds of safflower (accession: IMA 336) were distributed in each experimental unit, at depth of 2 cm. Four days after sowing, the plants began to emerge. Thinning was carried out twice to establish a final population of three plants per pot, which was similar to the plant population commonly encountered in the field.

To maintain adequate water conditions during the experiment, an Irrigas® device was installed inside each cylinder in the 0-0.10 m layer to measure the soil water content. This device, composed of a porous cup and a plunger, indicated the time for irrigation so that the soil water tensions were kept higher than 20 kPa.

Due to the chemical composition of the wood ash used, only nitrogen supplementation was performed in all treatments, at a dose of 150 mg dm^{-3}, using urea as a source due to its high nitrogen content and its availability at the experimental site. The application of the nutrient was split into three stages, at 15, 30, and 45 days after emergence, in the proportions of 26, 37, and 37%, respectively, following recommendations of Bonfim-Silva et al. (2015).

Three evaluations were performed, at 15, 45, and 75 days after emergence, to analyze the variables plant height (cm), number of leaves, and stem diameter (mm). At 15 and 45 days after emergence, the SPAD (Soil Plant Analysis Development) total chlorophyll index was obtained, indirectly indicating the chlorophyll content of six leaves of the middle third of the plants of each experimental unit, with a Minolta SPAD-502 device.

In the third and last evaluation, at 75 days after emergence, the SPAD index was not obtained as the plants were already in the senescence stage; however, the number of primary branches (descending from the main stem), secondary branches (originating from the primary branches), and total branches (primary + secondary branches) were counted.

The data were subjected to the normality test to check whether the errors followed a normal distribution. For variables with no normality, non-parametric statistical analysis was applied, while others were subjected to analysis of variance at $p \leq 0.05$ level, for subsequent regression analysis. Statistical analyses were carried out with R Studio software (R Development Core Team, 2018).

Results and Discussion

For plant height, the number of leaves, and SPAD chlorophyll index at 15 days after emergence only the wood ash doses caused significant effect ($p < 0.05$). Therefore, there was no significant interaction between wood ash dose and bulk density ($p > 0.05$) and there was no single effect of bulk density.

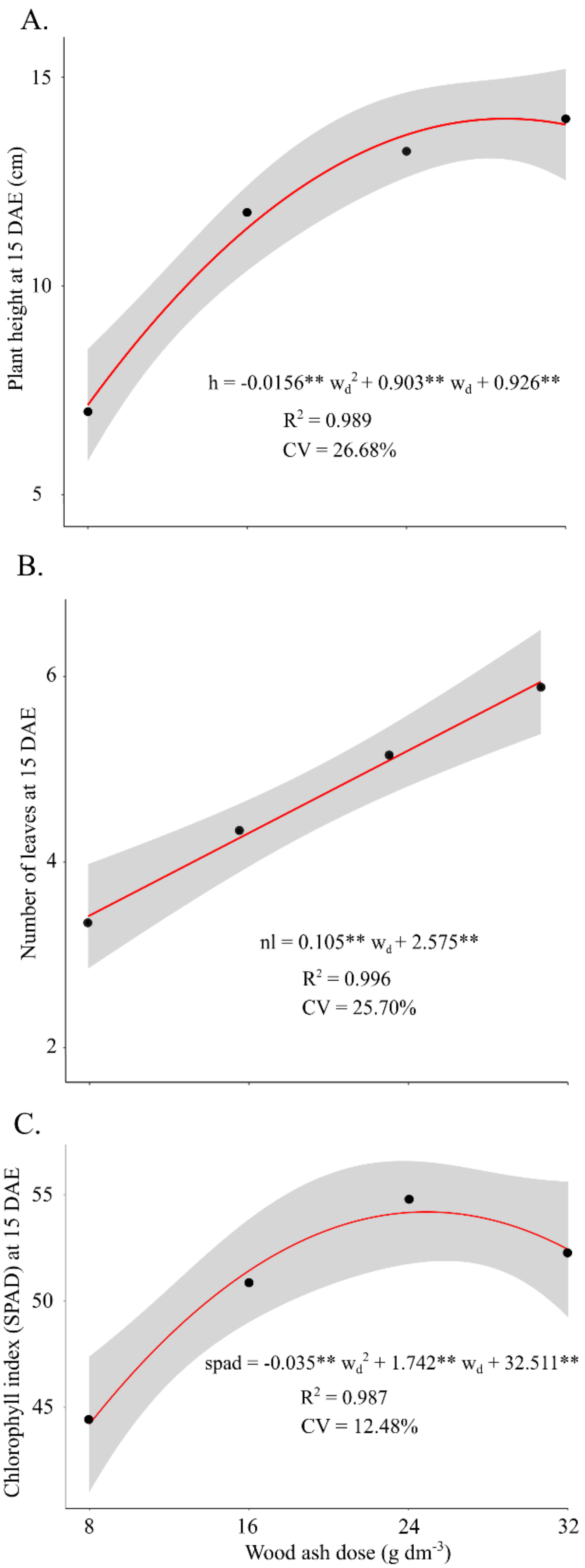
The absence of effect of subsurface soil bulk density on plant height at 15 days after emergence occurred because the root system probably had not yet reached the compacted soil layer in this growth stage according to the root growth pattern observed for this crop species.

The maximum height of safflower plants at 15 days after emergence was 14 cm, obtained for the wood ash dose of 28.93 g dm^{-3}. When comparing the dose that promoted the highest value of height with the lowest dose applied, there was an increase of 96% in plant height (Figure 1A).

The availability of potassium present in wood ash (Table 2) is one of the factors that explain the significant difference between the height of safflower plants at 15 days after emergence. Potassium acts as an enzymatic activator in the plant, as well as in the regulation of phytohormones that are responsible for regulating vegetative growth, such as auxins, cytokinin, gibberellin, abscisic acid and ethylene (Taiz et al., 2017).

In addition to potassium, wood ash contains a high concentration of silicon (Table 2). According to Janmohammadi et al. (2016), the growth of safflower plants was more vigorous under fertilizers with a higher concentration of silica (SiO_2) (e.g., bovine manure). According to the authors, there was an improvement in growth parameters given the increase in the efficiency of transport of elements in xylem sap, such as Mg and Fe, improvement in water absorption efficiency, as well as a stimulation of enzyme activity (nitrate reductase).

When evaluating the initial growth and agronomic performance of North American safflower cultivars in Brazil as a winter crop, Maziero et al. (2019) found a maximum mean plant height of approximately 13 cm at 30 days after emergence, that is, slightly lower than the values found in the present study



Data dispersion is shown by the shaded area. Significance level p = 0.05 (**)

Figure 1. Plant height (A), number of leaves (B), and SPAD chlorophyll index (C) of safflower at 15 days after emergence (DAE), grown in Latossolo Vermelho distrófico (Oxisol) and fertilized with wood ash doses (w_d)

at 15 days after emergence, which demonstrates the potential of wood ash to promote a more vigorous vegetative growth.

The evaluations of plant height at 45 and 75 days after emergence did not show a normal distribution of errors, so a non-parametric statistical analysis was performed. Table 3 presents Friedman's test values for these two evaluations.

Table 4 shows the adjusted p values for significant comparisons between treatments.

At 45 days after emergence, the dose of 32 g dm^{-3} at a bulk density of 1.0 kg dm^{-3} had a higher median when compared to the same dose at a bulk density of 1.6 kg dm^{-3} and to the dose of 8 g dm^{-3} at the density of 1.8 kg dm^{-3} (Table 5).

When the root system of the plants reached the compacted layer, there was a reduction in plant growth due to the physical impediment and restriction to the absorption of water and nutrients.

In addition to the physical impediment, plants in treatments that received the lowest doses of ash reduced their growth due to the lower availability of nutrients. This result is evident in the comparison of the dose of 32 g dm^{-3} at a bulk density of 1.0 kg dm^{-3} (median of 0.60 m), where there was a greater supply of nutrients and a lower bulk density, with the dose of 8 g dm^{-3} at a bulk density of 1.8 kg dm^{-3} (median of 30.83 cm) (Table 5).

At 75 days after emergence, the effect was similar to that obtained at 45 days after emergence. The dose of 32 g dm^{-3} at a bulk density of 1.0 kg dm^{-3} had a higher median compared to the three other treatments with higher densities (Table 5), demonstrating that the negative effect of soil compaction on plant height was more limiting than nutrient availability.

Table 3. Friedman's test for plant height of safflower at 45 and 75 days after emergence

Evaluation	Chi-square	DF	p-value
45 days after emergence	58.12	19	0.0000076***
75 days after emergence	53.07	19	0.0000561***

DF - Degrees of freedom; *** - Significant at $p < 0.001$

Table 4. Significant pairwise comparisons of plant height at 45 and 75 days after emergence of safflower plants

	Statistical test	Standard error	Standard statistical test	p-adjust.
Pairwise comparison - Plant height at 45 days after emergence				
D8N1.8-D32N1	15.25	4.18	3.64	0.051*
D32N1.6-D32N1	15.00	4.18	3.59	0.064*
Pairwise comparison - Plant height at 75 days after emergence				
D8N1.8-D32N1	16.62	4.18	3.97	0.013**
D32N1.6-D32N1	15.87	4.18	3.79	0.028**
D8N1.6-D32N1	15.50	4.18	3.70	0.040**

D8N1.8 - Dose of 8 g dm^{-3} at bulk density of 1.8 kg dm^{-3}; D8N1.6 - Dose of 8 g dm^{-3} at bulk density of 1.6 kg dm^{-3}; D32N1 - Dose of 32 g dm^{-3} at bulk density of 1.0 kg dm^{-3}; D32N1.6 - Dose of 32 g dm^{-3} at bulk density of 1.6 kg dm^{-3}; ** - Significant at $p < 0.05$; * - Significant at $p < 0.1$

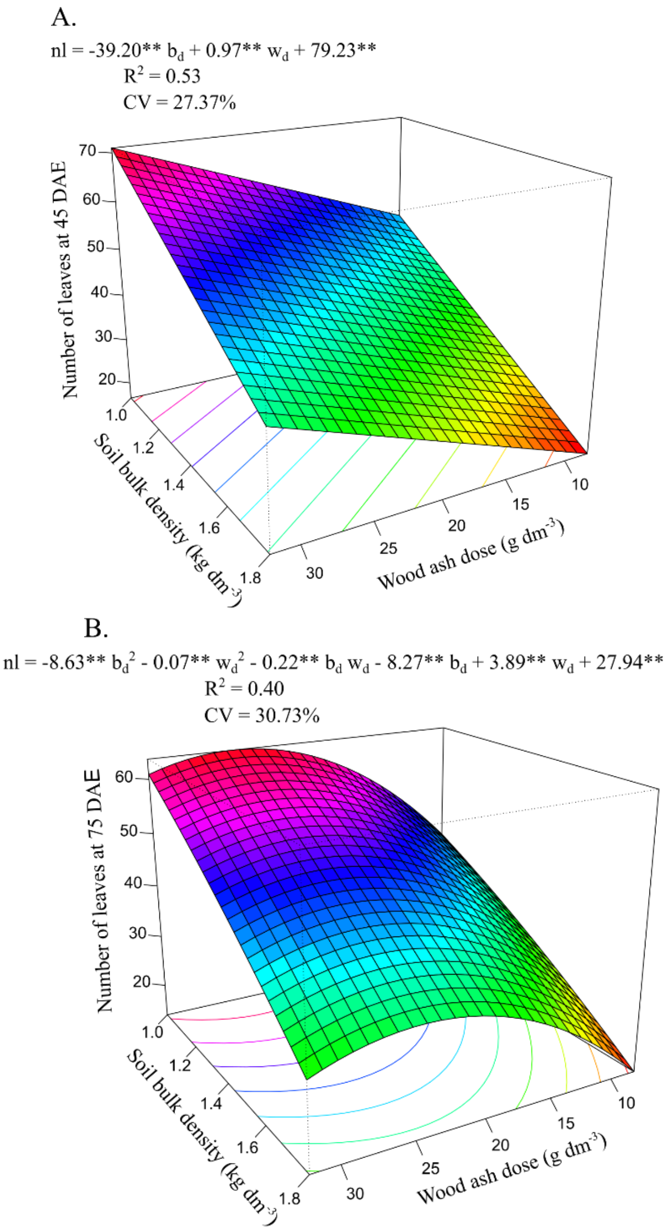
Table 5. Medians of treatments that showed significant difference in plant height in the pairwise comparison at 45 and 75 days after emergence of safflower plants

Ash dose (g dm^{-3})	Bulk density (kg dm^{-3})		
	1.0	1.6	1.8
Median - Plant height at 45 days after emergence			
8	-	-	30.83
32	60.0	32.50	-
Median - Plant height at 75 days after emergence			
8	-	33.33	31
32	60.67	31.67	-

The wood ash dose significantly affected the number of leaves ($p < 0.05$); the higher the dose applied to the soil, the higher the average number of leaves (Figure 1B) at 15 days after emergence. At 45 and 75 days after emergence, there was an interaction between the factors for this variable and normality errors.

Regarding the interaction, the higher the wood ash dose applied and the lower the bulk density, the higher was the number of leaves at 45 days after emergence (Figure 2A), indicating that in this phenological stage the root system of safflower plants was limited by the compacted layer of the soil.

According to Wang et al. (2019), the main effect of soil compaction on the availability of nutrients for vegetative growth occurs with inhibition in the absorption of the macronutrients P, K, and Mg and the micronutrients Mn, Fe, Cu, and Zn.



Significance level p = 0.05 (**)

Figure 2. Number of leaves (nl) of safflower plants at 45 (A) and 75 (B) days after emergence (DAE) grown in Latossolo Vermelho distrófico (Oxisol) with subsurface layer with different levels of bulk density (b_d) and fertilized with wood ash doses (w_d)

Similar behavior for this variable was observed at 75 days after emergence (Figure 2B), with the highest number of leaves (73 leaves) recorded for the wood ash dose of 28.57 g dm^{-3}, at a bulk density of 1.0 kg dm^{-3} (Figure 2B).

The number of leaves is directly related to the photosynthetic capacity of the plant since it usually allows a larger leaf area and, consequently, a larger area of photosynthetically active radiation absorption.

Ferreira et al. (2017) studied the development of safflower subjected to bulk density levels and nitrogen doses and observed a significant effect on shoot mass, directly related to the number of leaves, and more compacted soils limited the development of the aboveground biomass of the plant.

Regarding the single effect of wood ash as corrective and fertilizer on safflower development, Bonfim-Silva et al. (2018) observed a linear growth in the number of leaves in the vegetative stage, and the most appropriate dose of wood ash was 32 g dm^{-3}. Similar results were observed in the present study at 15 and 45 days after emergence.

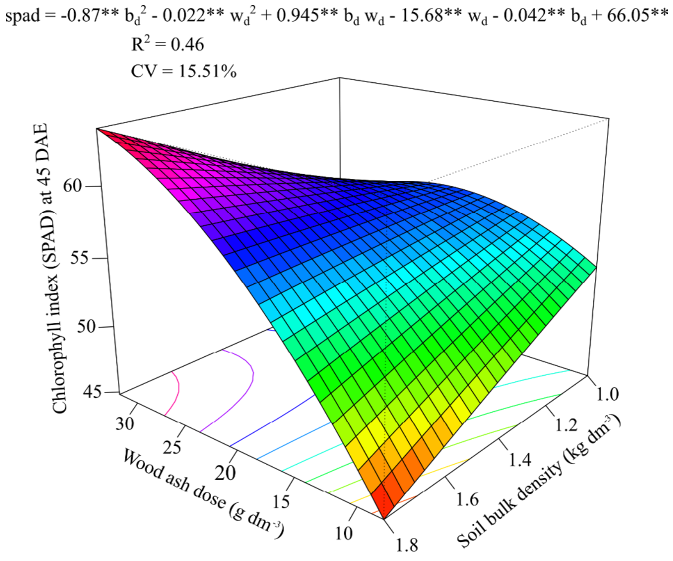
Applying correct doses of wood ash is important to avoid chemical imbalance during the final stage of the crop cycle. Given the high concentration of calcium carbonate, wood ash applied in an excessive dose may cause an increase in soil pH to values that are inadequate for nutrient absorption, above 6.5 (Malavolta, 2006). This process of pH elevation can reach critical levels at the end of the vegetative development stage of the crop, thus affecting the production stage (Sousa & Lobato, 2004).

Regarding the SPAD chlorophyll index, no interaction occurred between the factors (wood ash dose and soil bulk density) and there was no statistical difference ($p > 0.05$) for the single effect of bulk density at 15 days after emergence. However, the factor wood ash significantly affected the SPAD chlorophyll index at 15 days after emergence, when the highest value (54.18) was observed for the wood ash dose of 24.88 g dm^{-3} (Figure 1C).

For the SPAD readings at 45 days after emergence, there was an interaction between the factors. The highest SPAD index of safflower plants was 56.26, obtained at the wood ash dose of 32 g dm^{-3} and bulk density of 1.8 kg dm^{-3} (Figure 3).

The SPAD index is used as an indicator of total chlorophyll concentration in plant leaves, and the main advantage of the method is the rapid and nondestructive determinations. From the SPAD index, it is possible to infer the nutritional status of the plant and the metabolic processes related to chlorophyll content (Shah et al., 2017b). Higher values of this index point to a plant that is photosynthetically more active, which enables a higher biomass production (Taiz et al., 2017).

However, the SPAD index is an indicator that needs to be analyzed together with other variables (e.g., shoot dry mass) so that the result is interpreted correctly, since chlorophyll may be found at higher concentration in the leaves of plants that developed less, as occurred with the values recorded in this study for bulk density of 1.8 kg dm^{-3}. However, this highest SPAD value occurred because the vegetative growth of safflower was affected by the 1.8 kg dm^{-3} bulk density, leading to



Significance level p = 0.05 (**)

Figure 3. SPAD chlorophyll index of safflower plants at 45 days after emergence (DAE) grown in Latossolo Vermelho distrófico (Oxisol) with subsurface layer with different levels of bulk density (b_d) and fertilized with wood ash doses (w_d)

smaller leaves with a more intense green color due to a higher concentration of nitrogen.

Janmohammadi et al. (2016), when evaluating the efficiency of silica (SiO_2) in the growth and development of safflower plants under different fertilizer management conditions, found a maximum mean SPAD index of 63.67 for plants fertilized with manure, a value higher than those observed in treatments with industrial mineral fertilizers.

Ferreira et al. (2017) observed the highest SPAD index values of the order of 70.8 for safflower plants at 60 days after emergence grown under nitrogen dose of 128 mg dm^{-3}, and a similar result was found in this study at 45 days after emergence. The effect of wood ash doses on SPAD index values is expected and is due to the increase in the availability of some important elements in soil solution, such as magnesium, nitrogen, sulfur, zinc, copper, iron, and manganese, which are directly or indirectly involved in chlorophyll biosynthesis.

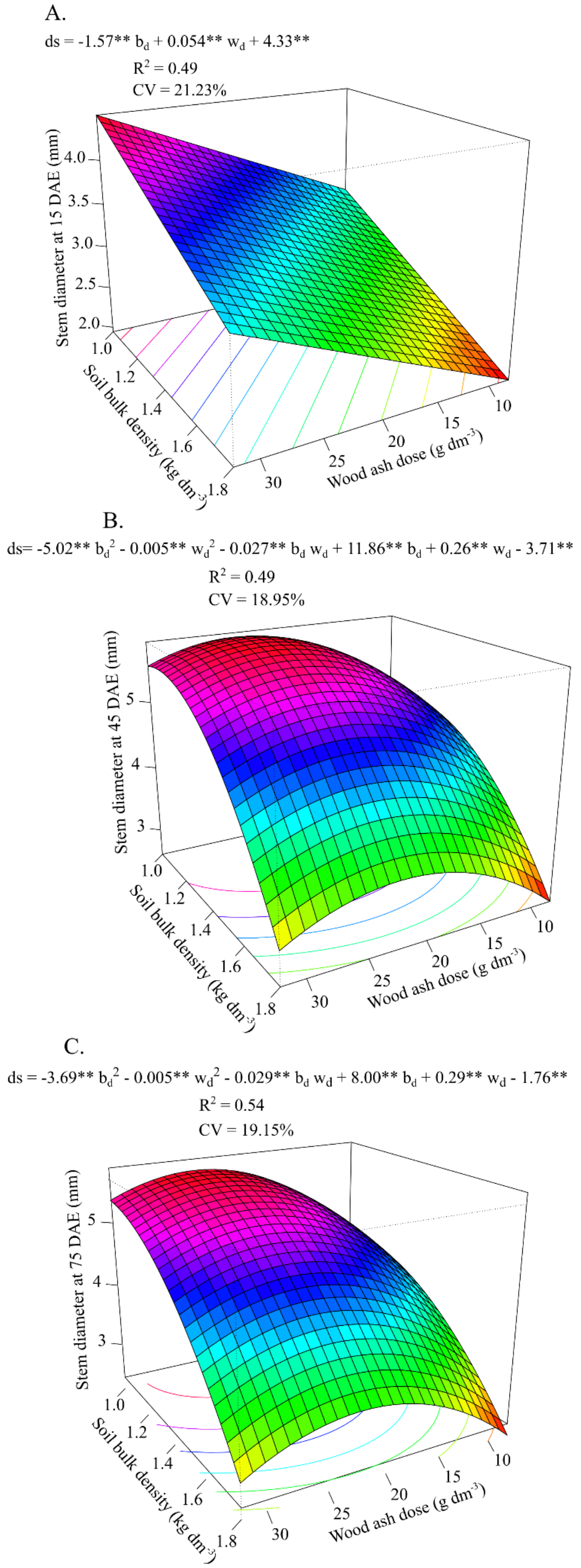
Stem diameter showed a significant interaction between the factors studied on all evaluations dates.

At 15 days after emergence, stem diameter showed linear behavior on the response surface, that is, the higher the wood ash dose applied and the lower the bulk density, the higher the mean stem diameter (Figure 4A).

At 45 days after emergence, the maximum value of stem diameter was 6.02 mm, obtained at the wood ash dose of 24.02 g dm^{-3} and the bulk density of 1.1 kg dm^{-3} (Figure 4B). At 75 days after emergence, the maximum value of the stem diameter was 5.68 mm for the wood ash dose of 24.27 g dm^{-3} and bulk density of 1.0 kg dm^{-3} (Figure 4C).

The stem, besides providing support for the plant, stores nutrients (Taiz et al., 2017). Therefore, stem growth throughout the cycle of a crop is an important indicator to analyze the relationship between the availability of nutrients in the soil and their absorption by the plant.

At 15 days after emergence, the absence of a compacted layer associated with increased doses of wood ash allowed



Significance level p = 0.05 (**)

Figure 4. Stem diameter (ds) of safflower plants at 15 (A), 45 (B), and 75 (C) days after emergence (DAE) grown in Latossolo Vermelho distrófico (Oxisol) with subsurface layer with different levels of bulk density (b_d) and fertilized with wood ash doses (w_d)

an increase in nutrient availability in the soil solution, thus promoting a positive linear effect on the development of the stem of safflower plants.

Other safflower accessions may produce higher values for stem diameter than the values reported in Figure 4, especially at the reproductive stage. For instance, Maziero et al. (2019) observed mean values of stem diameter for safflower of the order of 11.7 mm at the beginning of flowering, while Sampaio et al. (2016) found average stem diameter values of 10.6 mm at 60 days after emergence in plants fertilized with NPK.

Regarding bulk density, stem diameter was the only variable to show a significant interaction with wood ash doses at 15 days after emergence. This indicates that the root system of safflower plants already signaled the beginning of a restriction on nutrient absorption; however, given the ability of the stem to store nutrients, it is likely that it was able to partially meet the growth demand of the plants, and this explains the absence of effect of soil compaction on the other growth variables analyzed at 15 days after emergence.

According to Malavolta (2006), the ideal pH range for nutrient availability in the soil is 5.5 to 6.5 for most crops. As the neutralizing reactions of H^+ ions by wood ash occurs throughout the crop cycle, high doses of wood ash may thus cause an imbalance in nutrient absorption by plants in the more advanced stages of the phenological cycle.

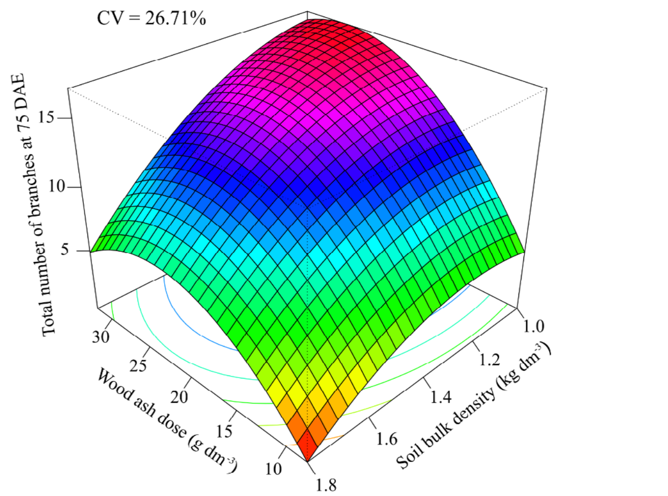
The number of branches, evaluated at the end of the experiment (at 75 days after emergence) showed a significant interaction between the two factors analyzed. The maximum value of the number of branches, 17, occurred at the bulk density of 1.0 kg dm^{-3} with a wood ash dose of 27.67 g dm^{-3} (Figure 5).

In the safflower crop, the number of branches defines the number of capitula; consequently, the larger the number of branches, the greater the number of inflorescences. However, according to Bellé et al. (2012), it is not interesting to have an excessive number of branches on the stems, since it can induce differences in flowering rates within the capitulum, resulting in uneven anthesis.

$$nb = -14.96^{**} b_d^2 - 0.032^{**} w_d^2 - 0.351^{**} b_d w_d + 38.69^{**} b_d + 2.11^{**} w_d + 30.68^{**}$$

$R^2 = 0.56$

CV = 26.71%



Significance level p = 0.05 (**)

Figure 5. Number of branches (nb) of safflower plants at 75 days after emergence (DAE) grown in Latossolo Vermelho distrófico (Oxisol) with the subsurface layer with different levels of bulk density (b_d) and fertilized with wood ash doses (w_d)

Ali et al. (2020), when evaluating the morphological and agronomic performance of 94 safflower genotypes in different locations found an ideal average of the number of branches of the order of 17, similar to the results of the present study.

Conclusions

1. Bulk density values of up to 1.2 kg dm^{-3}, associated with an average wood ash dose of the order of 25 g dm^{-3}, promoted better conditions for the vegetative growth of safflower plants.

2. The increase in soil fertility associated with a rotational crop with a robust tap root system alone may not be sufficient for the physical restoration of compacted soil layers in a single growth cycle.

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