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Physical-hydric properties of Oxisol and Quartzipsamment associated with the application of wood ash[1]

Propriedades físico-hídricas de Oxisol e Quartzipsamment associadas a aplicação de cinzas de madeira

Thiago F. Duarte[2*], Edna M. Bonfim-Silva[2], Tonny J. A. da Silva[2], Márcio Koetz[2] & Gabrielly F. Lima[2]

[1] Research developed at Rondonópolis, MT, Brazil
[2] Universidade Federal de Rondonópolis/Instituto de Ciências Agrárias e Tecnológicas, Rondonópolis, MT, Brazil

HIGHLIGHTS:
The addition of wood ash changed soil bulk density, which initially increased at a dose of 16 g dm^{-3}.
Increases in field capacity and total available water were effective only at doses of 64 g dm^{-3} of wood ash.
Saturated hydraulic conductivity reduced linearly with the addition of wood ash.

ABSTRACT: The addition of wood ash to soil is an alternative to disposing of this residue. However, the effects of wood ash on soil physical-hydric properties remain divergent. In this study, the effects of added wood ash on the soil water characteristic curve, gravitational water, field capacity, total available water, and saturated hydraulic conductivity were evaluated in Oxisol (40% clay and clay texture) and Quartzipsamment (6% clay and sand texture). The experimental design was completely randomized in a 2 × 4 factorial scheme, where the factors were two soils and four doses of wood ash, with three replicates. The wood ash came from an agribusiness and was the result of burning eucalyptus wood. The wood ash doses were 0, 16, 32, and 64 g dm^{-3}. The gravitational water, field capacity, and total available water were fitted to a quadratic model as a function of the wood ash dose. The saturated hydraulic conductivity decreased linearly with an increase in wood ash dose for both soil classes. The soil water characteristic curve only increased significantly ($p \le 0.05$) with a wood ash dose of 64 g dm^{-3}. The increase in total available water was more evident in Oxisol than that in Quartzipsamment, with increments of 64 and 31%, respectively, at a maximum dose of 64 g dm^{-3} of wood ash.

Key words: field capacity, total available water, water retention

RESUMO: A adição de cinza da madeira no solo é uma alternativa para a disposição deste resíduo. Porém, seus efeitos nas propriedades físico-hídricas do solo ainda são divergentes. Neste estudo, avaliou-se o efeito da adição de cinzas vegetal na curva característica da água do solo, água gravitacional, capacidade de campo, água total disponível e condutividade hidráulica saturada em um Oxisol e em um Quartzipsamment. O delineamento experimental foi inteiramente casualizado em esquema fatorial 2 × 4, correspondendo a dois solos e quatro doses de cinza vegetal, com três repetições. A cinza vegetal utilizada é proveniente de agroindústria, resultante da queima da madeira de eucalipto. As doses de cinza vegetal foram de 0, 16, 32 e 64 g dm^{-3}, em Oxisol (40% argila, textura Argila) e em Quartzipsamment (6% argila e textura Areia). A água gravitacional, a capacidade de campo e a água total disponível ajustaram-se ao modelo quadrático em função das doses de cinza de madeira. A condutividade hidráulica saturada reduziu linearmente com a aumento das doses de cinza vegetal para ambas as classes de solo. A curva característica do solo aumentou significativamente ($p \le 0{,}05$) apenas na dose de 64 g dm^{-3} de cinza vegetal. O aumento do total de água disponível foi mais evidente no Oxisol do que no Quartzipsamment, com incremento de 64 e 31%, respectivamente, na dose máxima de 64 g dm^{-3} de cinza vegetal.

Palavras-chave: capacidade de campo, água total disponível, retenção de água

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* Corresponding author - E-mail: thiago.duarte@ufr.edu.br
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Introduction

Wood ash is a residue produced by burning plant materials during the process of generating energy in agro-industries. The correct disposal of this residue is necessary to avoid environmental pollution. Research in cerrado soils has shown that wood ash can be used as a soil acidity corrective and fertilizer (Bonfim-Silva et al., 2019a). Species such as *Brachiaria* (Bonfim-Silva et al., 2019b), cowpea (Bonfim-Silva et al., 2019a), and peanuts (Bonfim-Silva et al., 2020) showed increased growth and yield with the application and incorporation of wood ash into the soil.

Although evidence relating to the addition of wood ash to soil and its effects on soil chemical attributes converge towards indicating a beneficial effect, studies reporting the effects of wood ash on soil physical-hydric properties are not yet fully convergent. Stoof et al. (2010) verified a 57% increase in the amount of available water (between 10 and 1550 kPa) and a change in the soil water characteristic curve (to increased water retention) with the addition and incorporation of 15.5% (by weight) of ash to an organic soil from Portugal. In contrast, Moragues-Saitua et al. (2017) verified a downward trend in water retention with the addition of ash to a Typic Udorthent with Loam texture and a Typic Dystrudept with Sandy-Loam texture. Although there is no single effect of the addition of wood ash on soil physical properties, there is a general opinion that the results are dependent on the type of soil, especially the texture (Moragues-Saitua et al., 2017; Razzaghi et al., 2020).

Therefore, the objective of this study was to verify the effect of the addition of wood ash at doses of 0, 16, 32, and 64 g dm^{-3} on the soil water retention curve, gravitational water (between 0 and 6 kPa for sand soils and 10 kPa for clay soils), field capacity determined in the laboratory (6 kPa for sand soils and 10 kPa for clay soils), total available water (between 6 or 10 and 1500 kPa), and saturated hydraulic conductivity (Ksat) in an Oxisol and Quartzipsamment soils.

Material and Methods

The experiment was conducted at the Federal University of Rondonópolis, with geographical coordinates of 16° 27' 41" S and 54° 4' 52" W, and altitude of 293 m.

The experimental design was completely randomized in a 2 × 4 factorial scheme, with factors being two soils (Oxisol and Quartzipsamment) and four doses of wood ash (0, 16, 32, and 64 g dm^{-3}), with three replicates.

According to the USDA classification, the soils used were Oxisol (sand: 41%, clay: 40%, and silt: 19% with a clay texture) collected in the experimental area, and Quartzipsamment (sand: 90.3%; clay: 7.3%, and silt: 2.4% with sand texture) collected from Rondonópolis, MT, Brazil. The soils were collected in the 0-0.20 m layer and later sieved through a 2.0 mm mesh to obtain air-dried fine soil. The chemical attributes of the two soils are listed in Table 1.

The wood ash came from an agribusiness and was the result of burning eucalyptus wood (*Eucalyptus grandis* L.). The physical characterization of the wood ash included determination of the bulk density and particle density, evaluation of the particle size distribution, and determination of the water retention curve.

The ash bulk density was determined by accommodating a known mass of wood ash in a 100 cm^3 steel cylinder without compacting. The relationship between the dry mass of wood ash and the total volume provides the bulk density of the ash. The ash particle density was evaluated using the volumetric flask methodology commonly used for the analysis of mineral soils (Santos et al., 2022).

The granulometry of the ash particles was determined using sieves with 2.00, 1.80, 0.60, 0.425, 0.30, 0.15, 0.125, and 0.075 mm meshes. The sieves were overlapped using a mechanical stirrer (Bertel) with a vibration intensity of 60 Hz for 60 s. Fifty grams of wood ash was used, and after stirring, the ash fractions retained in each sieve were weighed to determine the percentage of material retained in relation to the total sample.

To evaluate the water retention curve, wood ash samples were mounted in rings (1.0 cm high and 5.3 cm internal diameter), with three replicates, and the experimental design was completely randomized. The samples were saturated and subjected to pressures of 0, 6, 10, 33, 100, 300, 700, 1000, and 1500 kPa in a Richards pressure chamber (Soil Moisture Equipment Corp., Goleta, CA, USA). After water extraction, the samples were weighed and oven-dried at 105 °C to determine their moisture content. Subsequently, the data were fitted to the van Genuchten (1980) model using SWRC software, version 2.0. The fitted parameters are α, θr (residual water content), and n. The parameter θs (saturated water content) was obtained by direct measurement, and the parameter m was determined by the relation $m = 1 - n^{-1}$.

The wood ash doses were 0, 16, and 32 g dm^{-3} (Bonfim-Silva et al., 2019a) and 64 g dm^{-3} for both types of soil. After incorporating the ash into the soil, the soil + ash mixture was left for an incubation period of 30 days for chemical pH stabilization.

After the incubation period, the assessment of water retention in the soil + ash mixture began. Deformed samples were mounted on rings (1.0 cm high and 5.3 cm internal diameter) with three replicates. During the assembly of the samples, care was taken to accommodate the soil + ash mixture inside the rings until the volume was filled without causing compaction. Afterwards, the samples were saturated by capillarity and subsequently subjected to pressures of 0, 6, and 10 kPa using a suction table and 33, 100, 300, 700, 1000, and

Table 1. Chemical attributes of Oxisol and Quartzipsamment collected in the 0-0.2 m layer

Soil class	pH $CaCl_2$	P (mg dm^{-3})	K	Ca	Mg	Al	H + Al	SB	CEC	V (%)	OM (g kg^{-1})
			($cmol_c$ dm^{-3})								
Oxisol	4.7	10.7	0.21	1.2	0.7	0.2	4.0	2.1	6.1	34.5	20.7
Quartzipsamment	4.8	35.6	63	1.4	0.5	0.0	2.5	2.1	4.6	45.2	12.5

pH - Hydrogenionic potential; P - Phosphorus (Mehlich); K - Potassium; Ca - Calcium; Mg - Magnesium; Al - Aluminum; H - Hydrogen; CEC - Cation exchange capacity; V - Base saturation; OM - Organic matter

1500 kPa using the Richards pressure chamber. After stabilizing the water extraction, the samples were removed, weighed (W_h) on a semi-analytical balance, and subsequently oven-dried at 105 °C and weighed (W_d) to determine the gravimetric water content (θm), according to Eq. 1:

$$\theta_m = \frac{(W_h - W_d)}{W_d} \quad (1)$$

From the water retention data, the following were determined: gravitational water with pressures between 0 and 6 kPa for the Quartzipsamment and 0 to 10 kPa for the Oxisol; field capacity, with pressure of 6 kPa for the Quartzipsamment and 10 kPa for the Oxisol; and total available water with pressures of 6 to 1500 kPa and from 10 to 1500 kPa for Quartzipsamment and Oxisol.

Saturated hydraulic conductivity (K_{sat}) was measured using a constant head permeameter, with 4.0 cm piezometric head and collection time of 5 min (Silva et al., 2019).

To evaluate the saturated hydraulic conductivity in the permeameter, the soil samples were mounted in volumetric rings of approximately 100 cm^3 (diameter: 4.9 cm, height: 5.5 cm) and then saturated by capillarity for 48 hours.

The water retention curves (0-1500 kPa) for 16, 32, and 64 g dm^{-3} were compared with 0 g dm^{-3} using the t-test at $p \leq 0.05$, for each soil class, independently. For soil properties, gravitational water, field capacity, total available water, and saturated hydraulic conductivity, a two-way ANOVA (soil texture and wood ash doses) at $p \leq 0.05$, was performed. Regression analysis was performed for each soil type if the interaction between factors presented significant effect.

Results and Discussion

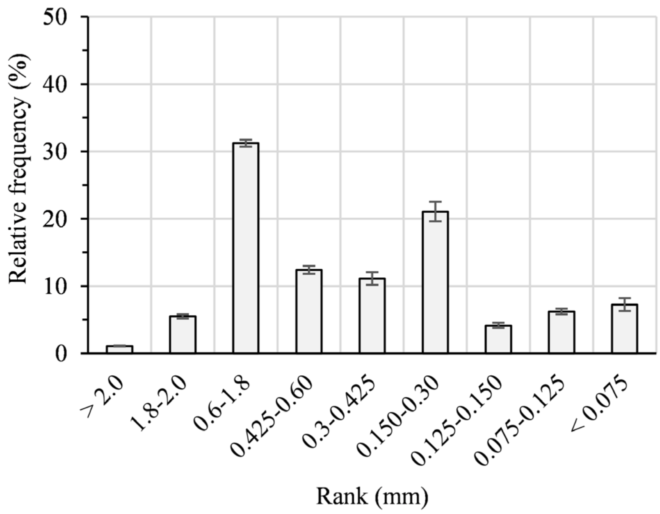
Most of the wood ash particles were of sizes ranging from 0.6-1.8 and 0.15-0.30 mm, as shown in Figure 1. Together, these two particle size groups represented more than 50% of the total size classes. The ash bulk density (repacked bulk density) and the ash particle density were 0.21 g cm^{-3} (± 0.012 SD) and 1.09 g cm^{-3} (± 0.067 SD), respectively, resulting in an average total porosity of 0.81 m^3 m^{-3}. In a recent study Stoof et al. (2016) evaluated several wood ash types and found porosity values between 0.52 to 0.81 m^3 m^{-3}, and bulk density ranging from 0.20 to 0.85 g cm^{-3}.

Regarding the water retention curve, wood ash had a water content of 371.8% (gravimetric basis) when saturated and a minimum value of 47.2% at 1500 kPa, as shown in Figure 2. Considering an ash bulk density of 0.21 g cm^{-3}, the volumetric water content at saturation and at a pressure of 1500 kPa were 78.07 and 9.9%, respectively. These results are close to those reported by Stoof et al. (2010), whose volumetric water content values of *Pinus* ash under saturated conditions and at a pressure of 1550 kPa were 96 and 11.3%, respectively.

Nevertheless, the wood ash water content was 371.8% when saturated, and there was an abrupt reduction in the water content with the application of the first pressure level (6 kPa), when the water content reached 116%; that is, a reduction of 69.06% in relation to the initial value. Subsequently, reduction occurred gradually with increasing pressure. This abrupt reduction in water content was also verified by Stoof et al. (2010), both in wood ash and in biochar from *Pinus*. According to the authors, this effect reflects the loose packing of these porous materials. Thus, much of the water that was initially retained in the ash was quickly lost when subjected to low levels of suction, making it unavailable to plants.

The effects of the addition of wood ash on water retention in the two soil classes are presented in Figure 3. The application of 16 g dm^{-3} of ash caused a change only in the initial part of the retention curve, specifically between pressures of 0 and 6 kPa. Interestingly, this change reduced water retention in both soil types. Subsequently, with an increase in the dose of wood ash (32 g dm^{-3}), the water content values tended to be equal to the values referring to the soil without the addition of wood ash. Finally, the application of the maximum dose of wood ash (64 g dm^{-3}) increased water retention in both soils.

The van Genuchten model parameters fitted for the different wood ash doses are listed in Table 2 for both soil classes. Note that the θs parameter varied as described above; in other words, there was a tendency to decrease with doses



The error bars represent standard errors

Figure 1. Relative frequency (% w/w) of particle size (mm) of wood ash

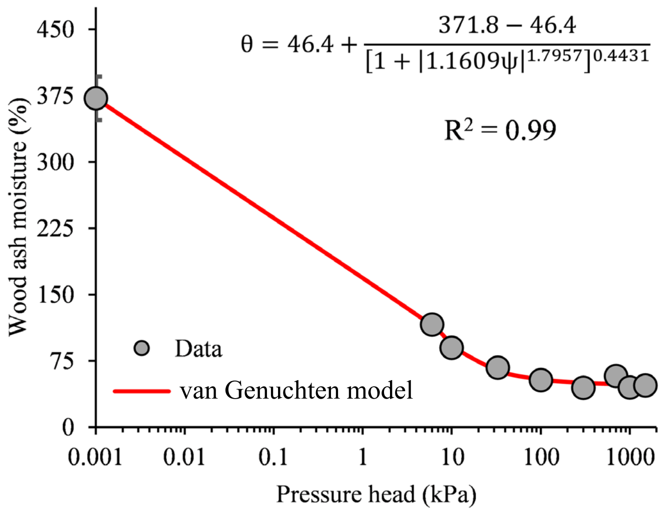


Figure 2. Water retention curve of wood ash fitted to the van Genuchten (1980) model

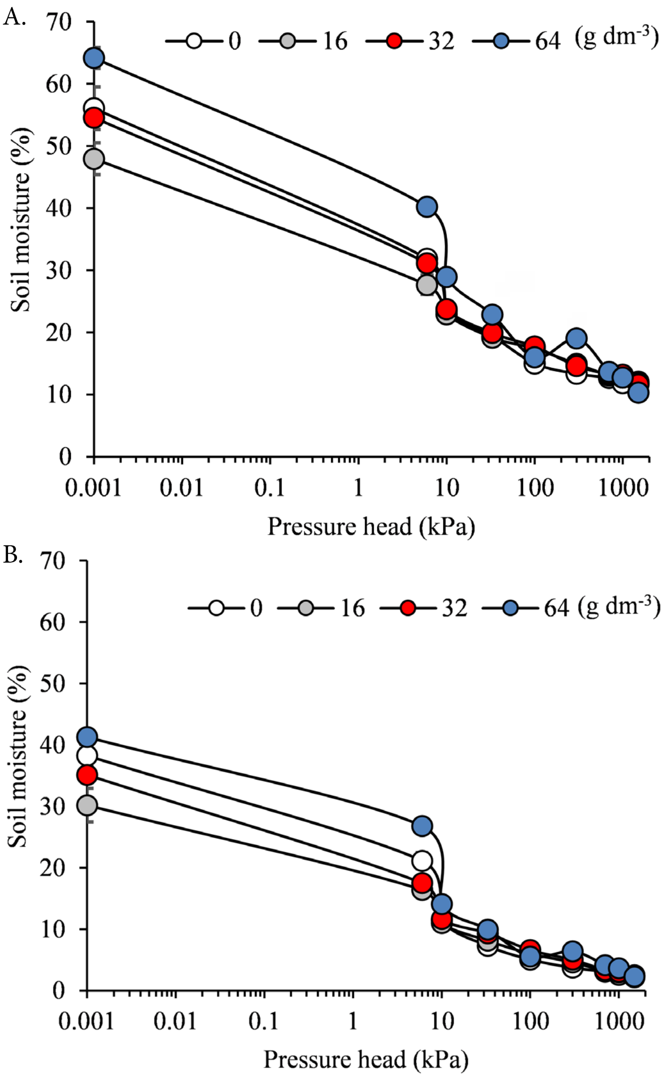


Figure 3. Soil water characteristic curve (gravimetric method) of Oxisol (A) and Quartzipsamment (B) at each of wood ash doses

Table 2. van Genuchten model parameters fitted for Oxisol and Quartzipsamment at each wood ash dose

Wood ash ($g\ dm^{-3}$)	van Genuchten equations parameters				
	θs	θr	α	n	m
			Oxisol		
0	0.561	0.115	0.593	1.633	0.387
16	0.479	0.064	3.356	1.240	0.194
32	0.546	0.080	1.832	1.322	0.243
64	0.642	0.055	0.919	1.345	0.257
			Quartzipsamment		
0	0.383	0.024	0.322	1.931	0.482
16	0.302	0.001	1.052	1.365	0.268
32	0.351	0.000	1.741	1.329	0.247
64	0.413	0.018	0.323	1.704	0.413

θs - Saturated water content; θr - Residual water content; m, n and α – Parameters

of 16 and 32 g dm^{-3}, and later, there was an increase with the maximum dose of 64 g dm^{-3}.

For the two soil classes, only the curve corresponding to the maximum wood ash dose (64 g dm^{-3}) differed significantly ($p \leq 0.05$) in relation to the soil without the addition of wood ash (Table 3). On average, the increase in water retention along the entire water characteristic curve was 27% for Quartzipsamment and 15% for Oxisol. In both soils there was a peak in the increase in water retention at pressure of 300 kPa (Figure 3), whose increase in relation to the absence of wood ash was 72% for the Quartzipsamment and 42% for the Oxisol.

Table 3. t-values comparing the soil water retention curve of Oxisol and Quartzipsamment with and without wood ash doses

Wood ash doses ($g\ dm^{-3}$)	Oxisol	Quartzipsamment
	(0 g dm^{-3})	
16	0.82^{ns}	1.11^{ns}
32	-1.08^{ns}	0.14^{ns}
64	-3.01*	-3.67*

ns - Not significant; * - Significant at $p \leq 0.05$

It is important to note that although there was a statistical difference between the water retention curves (0 and 64 g dm^{-3}), the addition of wood ash did not increase water retention at all pressures, but only at pressures less than the field capacity (Figure 3). This result is probably related to the wood ash characteristics. Note that in wood ash, most of the water is retained under pressures less than 10 kPa (Figure 2), precisely the pressures that were most altered in the soil-ash mixture. Thus, although wood ash has a porosity of 80% and a high water-holding capacity, most of this water is lost through drainage.

Among all physical-hydric variables analyzed, there was a significant effect ($p \leq 0.05$) only for the interaction between wood ash dose and soil type (Table 4).

In the case of gravitational water, the addition of wood ash induced a change according to a quadratic model only for Oxisol (Figure 4). For Quartzipsamment, it was not possible to obtain an adequate fit. The fitted equation was $y = -0.0003x^2 -0.0016x + 16.228$ ($R^2 = 0.1206$). A decrease in gravitational water at a dose of 16 g dm^{-3} in Oxisol was observed. For the maximum wood ash dose (64 g dm^{-3}), the increase in gravitational water in relation to soil without ash was 8% for Oxisol. Because gravitational water is a fraction of the water that is quickly lost by drainage and is therefore considered unavailable to plants, its increase is usually not considered an advantageous result.

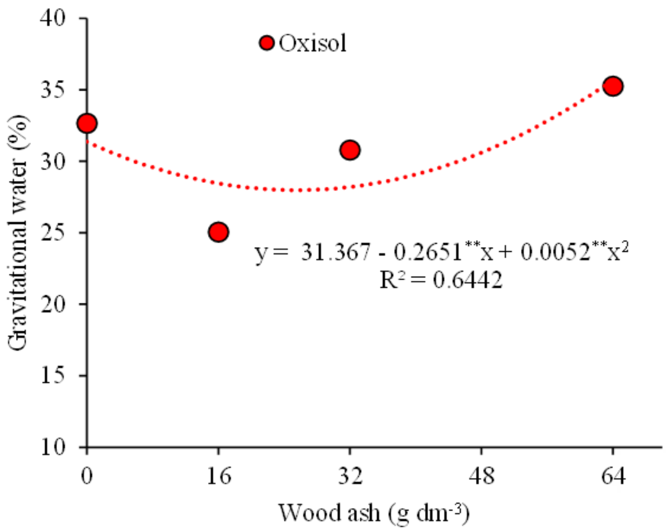
Field capacity and total available water also varied according to a quadratic function (Figures 5 and 6). For field capacity, the increase between the maximum dose and the absence of wood ash was approximately 23% for Oxisol and 27% for Quartzipsamment (Figure 5). For the total available water, for Oxisol, there was an increase of 64% for the dose of 64 g dm^{-3} in relation to the absence of wood ash, compared to 31% for Quartzipsamment (Figure 6).

Regarding the field capacity and total available water, the increase observed with the addition of wood ash can be

Table 4. Summary of analysis of variance for the effects of soil type, wood ash doses, and their interaction, on soil hydraulic properties

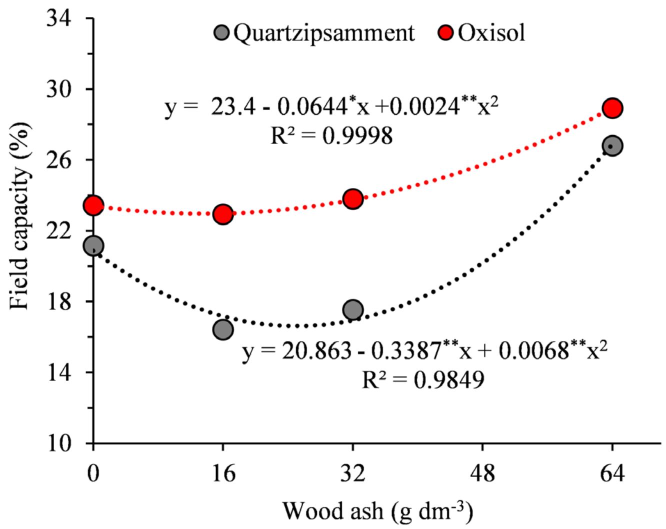
Soil property	F-value (soil type)	F-value (Wood ash doses)	F-value (interaction)	CV (%)
Gravitational water	325.044**	9.841**	5.954**	8.84
Field capacity	357.399**	258.919**	28.394**	2.46
TAW	444.506**	309.956**	22.392**	3.54
Ksat	83.339 **	16.319**	16.003**	8.59

TAW - Total available water; Ksat - Saturated hydraulic conductivity. ** - Significant at $p \leq 0.01$



** - Significant at $p \leq 0.01$ by F test

Figure 4. Gravitational water on a mass basis in Oxisol (0-10 kPa) as a function of wood ash doses



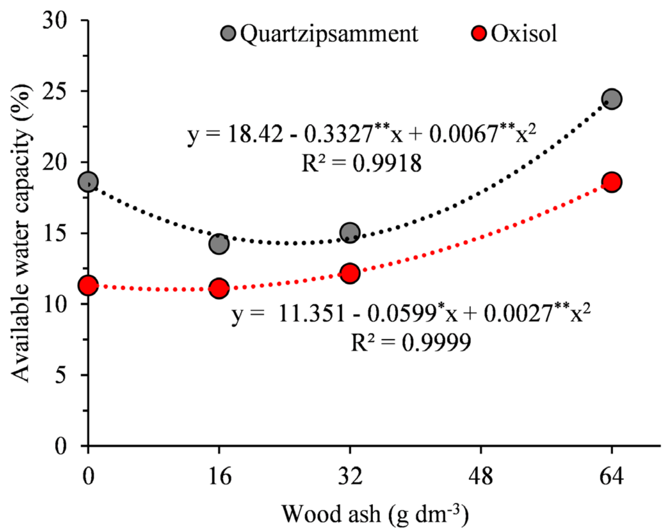
* - Significant at $p \leq 0.05$; ** - Significant at $p \leq 0.01$ by F test

Figure 5. Field capacity on a mass basis (6 kPa) in Quartzipsamment and Oxisol (10 kPa) as a function of wood ash doses

attributed to the porous nature of this residue and its high specific surface (Strandberg et al., 2021), which increases the water absorption and retention capacity, as shown previously (Figure 2). However, this increase was only significant with the addition of 64 g dm^{-3} of wood ash.

It is also interesting to note that the most significant increase in total available water was observed in the Oxisol, with clay texture, and not in the Quartzipsamment, with sand texture. This result is the opposite of some reports that more sandy soils were more likely to respond to the addition of wood ash or biochar (Blanco-Canqui, 2017). These conflicting results reinforce the fact that the interaction between soil and wood ash is complex, and the results are not always predictable.

The increase in total available water is related to the increase in field capacity associated with the reduction in the permanent wilt point. Although this effect occurred in both types of soils, it was more pronounced in the Oxisol, whose moisture at the permanent wilt point reduced by 15%, that is, from 12.1% to



* - Significant at $p \leq 0.05$; ** - Significant at $p \leq 0.01$ by F test

Figure 6. Total available water on a mass basis (6-1500 kPa) in Quartzipsamment and Oxisol (10-1500 kPa) as a function of wood ash doses

10.3%, for doses of 0 and 64 g dm^{-3} of wood ash, respectively, while for the Quartzipsamment, the reduction was only 8%, that is, from 2.5 to 2.3% (Figure 6).

In general, the saturated hydraulic conductivity showed a downward trend with wood ash dose in both soil classes. However, it was not possible to obtain an adequate fit for either soil. For Oxisol, the fitted equation was $y = -0.6114x + 152.19$ ($R^2 = 0.3028$), and for Quartzipsamment it was $y = -0.3483x + 107.57$ ($R^2 = 0.5843$). When the maximum dose was applied, the reduction was greater for Oxisol (34%) than that for the Quartzipsamment (18%). It is important to note that pure wood ash has a saturated hydraulic conductivity of 364 mm h^{-1}, which is on average 2.0 times greater than the conductivity of Oxisol and 3.0 times greater than that of Quartzipsamment. However, the addition of this material to both soil types did not increase hydraulic conductivity, even at the maximum dose of 64 g dm^{-3}.

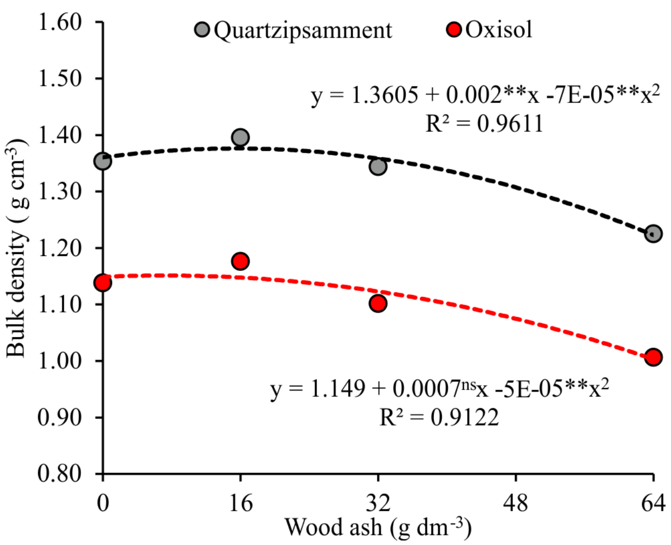
The effect of the wood ash dose on saturated hydraulic conductivity was a general reduction, in both soils. This effect has also been observed by other authors (Liu et al., 2016; Esmaeelnejad et al., 2017; Moragues-Saitua et al., 2017) following the application of ash or biochar to coarse-textured soils. According to Moragues-Saitua et al. (2017), this reduction is a probable sign of pore clogging caused by smaller particles of wood ash. This filling of the pores by ash particles causes a greater packaging of the soil-ash mixture, reducing the space available for the water flow to the detriment of the increased tortuosity (Esmaeelnejad et al., 2017). In fine-textured soil, in general, the addition of ash or biochar can increase the saturated hydraulic conductivity due to decreased bulk density and an increase in total porosity and mean pore size (Blanco-Canqui, 2017).

In this study, the wood ash doses reduced the saturated hydraulic conductivity in both soils, but the effect was more pronounced in Oxisol than that in Quartzipsamment. In Oxisol, the slope of the function was -0.6114 mm h^{-1}, while in Quartzipsamment it was -0.3483 mm h^{-1}. It is important to note that Oxisol always reached higher values regardless of the wood ash dose, and the reduction effect was more evident.

Although the bulk density decreased with the maximum wood ash dose (Figure 7), the saturated hydraulic conductivity did not increase. It is possible that although wood ash has a high total porosity, most of its pores are located inside the particles (intrapores) and are small enough to decrease the mean pore size in the soil (Gelardi et al., 2021). In biochar (mesquite feedstock) for example, Liu et al. (2017) verified an intraporosity of 0.6 m^3 m^{-3}, and considered that most intrapores have diameters < 0.01 mm.

It was also observed that a dose of 16 g dm^{-3} wood ash caused a reduction in water retention at pressures lower than 6 kPa for both soil types (Figure 3). This effect of reducing water retention with wood ash application was also verified in part by Chang et al. (1977) when ash doses lower than 10% (vol) were added to soils with different textures. The reasons for this reduction are not yet clear, and the authors have not yet explained the causes of these effects. The doses of wood ash changed the soil bulk density in a nonlinear manner (Figure 7). First, it was verified that a dose of 16 g dm^{-3} increased soil bulk density in both Oxisol and Quartzipsamment soils. This increase in soil bulk density reduces the porous space and consequently decreases water content at saturation. With the application of 32 g dm^{-3} of wood ash, the bulk density of the soil + ash mixture returned to the initial value, that is, in the condition of soil without the addition of wood ash. As a result, the application of the maximum ash dose promoted a marked reduction in bulk density and an increase in total soil porosity.

An explanation for the effect described above can be found in the morphology of the ash particles. These particles have very different sizes and shapes, which in low doses and in mixture with the mineral particles of the soil allow for a rearrangement and greater packaging of the particles of the mixture soil and ash as a whole, causing an increase in bulk density. Subsequently, with the increase in ash dose until reaching the maximum value of 64 g dm^{-3}, the reduction in bulk density occurred because of the presence of ash particles, whose bulk density was on average 83% lower than the bulk density of pure soil.



** - Significant at $p \leq 0.01$; ns - Not-significant

Figure 7. Bulk density in Quartzipsamment and Oxisol as a function of wood ash doses

Although generally, the application of ash or biochar tends to reduce the bulk density of the mixture of soil and ash as a whole (Blanco-Canqui, 2017), Esmaeelnejad et al. (2017) suggested that fine particles of a similar material (biochar) can fill the pores between the soil particles, resulting in more effective packaging and higher bulk density of the soil + biochar. However, Liu et al. (2016) demonstrated that when biochar particles are larger than soil mineral particles (the authors evaluated sandy soil), these mineral grains probably surround the biochar particles, which increases the packaging of the soil + biochar mixture.

Conclusions

1. The physical-hydric properties of Oxisol and Quartzipsamment change according to the doses of wood ash, with increased values at the maximum dose.
2. At a dose of 16 g dm^{-3}, gravitational water was reduced in both soil classes.
3. The field capacity, total available water, and soil water characteristic curve showed the highest values at 64 g dm^{-3} wood ash.
4. The saturated hydraulic conductivity decreased linearly with the wood ash dose in both soil classes.

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