Received: 21 September 2021 | Revised: 4 January 2022 | Accepted: 8 January 2022

DOI: 10.1002/ldr.4202

RESEARCH ARTICLE

WILEY

Liming and co-application of water treatment residuals with biosolids for conditioning sandy soils

Pablo Lacerda Ribeiro[1,2] | Adilson Luís Bamberg[2] | Ivan dos Santos Pereira[1,2] | Alex Becker Monteiro[1,2] | Mariana da Luz Potes[3,4] | Cláudia Liane Rodrigues de Lima[1]

[1]Soil Science Department, Universidade Federal de Pelotas, Campus Capão do Leão, Campus Universitário, Capão do Leão, Rio Grande do Sul, Brazil

[2]Sustainable Use of Natural Resources Division, EMBRAPA Clima Temperado, Pelotas, Rio Grande do Sul, Brazil

[3]Analysis of organic compounds and metals laboratory, Universidade Federal do Rio Grande, Campus Carreiros, Rio Grande, Rio Grande do Sul, Brazil

[4]Kiel University, Institute of Plant Nutrition and Soil Science, Kiel, Germany

Correspondence
Pablo Lacerda Ribeiro, Soil Science Department, Universidade Federal de Pelotas, Campus Capão do Leão, Campus Universitário, S/N, CEP: 96160-000, Capão do Leão, RS, Brazil.
Email: pabloribeirolr@gmail.com

Funding information
Companhia Riograndense de Saneamento, Grant/Award Numbers: SEG, 02.17.00.003.00.00

Abstract

Application of water treatment residuals (WTR) and biosolids (BS) might ameliorate fragile soils. However, studies integrating impacts of waste preparation methods such as liming and grinding associated with co-application approaches for soil conditioning are lacking. The present study aimed to evaluate the feasibility of agricultural use of WTR as well as their co-application with BS to ameliorate a sandy soil through assessing impacts on selected soil quality indicators and on nutrient and potentially toxic element concentration in plant tissue in addition to the biomass yield of annual crops. The following treatments were evaluated: non-amended soil (control); drying plus grinding and liming WTR; WTR co-application with BS at 3:1 ratio; and a soil amendment commercially available in Brazil. All treatments were soil incorporated in the 0.0–0.2 m layer at 30 Mg ha^{-1} dose (dry mass). Selected soil physical, hydraulic, and chemical parameters were determined. Furthermore, nutrients and potentially toxic elements concentration in plant tissue as well as the agronomic performance of maize and ryegrass were measured. The co-application of WTR and BS increased the soil content of P, Zn, and Cu in the 0.0–0.1 m layer. The concentration of these nutrients also was greater in ryegrass tissue and promoted the biomass yield in 51%. WTR did not increase contaminants and did not decrease the P content in soil and in plant tissue, independently of drying plus grinding and liming. Considering the conditions investigated in our study, WTR/BS co-application was environmentally safe and effective in ameliorating soil quality.

KEYWORDS
alum sludge, nutrient availability, recycling, soil amendments, soil quality

1 | INTRODUCTION

Water treatment residuals (WTR) and biosolids (BS) (i.e. treated sewage sludge) (Mohajerani & Karabatak, 2020) are the main solid wastes generated during water purification for human consumption and wastewater treatment, respectively (Kleemann et al., 2020; Mahdy et al., 2020). The recycling of WTR and BS in fragile cropped soils is particularly promising (Dassanayake et al., 2015; Mukherjee et al., 2014b; Zhao et al., 2018). There are approximately 199,600,000 ha of cultivated sandy soils in the world and they are vulnerable to degradation processes such as disaggregation, erosion, organic matter losses, and groundwater contamination as well as to drought events which could compromise their productivity and ecosystem services (Huang & Hartemink, 2020).

WTR are mainly composed of finer mineral particles (Petterle et al., 2018) and, thus, their application in sandy soils may maintain or increase the cation exchangeable capacity and water holding capacity (Heil & Barbarick, 1989; Ibrahim et al., 2015, 2020; Mahmoud et al., 2020). Furthermore, BS can provide significant amounts of organic matter and nutrients such as phosphorus and nitrogen (Mossa et al., 2020; Pereira et al., 2020).

Contamination risks for recycling of wastes in agricultural soils must be assessed. They include accumulation of potentially toxic elements (PTEs) (Mossa et al., 2020; Wasserman et al., 2018), whereas WTR is commonly highlighted by presenting high total content of Al, Fe, and Mn which may generate deleterious effects on plant growth (Kluczka et al., 2017; Lombi et al., 2010; Silveira et al., 2013). In addition, loads of pathogenic organisms in BS must be monitored and kept under safe levels (Pereira et al., 2020).

The adoption of treatment processes can enable the agricultural use of WTR. Dewatering, drying, and stockpiling these materials form large and very stable aggregates which probably work as inert materials and do not interact with soil in the short-term. Consequently, dewatering plus grinding (Ippolito et al., 2009; Silveira et al., 2013) WTR have been implemented to adequately distribute and incorporate them into the soil. Applying WTR still wet (moisture around 50% wt/wt) to soil may be an alternative to avoid steps like drying and grinding, but available forms of Al may be highly increased in the soil once dewatering act as an Al stabilizer in WTR (Agyin-Birikorang & O'Connor, 2009).

The main agronomic barrier for WTR use in agriculture is the risk of triggering Al toxicity and P deficiency (Turner et al., 2019; Zhao et al., 2018). However, it probably can be prevented by keeping the pH of WTR and soil around 6.5 (Penn & Camberato, 2019). Although liming is widely used to correct acidity and to improve soil fertility status, previous studies have not investigated it for more appropriate WTR recycling nor have studied the effect of dewatering plus grinding the WTR before soil incorporation.

The nutrient content in WTR is usually low, hence mixing it with organic and nutrient-enriched materials like BS increases their potential for improving the quality of sandy soils (Bittencourt et al., 2012; Ibrahim et al., 2020). This co-application approach is also important since WTR and BS can increase the adsorptive capacity of chemical elements and the mitigation of nutrient leaching. Furthermore, the associated utilization of these wastes characterizes a waste-to-product strategy and can provide an integrated solution for managing both materials while a value-added product (i.e., soil conditioner) is developed (Banet et al., 2020; Pereira et al., 2020). While BS use in agriculture has been extensively reported, few studies have investigated the co-application of WTR and BS in field-scale conditions (Ippolito et al., 2009; Mahdy et al., 2020).

Considering the aforementioned benefits and uncertainties regarding WTR and BS use to improve sandy soils, we hypothesized: (i) liming WTR and soil avoids Al phytotoxicity and P deficiency, as well as dewatering and grinding can enhance the conditioning characteristics of WTR, benefitting soil quality indicators and crop growth; and (ii) the co-application of WTR and BS is environmentally safe and suitable as a soil conditioner, ameliorating soil fertility, and preventing nutrient losses by leaching and runoff.

This study aimed to evaluate the feasibility of agricultural use of WTR and their co-application with BS through assessing impacts on selected soil quality indicators and on nutrient and potentially toxic element concentration in plant tissue in addition to the biomass yield of annual crops.

2 | MATERIALS AND METHODS

2.1 | Waste origination, characterization, and preparation

Sludges from drinking water treatment plants, known as WTR, were obtained from surface water sources and collected from three drinking water treatment plants of the “Companhia Riograndense de Saneamento (CORSAN)”, responsible for two-thirds of the water supply of the State of Rio Grande do Sul (RS) population, around 7 million people, Southern Brazil. The water treatment facilities were located at the municipalities of Santa Maria, Gravataí, and Rio Grande. While the first station treats water withdrawn from an artificial dam, the others do so from the Gravataí and São Gonçalo Rivers, respectively. These locations were chosen because each one supplies treated water for more than 200,000 habitants and belongs to distinct geographic regions. Therefore, they can be considered representative of three important regions of the Rio Grande do Sul State.

The WTR were originated from the periodical backwash of sand filters after the sludge discharge from tank decants. Raw sludges with 1%–2% total solids were centrifuged to reduce humidity and to obtain WTR with 30% total solids. Representative samples (batches of about 5 m^{-3}) of the WTR were collected, transported, and stored in the Lowland Experimental Station of EMBRAPA Clima Temperado, geographic coordinates 31°49′9.70″S and 52°26′23.50″W until our experiment began.

The sewage sludge utilized to produce BS was also provided by CORSAN and it was collected from the Miranda Sewage Treatment Station of Rio Grande, Rio Grande do Sul, Brazil, after aerobic digestion with prolonged aeration. The maximum treatment capacity of this facility is 66.51 L s^{-1} and it serves approximately 22,000 habitants. The sludge was of urban domestic origin with irrelevant contribution of soil sediments and with no industrial contribution.

The following treatments were set up as a field experiment: control: non-amended soil; WTRc: drying plus grinding and liming WTR; WTRnc: drying plus grinding without liming; WTRw: wet, non-ground and limed WTR; WTR/BS: WTRc co-application with BS at 3:1 ratio and COM: soil amendment commercially available in Brazil. Tables 1 and 2 show the treatments description and their characterization, respectively.

The WTRc and WTRnc were disposed in layers of 0.1 m and dried in an agricultural greenhouse covered by translucent plastic of 200 μm thickness until the moisture content was below 20% and only WTRc was limed. On the other hand, WTRw was stored in the water treatment plant for approximately 3 months, then liming was performed before soil application. Liming of the WTRc and WTRw was carried out by applying 0.83% (mass/mass) of hydrated lime (neutralizing power of 86% and granulometry lower than 0.3 mm) to achieve a

TABLE 1 General description of the experimental treatments composed by water treatment residuals and biosolids

Treatments	[a]Dose (Mg ha^{-1})	Moisture	[b]Grinding plus sieving	[c]Liming	Description
Control	-	-	-	-	Non-amended soil
WTRc	30	<20%	Yes	Yes	Equitable mix of dried WTR from three origins—Rio Grande, Gravataí and Santa Maria, Rio Grande do Sul (RS) State, Brazil
WTRnc	30	<20%	Yes	No	Equitable mix of dried WTR from three origins—Rio Grande, Gravataí and Santa Maria, RS State, Brazil
WTRw	30	50%	No	Yes	Centrifuged WTR from Rio Grande, RS State, Brazil
WTR/BS	30	<20%	Yes	-	Mix of WTRc and BS at 3:1 ratio (dry mass)
Com	30	50%	-	-	Soil amendment, composed by bio-stabilized pine bark, registered and commercially available product in Brazil

[a] Dry mass

[b] Ground plus sieved to obtain clods smaller than 2.0 mm

[c] WTR limed by adding 0.83% (mass/mass) of hydrated lime (neutralizing power of 86% and particles smaller than 0.3 mm) to achieve a final pH of 6.5

final pH of 6.5. The lime rate had been previously determined through incubation trials. In addition, solarization was performed on the sewage sludge, following the procedures indicated by Pereira et al. (2020), to convert it into BS and to prevent any contamination risk by pathogens.

2.2 | Study site and experimental design

The field experiment was carried out in an arenic Albaqualf (Soil Survey Staff, 2014) with 8%, 18%, and 74% of clay, silt, and sand content, respectively, in the 0.0–0.2 m layer. The experimental area had been previously managed as a grazed native field covered by spontaneous vegetation, then prepared by plowing and harrowing 1 month before the experiment installation. The six treatments were set on a randomized block design, with four replications, with the area of each plot equal to 25 m^2. The incorporation of all treatments was made at a constant application rate of 30 Mg ha^{-1} (dry basis) in the 0.0–0.2 m soil layer with a disk harrow moved by tractor in January 2019. The rate of 30 Mg ha^{-1} and the 3:1 ratio in WTR/BS treatment were chosen according to previous pot trials conducted in greenhouse under controlled conditions.

2.3 | Soil sampling for physical analysis

Soil samples with undisturbed structure (6 treatments × 4 experimental replications × 3 sampling repetitions × 2 soil layers = 144 samples) were collected after the first cropping cycle, 3 months after the experiment installation in the layers 0.0–0.1 and 0.1–0.2 m with metal cylinders of 0.05 m height and 0.05 m diameter to determine the bulk density (Bd), total porosity (Tp), macroporosity (Ma), and microporosity (Mi) according to Teixeira et al. (2017); as well as resistance to penetration (Rp), volumetric water content at field capacity (θ_{FC}), and at permanent wilting point (θ_{PWP}), and available water content (AW).

In the laboratory, these samples were saturated by capillarity and equilibrated at the tension of 10 kPa in a Richards pressure chamber (Klute, 1986) for Rp determination with an electronic penetrometer (MA 933) (Tormena et al., 2007). The water content retained in samples equilibrated at the tension of 6 kPa was adopted to distinguish Ma from Mi.

The soil water retention curves (SWRC) were obtained by subjecting saturated samples to the tensions of 1 and 6 kPa on a tension table and to the tensions of 10 and 100 kPa in Richards pressure chambers with porous plates (Klute, 1986). Water contents retained in higher tensions than 300 kPa were estimated in samples with unpreserved structure by using a psychrometer (WP4c Decagon Devices).

The van Genuchten's model (van Genuchten, 1980) was used for adjusting the SWRC raw data using the MATHCAD software (Mathsoft, 1998). Then, after obtaining the empirical parameters and adjusted data, θ_{FC} and θ_{PWP} were considered as the estimated volumetric water contents retained in the soil at the tensions of 10 and 1500 kPa, respectively, while AW was calculated by subtracting θ_{PWP} from θ_{FC}.

2.4 | Soil sampling for chemical analysis

Soil samples with disturbed structure (6 treatments × 4 experimental replications × 3 soil layers = 72 samples) were collected 3 months after experiment implantation in the layers 0.0–0.1; 0.1–0.2 and 0.2–0.4 m. Then, they were air-dried in the laboratory and passed through a 2 mm sieve for the following measurements: pH$_{H2O}$, organic matter, effective cation exchangeable capacity (ECEC), base saturation percentage (V%), aluminum saturation percentage (m%), content of available phosphorus—Mehlich-1 (P), available potassium—Mehlich-1 (K), exchangeable calcium—KCl 1 mol L^{-1}(Ca), magnesium—KCl 1 mol L^{-1} (Mg), available sulfur—S-SO$_4$ (S), available manganese (Mn) and available zinc (Zn) (Teixeira et al., 2017).

TABLE 2 Physicochemical characteristics of the evaluated treatments and raw materials

		Treatments/raw materials							
Parameters	**Unit**	**WTRc**	**WTRnc**	**WTRw**	**WTR/BS**	**BS**	**Com**	**MSS**[a]	**MSA**[b]
Density	Mg m^3	1.04	1.03	1.09	0.97	0.72	0.55		
pH_{H2O}		7.2	6.30	5.70	6.90	6.25	5.30		
TOC	%	10.8	9.22	4.27	15.70	31.25	7.32		
CEC	mmol kg^{-1}	478	517	366	538	585	989		
Total nitrogen	g kg^{-1}	0.61	1.42	0.49	1.81	57.5	2.18		
Total phosphorus	g kg^{-1}	1.20	1.69	0.54	5.26	25.25	0.37		
Total potassium	g kg^{-1}	2.07	2.05	9.02	3.61	3.37	3.81		
Total calcium	g kg^{-1}	3.38	2.44	3.13	17.20	20	23.49		
Total magnesium	g kg^{-1}	3.53	2.96	11.92	7.44	6.6	9.85		
Total sulfur	g kg^{-1}	10.72	7.18	8.41	13.07	9.8	3.56		
Total aluminum	g kg^{-1}	101.25	107.87	227.96	61.08	10.62	9.62		
Total iron	g kg^{-1}	25.17	27.07	98.02	13.62	27	14.23		
Total manganese	g kg^{-1}	1.34	1.28	0.43	0.94	0.41	0.43		
Total boron	mg kg^{-1}	<5.81	<5.72	<5.66	<6.57	55.25	<12.93		
Total sodium	mg kg^{-1}	251	240	416	375	939	640		
Inorganic contaminants									
Total mercury	mg kg^{-1}	<0.01	<0.01	<0.01		<0.118		17	1
Chromium^{6+}	mg kg^{-1}	1.35	1.39	0.33		<0.172			2
Total selenium	mg kg^{-1}	<0.27	<0.28	<0.28		<0.2		100	80
Total cadmium	mg kg^{-1}	<0.16	<0.11	<0.17		0.85		39	3
Total arsenic	mg kg^{-1}	5.26	12.65	8.10		1.1		41	20
Total nickel	mg kg^{-1}	13.75	4.48	7.02		11.41		420	70
Total lead	mg kg^{-1}	17.89	19.87	16.33		16.25		300	150
Total barium	mg kg^{-1}	16.50	97.62	49.93		151.15		1300	
Total zinc	mg kg^{-1}	64	78.80	130.20	456.40	1003	79.20	2800	
Total copper	mg kg^{-1}	38.81	39.96	45.03	134.40	106.99	26.02	1500	
Total molybdenum	mg kg^{-1}	3.20	<0.28	<0.28		4.37		50	
Pathogenic contaminants									
Thermotolerant coliforms	MPN/g of dry matter	<1.8	<1.8	<1.8		1.0		<1000	<1000
Viable eggs of helminths	eggs/g of dry matter	<0.25	<0.25	<0.25		<0.25		<0.25	<0.25
Salmonella	MPN/10 g of dry matter	Absent	Absent	Absent		Absent		Absent	Absent
Enteric virus	PFU/4 g of dry matter	Absent	Absent	Absent		Absent		<1.0	Absent

Abbreviations: CEC, cation exchangeable capacity; MPN, most probable number; PFU, plaque-forming unit; TOC, total organic carbon

[a] Maximum value allowed in BS (BRAZIL, 2006)

[b] Maximum value allowed in soil amendments (BRAZIL, 2016)

2.5 | Plant sampling, tissue analysis, and agronomic performance

Maize was sown with the target of 60,000 plants ha^{-1} in January 2019. Fertilization followed the regional technical recommendations for the crop (Committee on Soil Chemistry and Fertility [CSCF], 2016). Chlorophyll index and shoot dry mass were quantified 60 days after sowing on the crop vegetative stage. Fifteen plants within each plot were randomly chosen to be evaluated. Chlorophyll index was determined in two completely expanded leaves per plant with a portable chlorophyll meter (ClorofiLOG—Falker Automação Agrícola Ltda., Porto Alegre, Brazil). After sampling and measuring, maize plants were harvested and removed from the experimental area as if they were used for silage.

Ryegrass (cultivar Embrapa BRS-Ponteio®) was utilized in the second cropping cycle. It was sown on April 2019 by throwing with a seeding density of 35 kg ha^{-1}. There was no basic fertilization and 57 kg ha^{-1} of N was applied 30 days after sowing (CSCF, 2016). Shoot dry mass was measured 90 days after sowing. Four sub samples with 0.25 m^2 were collected in each plot, totalizing 1 m^2.

After the evaluations described for maize and ryegrass, plant shoot samples were dried in an oven at 65°C until constant mass, ground in a sample mill and homogenized for analyzing the concentration of nutrients and PTEs. Tissue samples were subjected to nitric-perchloric acid digestion (3:1 ratio) in digester block (MA-4025, Marconi, Brazil) under increasing temperature until reaching 200°C then maintained for about 6 hr, as described in Silva (2009), followed by quantification in a microwave-induced plasma optical emission spectrometer, model 4200 (Agilent Technologies, Melbourne, Australia). The instrumentation is detailed in Kleemann et al. (2020).

2.6 | Statistical data analysis

The response variable results were subjected to the normality analysis of the frequency distribution and verification for the presence of

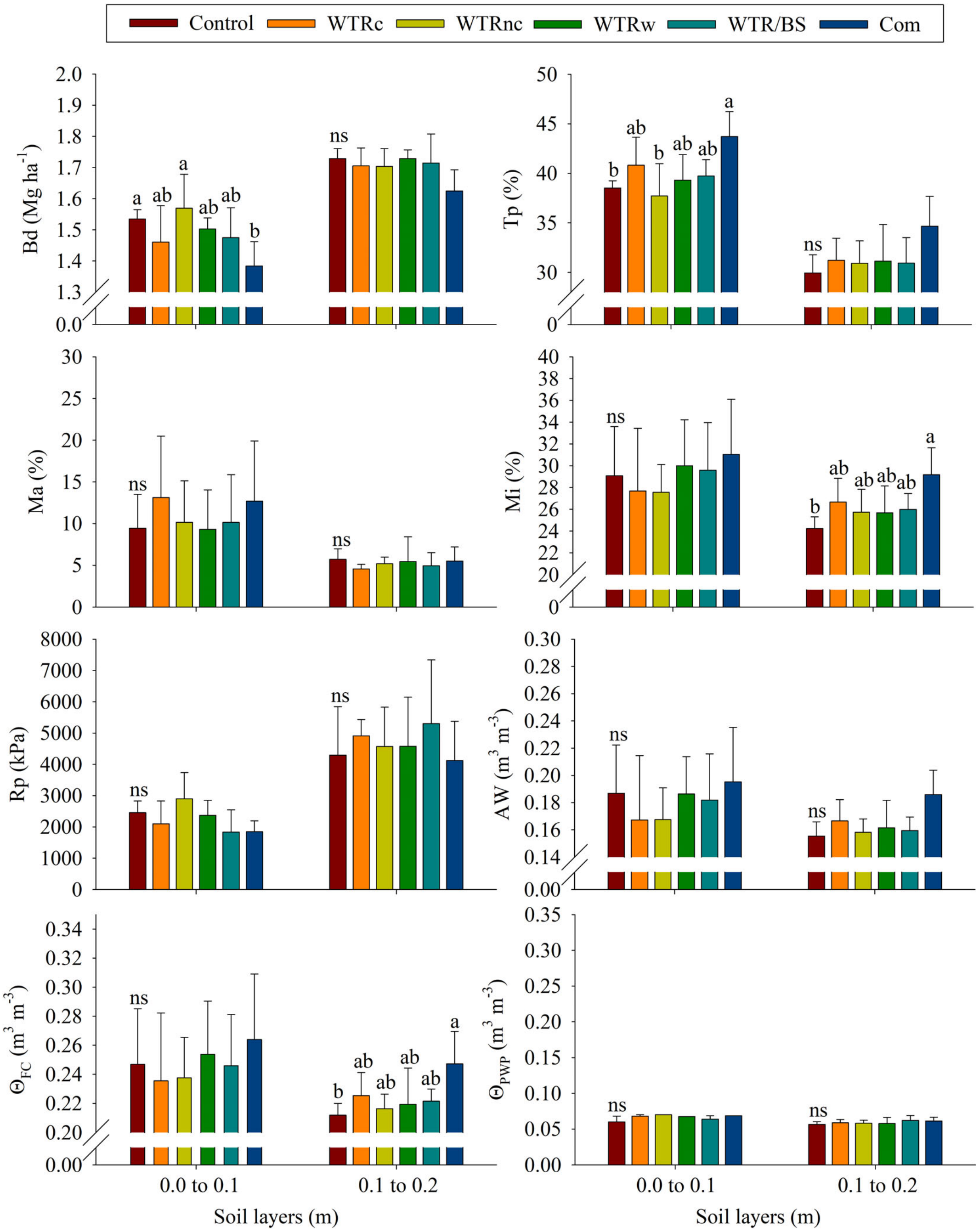

FIGURE 1 Mean values of bulk density (Bd), total porosity (Tp), macroporosity (Ma), microporosity (Mi), soil resistance to penetration (Rp), available water content (AW), volumetric water content at field capacity (θ_{FC}) and volumetric water content at permanent wilting point (θ_{PWP}) in the layers of 0.0–0.1 and 0.1–0.2 m of an albaqualf under different treatments. Vertical bars represent mean standard deviation. Means followed by the same letter within the same layer are not significantly different according to the Tukey test $p < 0.05$. ns, non-significant [Color figure can be viewed at wileyonlinelibrary.com]

outliers, then to the one-way analysis of variance (*F* test). The response variables which presented significant treatment effects were submitted to the Tukey test ($p < 0.05$) using the WINSTAT software (Machado & Conceição, 2003).

3 | RESULTS

3.1 | Physicochemical characteristics of the treatments and raw materials

The WTR presented high total aluminum and low nutrient content (Table 2) while the BS showed significant contents of TOC, total nitrogen, total phosphorus, and total zinc. The treatments and raw materials did not present any inorganic and pathogenic contaminants above the limits indicated by Brazilian legislation for BS and soil amendments (Table 2). This fact is also true when considering the regulations adopted by the United States for land application of BS (USEPA, 1993). In addition, significant concentrations were not detected when taking into consideration the monitoring of organic contaminants listed as potentially toxic to the environment (Table S1).

3.2 | Soil physical-hydric attributes under different preparations and co-application strategies of WTRs and BS

Except for Com, all treatments resulted in statistically equal Bd and Tp (Figure 1). Com provided the lowest Bd and the highest Tp average values in the 0.0–0.1 m layer. Ma was not influenced by the treatments in both layers. All treatments provided Ma greater or very close to 10% in the 0.0–0.1 m layer, while in the 0.1–0.2 m layer, lower values than 10% were found. Mi was not altered in the 0.0–0.1 m layer. However, Com resulted in greater Mi values in 0.1–0.2 m layer.

WTR/BS and Com showed Rp values lower than 2000 kPa which is considered a critical limit for crop growth and development (Li et al., 2020). However, all the treatments were statistically equal in both evaluated layers. In addition, the Rp values in the 0.1–0.2 m layer were more than 100% higher than the critical limit. AW, θ_{FC}, and θ_{PWP} were not impacted by the tested treatments in the 0.0–0.1 m layer. Furthermore, θ_{FC} increased with Com application in the 0.1–0.2 m layer that corroborates the higher Mi shown in this layer. The SWRC confirmed Com as the only treatment that altered the soil Mi and water retention (Figure S1).

3.3 | Chemical attributes related to soil fertility

All the treatments showed pH_{H2O}, organic matter, ECEC; V% and m% statistically equal to the control in the three evaluated layers, except for Com which increased organic matter in the 0.0–0.1 m layer, changing its classification from low to medium level (Figure 2).

WTR/BS increased available soil P content by 137% in comparison to the control, also changing the nutrient classification from medium to very high in the 0.0–0.1 m layer (Figure 3).

WTR/BS increased the content of Zn by 506% and 301% in the 0.0–0.1 m and 0.1–0.2 m layers, respectively. They also generated 33% higher Cu content in the 0.0–0.1 m layer (Figure 4).

None of the treatments composed by WTR was inferior to the control, which shows that there was no significant reduction of soil nutrients availability due to the addition of these materials to soil nor substantial increase in the available levels of Al saturation (m, %), Fe and Mn (Figures 2–4). In addition, the 0.2–0.4 m layer was not influenced by the treatments after superficial incorporation, which indicates that there was no significant vertical mobility of the evaluated chemical elements in soil profile.

3.4 | Absorption of nutrients and potentially toxic elements by maize and ryegrass plants

Nutrient concentration in maize tissue was not impacted by the treatments (Figure 5). On the other hand, WTR/BS increased the content of P, Cu, and Zn by 34%, 63%, and 44%, respectively, when compared to the control in ryegrass tissue (Figures 4 and 5).

The treatments with only WTR in their composition did not differ from the control for any of the analyzed variables, which shows that these materials did not decrease the concentration of P and did not increase the levels of Fe, Mn, and Al in the ryegrass tissue. The different WTR preparation methods (WTRc, WTRnc, and WTRw) also did not impact the nutrient concentration in maize and ryegrass tissue. PTEs in ryegrass tissue were not modified by the treatments (Table 3).

3.5 | Agronomic performance of maize and ryegrass crops

WTR/BS increased chlorophyll index in maize (Figure 6). The second crop (ryegrass) confirms WTR/BS favored plant biomass production by increasing dry mass by 51% in comparison to the control. Com and treatments composed only by WTR showed chlorophyll index and dry mass mean values equal to the control.

4 | DISCUSSION

Com was the only treatment that significantly affected the evaluated indicators of soil physical quality, slightly improving some of them (Figure 1). The organic nature of Com® (bio stabilized pine bark) resulted in a density equal to 0.55 Mg m^{-3} of this soil amendment (Table 2). Despite the contrasting particle size distribution of the studied sandy soil and WTR, the treatments composed by WTR demonstrated no short-term effects on the selected indicators of soil physical quality. Thus, probably cumulative applications or higher rates would be necessary to generate any significant improvement on them.

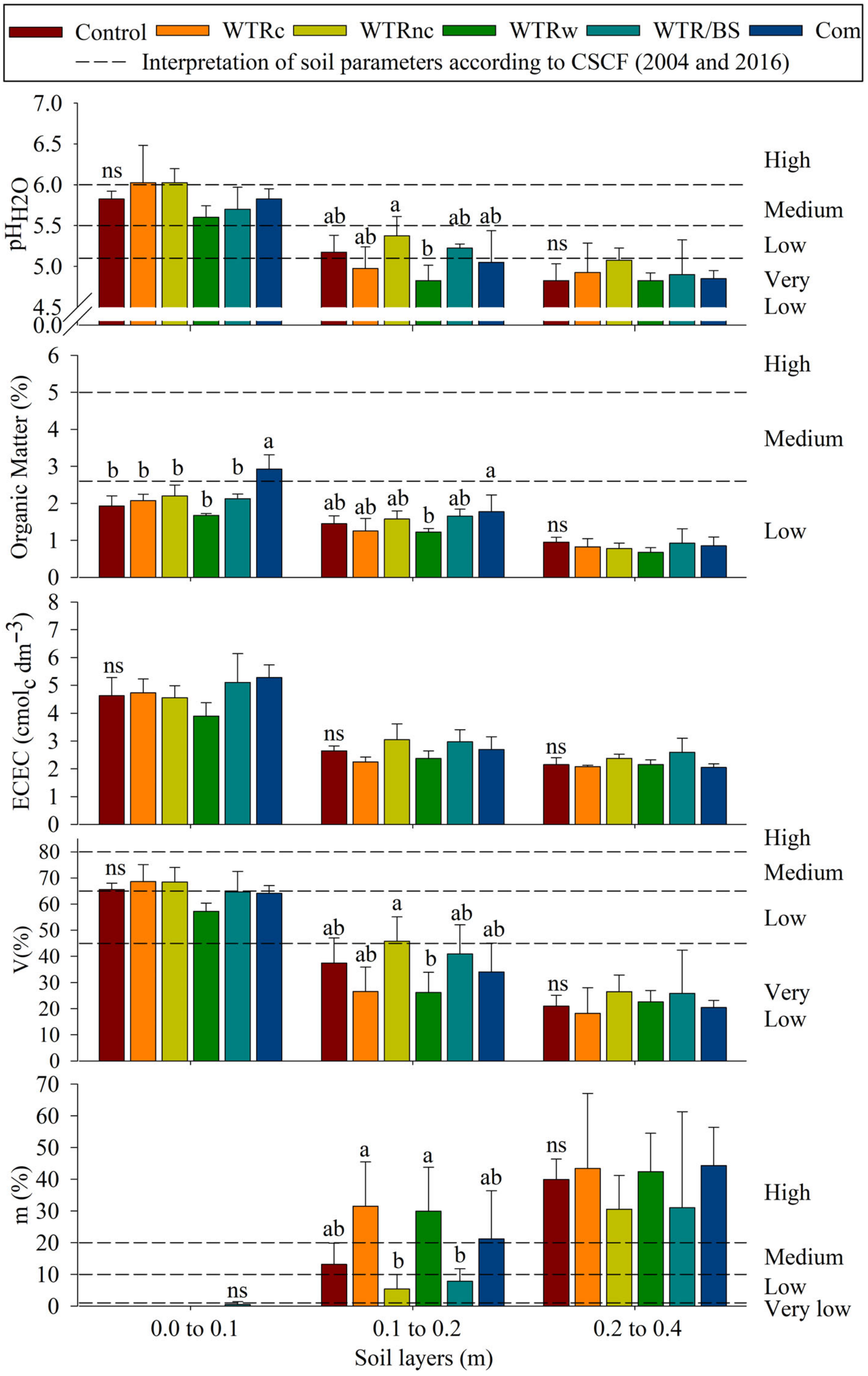

FIGURE 2 Mean values of pH_{H2O}, organic matter, effective cation exchange capacity (ECEC), base saturation percentage (V%) and aluminum saturation percentage (m%) in the layers of 0.0–0.1; 0.1–0.2 and 0.2–0.4 m of an albaqualf under different treatments. Vertical bars represent mean standard deviation. Means followed by the same letter within the same layer are not significantly different according to the Tukey test $p < 0.05$. ns, non-significant [Color figure can be viewed at wileyonlinelibrary.com]

Maria et al. (2010) reported BS decreased Bd and Mi while Ma was increased by long-term BS reapplication in a degraded Oxisol under field conditions. However, only one application at doses up to 21.6 Mg ha^{-1} was not enough to change the studied soil physical attributes in short-term (one crop season), corroborating our results. Mukherjee et al. (2014a, 2014b) also demonstrated WTR did not modify soil physical quality indicators such as Bd, Rp, and AW under short-term and low application rates (7.5 Mg ha^{-1}).

Liming the experimental area concomitantly to the incorporation of treatments was sufficient to keep the pH_{H2O} higher than 5.5 and to avoid the presence of exchangeable Al on soil ECEC and available Mn in the 0.0–0.1 layer (Figures 2 and 3), which are considered toxic elements for most crops. The significant correlation between pH_{H2O} and V% ($r = 0.74$, $p < 0.01$), m% ($r = -0.42$, $p < 0.05$) and Mn ($r = -0.48$, $p < 0.05$) in the 0.0–0.1 m layer confirmed this assumption. This lime application probably contributed to the absence of significant differences between control and limed (WTRc) or non-limed (WTRnc and WTRw) treatments for soil fertility parameters. Therefore, managing pH by liming the soil and/or the amendment directly enabled the successful use of WTR because it kept the Al in precipitated forms. Thus,

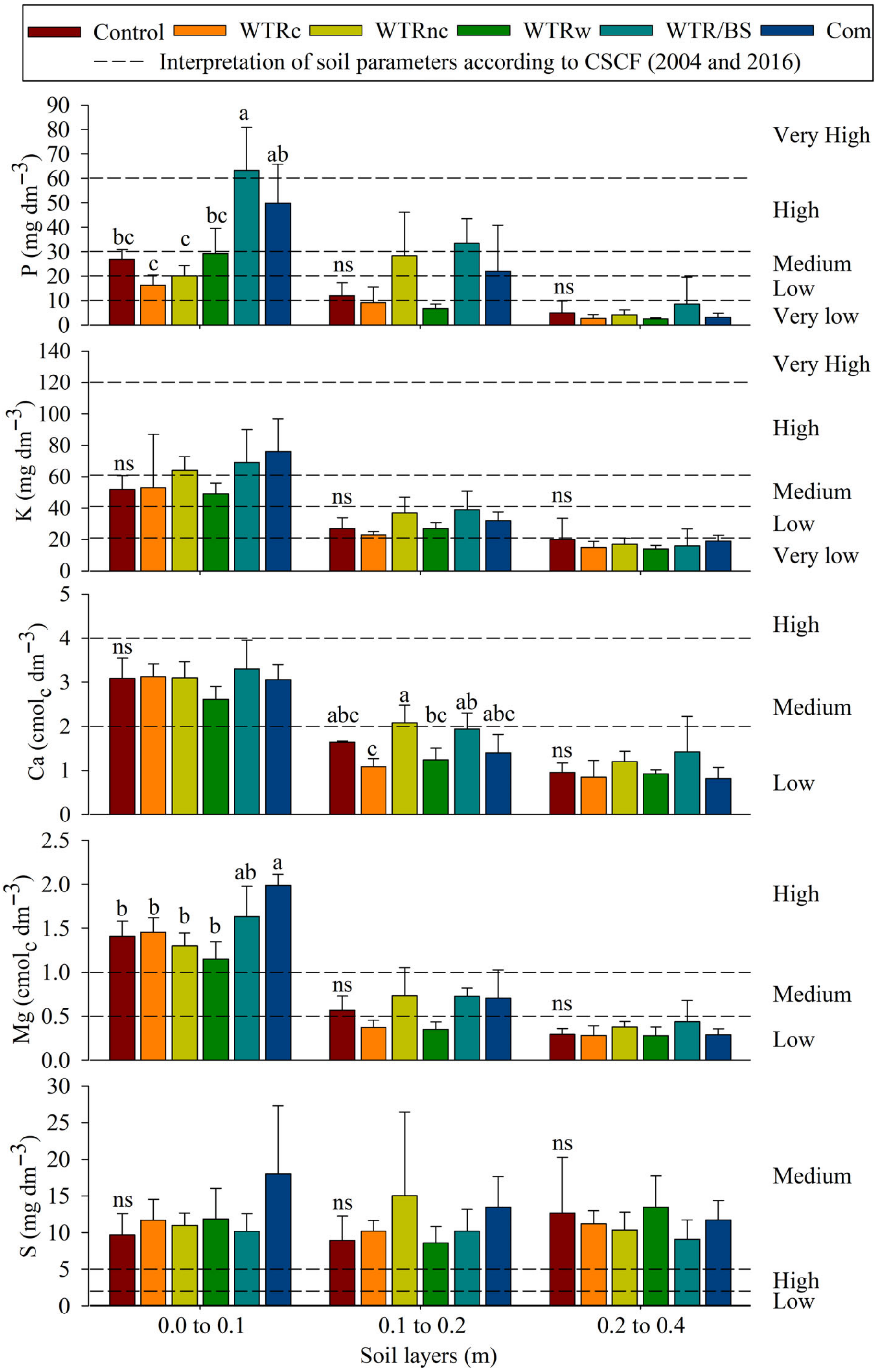

FIGURE 3 Mean values of available phosphorus—Mehlich-1 (P), available potassium—Mehlich-1 (K), exchangeable calcium—KCl 1 mol L^{-1} (Ca), magnesium—KCl 1 mol L^{-1} (Mg) and available sulfur—S-SO$_4$ (S) in layers of 0.0–0.1; 0.1–0.2 and 0.2–0.4 m of an albaqualf under different treatments. Vertical bars represent mean standard deviation. Means followed by the same letter within the same layer are not significantly different according to the Tukey test $p < 0.05$. ns, non-significant. CSCF (2004 and 2016) [Color figure can be viewed at wileyonlinelibrary.com]

high contents of elements like Al, Fe, and Mn in WTR are not supposed to prevent their use in sandy soils intended for agricultural purposes if practices such as liming are adopted.

While WTR did not provide significant nutrient loads to the soil, their co-application with BS was efficient to improve soil fertility as well as increase available forms of soil P, Zn, and Cu, and their concentrations in ryegrass tissue (Figures 3–5). WTR plays an important role when co-applied with BS seeing that they may increase soil cation exchangeable capacity and present significant amounts of aluminum, iron, and manganese oxides which can adsorb excessive amounts of available phosphates and metals like Zn and Cu, preventing subsoil and water contamination due to runoff and leaching. Therefore, WTR and BS co-application is a useful strategy for cropping and fertilizing fragile soils (Barrón & Torrent, 2013; Mahdy et al., 2009; Mahdy et al., 2020). Nevertheless, further research is still demanded to define how efficient the WTR are in preventing nutrient losses and mobility of other relevant chemical elements by leaching mainly into sandy soils.

As the characterization of the treatments and raw materials indicated (Table 2), the investigated WTR and BS did not present

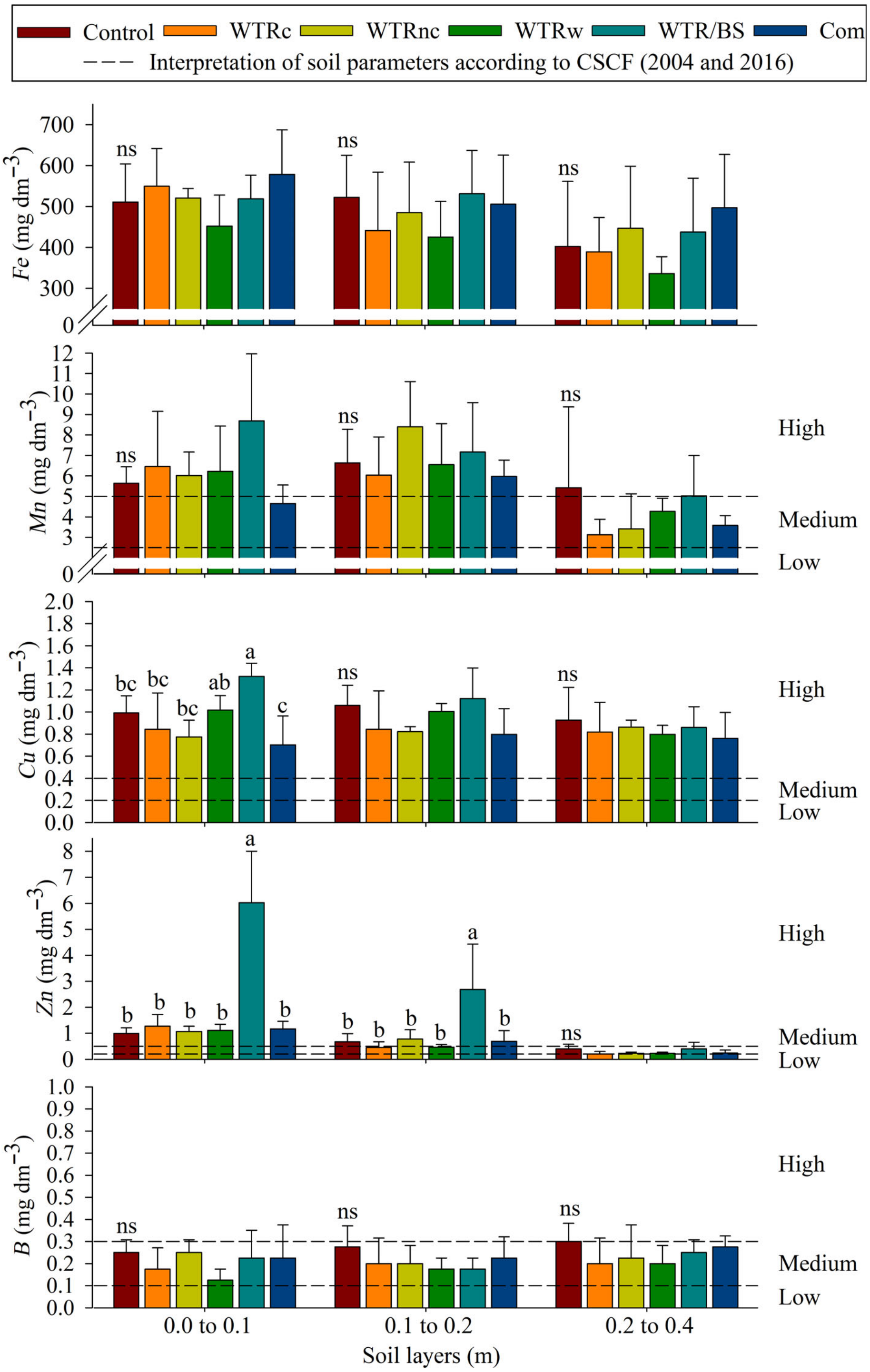

FIGURE 4 Mean values of available iron (Fe), manganese (Mn), copper (Cu), zinc (Zn) and boron (B) in the layers of 0.0–0.1; 0.1–0.2 and 0.2–0.4 m of an albaqualf under different treatments. Vertical bars represent mean standard deviation. Means followed by the same letter within the same layer are not significantly different according to the Tukey test $p < 0.05$. ns, non-significant. CSCF (2004 and 2016) [Color figure can be viewed at wileyonlinelibrary.com]

significant loads of potentially toxic elements. Nevertheless, this fact cannot be generalized once the waste characteristics vary due to the local particularities from where the water and wastewater treatment facilities are located, demanding regional and periodic waste characterizations. In addition, it is important to use previously tested and validated ratios of WTR and BS to avoid over-immobilization of nutrients and harmful effects on crop growth.

Corroborating our results, Mahdy et al. (2017) demonstrated that WTR have high capacity of adsorbing P on BS amended soil. However, when using appropriate application ratios and rates such as the suggested on this study, soil P can be increased and the crops can benefit from it. Ippolito et al. (2009) reported an increase in plant uptake of Cu and Zn in short-term as a response to WTR and BS repeated co-application. Mahdy et al. (2009) found an increase in P content in maize tissue when combining WTR and BS in the proportion 1:1 up to the dose of 3% (wt/wt).

Even though Zn and Cu soil content were considered high in the 0.0–0.1 layer according to the CSCF (2016) (Figure 4), the mean values were far below the average quality reference values, fixed in the 90th percentile, by soil groups for the natural metal contents in

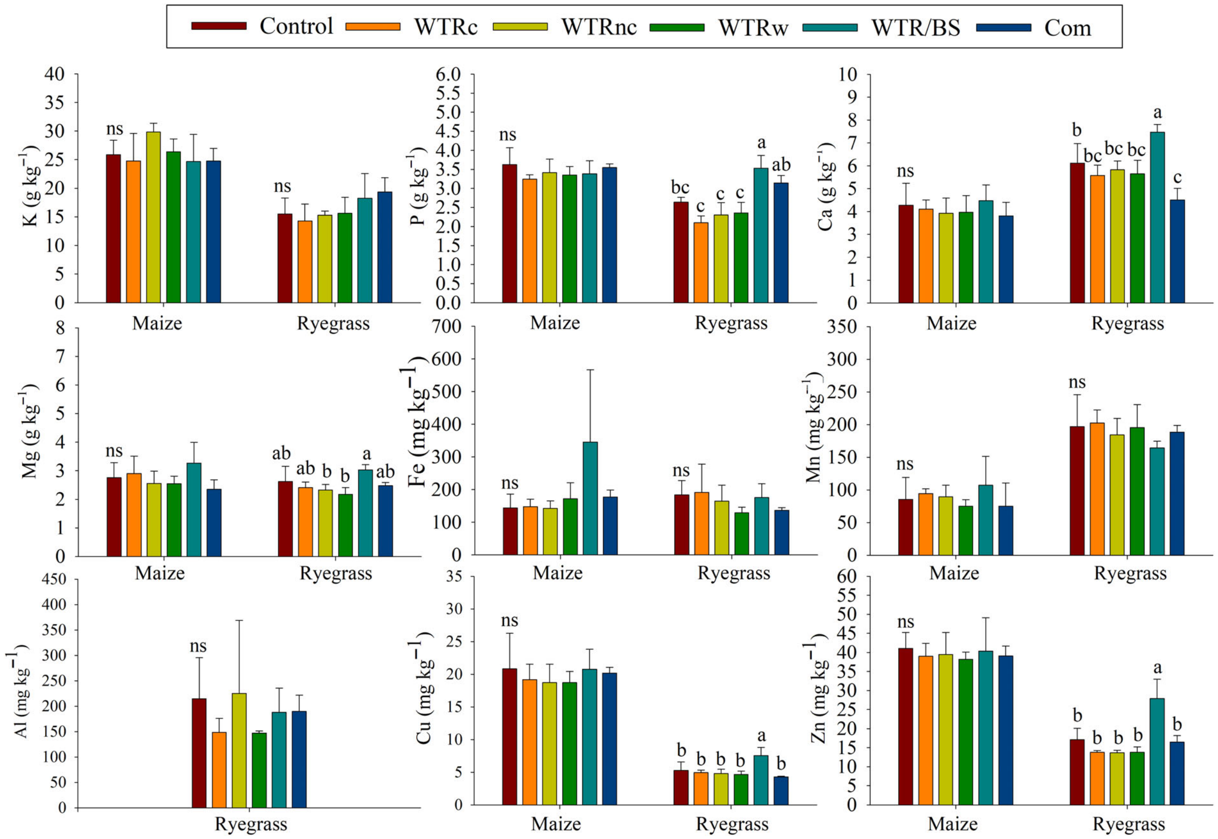

FIGURE 5 Mean contents of potassium (K), phosphorus (P), calcium (Ca), iron (Fe), manganese (Mn), aluminum (Al), copper (Cu) and zinc (Zn) in the tissues of maize and of ryegrass plants cultivated in an albaqualf under different treatments. Vertical bars represent mean standard deviation. Means followed by the same letter within the same crop are not significantly different according to the Tukey test $p < 0.05$. ns, non-significant [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Mean values of total concentrations of barium (Ba), cadmium (Ca), cobalt (Co), chromium (Cr), nickel (Ni) and lead (Pb) in the tissues of ryegrass plants cultivated in an albaqualf under different treatments

	Ba	Cd	Co	Cr	Ni	Pb
Treatments	mg kg^{-1}					
Control	29.8	<2.85	<9.5	<2.85	<38.5	<28.5
WTRc	24.1	<2.85	<9.5	<2.85	<38.5	<28.5
WTRnc	26.5	<2.85	<9.5	<2.85	<38.5	<28.5
WTRw	23.3	<2.85	<9.5	<2.85	<38.5	<28.5
WTR/BS	23.5	<2.85	<9.5	<2.85	<38.5	<28.5
Com	22.5	<2.85	<9.5	<2.85	<38.5	<28.5

Abbreviations: BS, biosolids; WTR, water treatment residuals

soils of Rio Grande do Sul, Brazil (31 and 17 mg dm^{-3} for Zn and Cu, respectively) (Althaus et al., 2018). Thus, this increase did not represent contamination risks. Pereira et al. (2020) indicated BS can be a source of Zn and Cu for lettuce when soil incorporated compounds and both micronutrients were positively correlated with chlorophyll index, likely stimulating the photosynthetic rate.

WTR/BS increased chlorophyll index on maize probably due to the higher availability of N, P, Zn, and Cu (Figure 6). Chlorophyll index is directly associated with nitrogen uptake by maize, which stimulates enzyme content, enzyme activity, and chlorophyll content in the leaves (Nasar et al., 2020), so the BS, which was introduced in the mix WTR/BS, probably represented the main additional input of N to the standard fertilization (Table 2). Bittencourt et al. (2012) reported that WTR doses up to 37 Mg ha^{-1} associated with BS favored soil N availability to plants. Roman-Perez et al. (2021) and Roman-Perez & Hernandez-Ramirez (2021) showed that BS can promote N availability and, if associated with urea, they represent an efficient N source to barley, enabling the reduction of N rates.

The higher nutrient soil availability and concentration in plant tissue promoted by WTR/BS occasioned superior biomass production in ryegrass. Soil available P was positively correlated with both dry mass of maize ($r = 0.57$, $p < 0.01$) and ryegrass ($r = 0.43$, $p < 0.05$). In addition, ryegrass dry mass was positively correlated to soil available Zn and Cu and Zn tissue concentration (Table S3), while maize dry mass was strongly regulated by soil physical parameters like Tp and Ma, in which higher values were beneficial, and Bd and Rp, in which higher values were deleterious (Table S2). Therefore, maize biomass productivity was more affected by physical parameters than ryegrass, probably due to abiotic factors like drought stress which led to less prominent effects of the applied treatments on tissue concentration and agronomic parameters. At the same time, ryegrass clearly

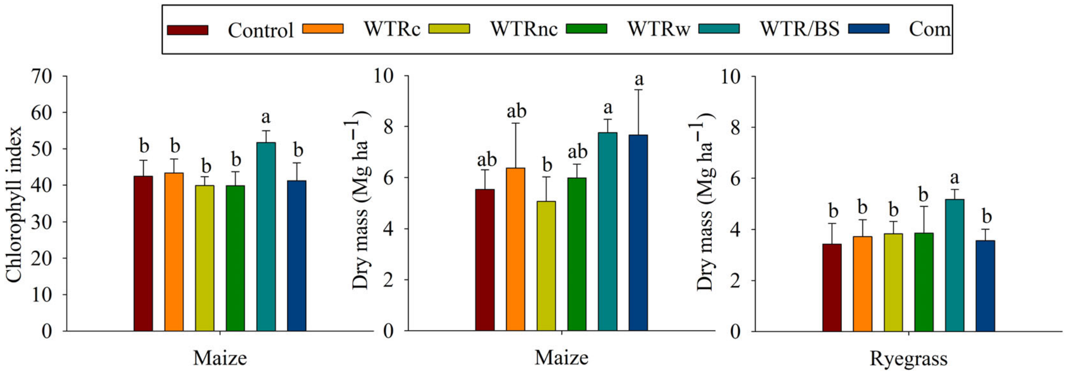

FIGURE 6 Mean values of chlorophyll index and dry mass of maize and ryegrass cultivated on an Albaqualf under different treatments. Vertical bars represent mean standard deviation. Means followed by the same letter within the same crop are not significantly different according to the Tukey test $p < 0.05$ [Color figure can be viewed at wileyonlinelibrary.com]

evidenced the conversion of the higher soil nutrient availability (Figures 3 and 4) in higher nutrient concentration in plant tissue and biomass production (Figures 5 and 6).

Corroborating our results, Mahdy et al. (2009) found greater production of maize biomass grown in a greenhouse when combining WTR with BS at 1:1 ratio with a dose of 3% (wt/wt), attributing this effect mostly to the greater availability of P. Ippolito et al. (1999) found that increasing WTR application even in high rates (750 Mg ha^{-1}) combined with a BS dose (15 Mg ha^{-1}) in a sandy loam soil increased the dry mass production of blue grama (*Bouteloua gracilis*). Mahdy et al. (2020) reported higher maize biomass production due to the application of mixed WTR nanoparticles and BS. Roman-Perez et al. (2021) indicated BS associated with urea can be as efficient as only urea fertilization for barley.

The treatments containing only WTR showed statistically equal results to the control for plant growth parameters and for all other studied variables, independently of drying plus grinding and liming. No significant differences between liming and non-liming WTR were observed in short-term (two cropping seasons) probably due to the application of lime in the experimental area, which was done concomitantly to the application of the treatments. Agreeing with our results, increasing WTR doses up to 70 Mg ha^{-1} did not affect forage dry mass yield of Bahiagrass (*Paspalum notatum*) (Silveira et al., 2013), pearl millet (*Pennisetum americanum*) (Bittencourt et al., 2012) and ryegrass (Oladeji et al., 2009). Mukherjee et al. (2014b) and (Mukherjee et al., 2014a) also did not find effects of applying WTR on soybean and maize growth, respectively. Therefore, despite not offering significant benefits for crops in general, WTR can be applied without negative effects or environmental risks when some practices, as liming and using it at previously tested doses, are adopted.

Keeping the soil pH around 6 is fundamental for the successful utilization of these residues in agricultural soils. More studies about the effect of liming the WTR directly are recommended, focusing on long-term effects and on nutrients and PTE availability regarding the soil natural reacidification. In relation to the decision of drying plus grinding WTR, logistic issues such as viability and costs associated with the proximity to receiver farms and storage capacity in the water treatment facilities should be considered. In this sense, drying plus grinding are encouraged because the transport and storage efficiency is increased by including these steps while managing water treatment wastes.

Following the conditions used in our study, the co-application of WTR and BS was environmentally safe and promoted nutrient availability and crop yield, representing an excellent material for developing a value-added product (soil conditioner), promoting the recycling of two important wastes worldwide and promoting agroecosystem services of sandy soils. These soils have poor cation exchangeable capacity and organic matter, low nutrient and water holding capacities, being usually considered fragile and limited for agricultural use, particularly under tropical and sub-tropical environments. Thus, WTR/BS should be designated to these soils seeing that it has, exactly, the main potential of benefiting these soil properties. The suggested rate of 30 Mg ha^{-1} at 3:1 ratio of WTR and BS demonstrated to be suitable for agricultural use and is in accordance with the proportion of both wastes generated by sanitation companies in small to medium-size cities. Further studies are still necessary to fully understand the long-term effects and to validate other ratios and/or wastes from different origins.

5 | CONCLUSIONS

This work evaluated different preparations of WTR and the co-application of WTR with BS, aiming to validate this strategy as a solution to ameliorate sandy soils and for safe, efficient, and sustainable disposal of solid wastes from water and wastewater treatment plants in agricultural soils.

When singly applied, WTR are environmentally and agronomically safe for agricultural use at doses up to 30 Mg ha^{-1}, causing no negative or positive effects in soil and plants. Drying plus grinding and liming the WTR did not change the achieved results, while liming the receiver soil prevented the occurrence of Al phytotoxicity (m, %) and P deficiency. However, dewatering and grinding the WTR did not enhance the conditioning potential in the short-term. Nevertheless, as drying plus grinding facilitate the storage and transport of these wastes from water treatment plants to farmlands, and liming may avoid Al release from acid WTR and mitigate P and micronutrients immobilization, these practices are highly encouraged to be taken as preventive against side-effects of WTR application.

Co-application of WTR and BS is suitable as a soil conditioner and it is environmentally safe, promoting soil fertility and crop yield. In addition, the characterization of WTR and BS must be regionally and periodically executed before planning soil application to ensure the absence of contaminations risks which may occur as a consequence of local variability aspects related to wastes origin, generation and treatment.

ACKNOWLEDGMENTS

To the Companhia Riograndense de Saneamento for the financial support (Grant No SEG: 02.17.00.003.00.00) and for providing the studied water treatment residuals; to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for scholarship concession and to EMBRAPA Clima Temperado for providing its facilities to support our research.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Pablo Lacerda Ribeiro https://orcid.org/0000-0001-7512-1390

REFERENCES

Agyin-Birikorang, S., & O'Connor, G. A. (2009). Aging effects on reactivity of an aluminum-based drinking-water treatment residual as a soil amendment. *Science of the Total Environment*, *407*, 826–834. https://doi.org/10.1016/j.scitotenv.2008.09.025

Althaus, D., Gianello, C., Tedesco, M. J., Silva, K. J. D., Bissani, C. A., & Felisberto, R. (2018). Natural fertility and metals contents in soils of Rio Grande do Sul (Brazil). *Revista Brasileira de Ciência do Solo*, *42*, 1–15. https://doi.org/10.1590/18069657rbcs20160418

Banet, T., Massey, M. S., Zohar, I., Litaor, M. I., & Ippolito, J. A. (2020). Assessing modified aluminum-based water treatment residuals as a plant-available phosphorus source. *Chemosphere*, *247*, 125949. https://doi.org/10.1016/j.chemosphere.2020.125949

Barrón, V., & Torrent, J. (2013). Iron, manganese and aluminium oxides and oxyhydroxides. *Minerals at the Nanoscale*, *14*, 297–336. https://doi.org/10.1180/EMU-notes.14.9

Bittencourt, S., Serrat, B. M., Aisse, M. M., Marin, L. M. K. D. S., & Simão, C. C. (2012). Application of sludges from water treatment plant and from sewage treatment plant in degraded soil. *Engenharia Sanitaria e Ambiental*, *17*(3), 315–324. https://doi.org/10.1590/S1413-41522012000300008

BRAZIL (2006). Resolution of National Environment Council (CONAMA) Nr 375. August 29. Brasília.

BRAZIL (2016). Regulatory Instructions of Ministry of Agriculture, Livestock and Food Supply (MAPA) No 7. April 12. Brasília.

CSCF-RS/SC—Committee on Soil Chemistry and Fertility. (2004). *Liming and fertilization manual for Rio Grande do Sul and Santa Catarina States.* (10th ed.) Retrieved March 13, 2020, from Porto Alegre: Núcleo Regional Sul - Sociedade Brasileira de Ciência do Solo. http://www.sbcs-nrs.org.br/docs/manual_de_adubacao_2004_versao_internet.pdf (in Portuguese)

CSCF-RS/SC—Committee on Soil Chemistry and Fertility (2016). . In *Liming and fertilization manual for Rio Grande do Sul and Santa Catarina States* (11th ed.) Retrieved March 15, 2020, from Porto Alegre: Núcleo Regional Sul - Sociedade Brasileira de Ciência do Solo. http://www.sbcs-nrs.org.br/docs/Manual_de_Calagem_e_Adubacao_para_os_Estados_do_RS_e_de_SC-2016.pdf (in Portuguese)

Dassanayake, K. B., Jayasinghe, G. Y., Surapaneni, A., & Hetherington, C. (2015). A review on alum sludge reuse with special reference to agricultural applications and future challenges. *Waste Management*, *38*, 321–335. https://doi.org/10.1016/j.wasman.2014.11.025

Heil, D. M., & Barbarick, K. A. (1989). Water treatment sludge influence on the growth of sorghum-sudangrass. *Journal of Environmental Quality*, *18*(3), 292–298. https://doi.org/10.2134/jeq1989.00472425001800030008x

Mathsoft. (1998). *Mathcad 8 professional academic*. Mathsoft Inc Retrieved May 10, 2014, from http://www.mathsoft.com

Huang, J., & Hartemink, A. E. (2020). Soil and environmental issues in sandy soils. *Earth-Science Reviews*, *208*, 103295. https://doi.org/10.1016/j.earscirev.2020.103295

Ibrahim, M., Mahmoud, E., & Ibrahim, D. (2020). Assessing the impact of water treatment residuals and rice straw compost on soil physical properties and wheat yield in saline sodic soil. *Communications in Soil Science and Plant Analysis*, *1-10*, 2388–2397. https://doi.org/10.1080/00103624.2020.1836206

Ibrahim, M. M., Mahmoud, E. K., & Ibrahim, D. A. (2015). Effects of vermicompost and water treatment residuals on soil physical properties and wheat yield. *International Agrophysics*, *29*(2), 157–164. https://doi.org/10.1515/intag-2015-0029

Ippolito, J. A., Barbarick, K. A., & Redente, E. F. (1999). Co-application effects of water treatment residuals and biosolids on two range grasses. *Journal of Environmental Quality*, *28*(5), 1644–1650. https://doi.org/10.2134/jeq1999.00472425002800050031x

Ippolito, J. A., Barbarick, K. A., Stromberger, M. E., Paschke, M. W., & Brobst, R. B. (2009). Water treatment residuals and biosolids long-term co-applications effects to semi-arid grassland soils and vegetation. *Soil Science Society of America Journal*, *73*(6), 1880–1889. https://doi.org/10.2136/sssaj2008.0352

Kleemann, N., Torres, D. P., Ribeiro, A. S., & Bamberg, A. L. (2020). Cold finger with semi closed reflux system for sample preparation aiming at Al, Ca, Cr, Cu, Fe, K, Mg, Mn, Ni, V and Zn determination in drinking water treatment sludge by MIP OES. *Analytica Chimica Acta*, *1096*, 9–17. https://doi.org/10.1016/j.aca.2019.10.064

Kluczka, J., Zołotajkin, M., Ciba, J., & Staroń, M. (2017). Assessment of aluminum bioavailability in alum sludge for agricultural utilization. *Environmental Monitoring and Assessment*, *189*(8), 422. https://doi.org/10.1007/s10661-017-6133-x

Klute, A. (1986). Water retention: Laboratory methods. In A. Klute (Ed.), *Methods of soil analysis: Part 1: Physical and mineralogical methods* (2nd ed.). Madison, WI: American Society of Agronomy, Soil Science Society of America.

Li, S., Wu, X., Liang, G., Gao, L., Wang, B., Lu, J., Abdelrhman, A. A., Song, X., Zhang, M., Zheng, F., & Degré, A. (2020). Is least limiting water range a useful indicator of the impact of tillage management on maize yield? *Soil and Tillage Research*, *199*, 104602. https://doi.org/10.1016/j.still.2020.104602

Lombi, E., Stevens, D. P., & McLaughlin, M. J. (2010). Effect of water treatment residuals on soil phosphorus, copper and aluminium availability and toxicity. *Environmental Pollution*, *158*(6), 2110–2116. https://doi.org/10.1016/j.envpol.2010.03.006

Machado, A. A., & Conceição, A. R. (2003). *Sistema de análise estatística para Windows – Winstat. Versão 2.0*. Universidade Federal de Pelotas (UFPel). [In Portuguese].

Mahdy, A. M., Elkhatib, E., Sherif, F., Fathi, N., & Folaa, M. (2020). Nanosized water treatment residuals improve water retention and phytoavailability of P and Al in biosolids-amended soil. *Journal of Plant Nutrition*, *43*(18), 2712–2727. https://doi.org/10.1080/01904167.2020.1792493

Mahdy, A. M., Elkhatib, E. A., Balba, A. M., & Ahmed, G. E. (2017). Speciation and fractionation of phosphorus in biosolids-amended soils: Effects of water treatment residual nanoparticles. *International journal of Environmental Science and Technology*, *14*(8), 1729–1738. https://doi.org/10.1007/s13762-017-1264-8

Mahdy, A. M., Elkhatib, E. A., Fathi, N. O., & Lin, Z. Q. (2009). Effects of co-application of biosolids and water treatment residuals on corn growth and bioavailable phosphorus and aluminum in alkaline soils in Egypt. *Journal of Environmental Quality*, *38*(4), 1501–1510. https://doi.org/10.2134/jeq2008.0335

Mahmoud, E., Ghoneim, A., El Baroudy, A., Abd El-Kader, N., Aldhumri, S. A., Othman, S., & El Khamisy, R. (2020). Effects of phosphogypsum and water treatment residual application on key chemical and biological properties of clay soil and maize yield. *Soil Use and Management*, *00*, 1–10. https://doi.org/10.1111/sum.12583

Maria, I. C.d., Chiba, M. K., Costa, A., & Berton, R. S. (2010). Sewage sludge application to agricultural as soil physical conditioner. *Revista Brasileira de Ciência do Solo*, *34*(3), 967–974. https://doi.org/10.1590/S0100-06832010000300038

Mohajerani, A., & Karabatak, B. (2020). Microplastics and pollutants in biosolids have contaminated agricultural soils: An analytical study and a proposal to cease the use of biosolids in farmlands and utilise them in sustainable bricks. *Waste Management*, *107*, 252–265. https://doi.org/10.1016/j.wasman.2020.04.021

Mossa, A. W., Bailey, E. H., Usman, A., Young, S. D., & Crout, N. M. (2020). The impact of long-term biosolids application (> 100 years) on soil metal dynamics. *Science of the Total Environment*, *720*, 137441. https://doi.org/10.1016/j.scitotenv.2020.137441

Mukherjee, A., Lal, R., & Zimmerman, A. R. (2014a). Impacts of 1.5-year field aging on biochar, humic acid, and water treatment residual amended soil. *Soil Science*, *179*(7), 333–339. https://doi.org/10.1097/SS.0000000000000076

Mukherjee, A., Lal, R., & Zimmerman, A. R. (2014b). Effects of biochar and other amendments on the physical properties and greenhouse gas emissions of an artificially degraded soil. *Science of the Total Environment*, *487*, 26–36. https://doi.org/10.1016/j.scitotenv.2014.03.141

Nasar, J., Shao, Z., Arshad, A., Jones, F. G., Liu, S., Li, C., Khan, M. Z., Khan, T., Banda, J. S. K., Zhou, X., & Gao, Q. (2020). The effect of maize–alfalfa intercropping on the physiological characteristics, nitrogen uptake and yield of maize. *Plant Biology*, *22*(6), 1140–1149. https://doi.org/10.1111/plb.13157

Oladeji, O. O., Sartain, J. B., & O'Connor, G. A. (2009). Land application of aluminum water treatment residual: Aluminum phytoavailability and forage yield. *Communications in Soil Science and Plant Analysis*, *40*(9–10), 1483–1498. https://doi.org/10.1080/00103620902818112

Penn, C. J., & Camberato, J. J. (2019). A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. *Agriculture*, *9*(6), 120. https://doi.org/10.3390/agriculture9060120

Pereira, I. d. S., Bamberg, A. L., de Sousa, R. O., Monteiro, A. B., Martinazzo, R., Silveira, C. A. P., & Silveira, A. d. O. (2020). Agricultural use and pH correction of anaerobic sewage sludge with acid pH. *Journal of Environmental Management*, *75*, 111203. https://doi.org/10.1016/j.jenvman.2020.111203

Petterle, A. R., Santiago, G. G., Chong, W., Somensi, L., & Tamborim, S. M. (2018). Ceramic plates containing sludge from a water treatment plant and the rice husk ash: Relation between physical-chemistry properties and microstructure. *Química Nova*, *41*(10), 1117–1126. https://doi.org/10.21577/0100-4042.20170288

Roman-Perez, C. C., & Hernandez-Ramirez, G. (2021). Nitrous oxide production and nitrogen transformations in a soil amended with biosolids. *Canadian Journal of Soil Science*. https://doi.org/10.1139/CJSS-2021-0064

Roman-Perez, C. C., Hernandez-Ramirez, G., Kryzanowski, L., Puurveen, D., & Lohstraeter, G. (2021). Greenhouse gas emissions, nitrogen dynamics and barley productivity as impacted by biosolids applications. *Agriculture, Ecosystems & Environment*, *320*, 107577. https://doi.org/10.1016/j.agee.2021.107577

Silva, F. C. (2009). *Manual de análises químicas de solos, plantas e fertilizantes* (2nd ed., p. 627). Brasília: EMBRAPA Informação Tecnológica. [In Portuguese].

Silveira, M. L., Driscoll, J. L., Silveira, C. P., Graetz, D. A., Sollenberger, L. E., & Vendramini, J. M. (2013). Land application of aluminum water treatment residual to Bahiagrass pastures: Soil and forage responses. *Agronomy Journal*, *105*(3), 796–802. https://doi.org/10.2134/agronj2012.0385

Soil Survey Staff. (2014). *Keys to soil taxonomy* (12th ed.). Washington, DC: USDA-Natural Resources Conservation Service.

Teixeira, P. C., Donagemma, G. K., Fontana, A., & Teixeira, W. G. (2017). *Manual de métodos de análise de solo* (p. 573) [In Portuguese]. Brasília: Empresa Brasileira de Pesquisa Agropecuária, EMBRAPA Solos.

Tormena, C. A., Araújo, M. A., Fidalski, J., & Costa, J. M. D. (2007). Variação temporal do intervalo hídrico ótimo de um Latossolo Vermelho distroférrico sob sistemas de plantio direto. *Revista Brasileira de Ciência do Solo*, *31*(2), 211–219. https://doi.org/10.1590/S0100-06832007000200003

Turner, T., Wheeler, R., Stone, A., & Oliver, I. (2019). Potential alternative reuse pathways for water treatment residuals: Remaining barriers and questions—A review. *Water, Air, & Soil Pollution*, *230*(9), 227. https://doi.org/10.1007/s11270-019-4272-0

USEPA. (1993). The US Environmental Protection Agency adopted Regulations in 1993 (40 CFR Part 503, known as Part 503). Retrieved January 20, 2020, from http://cwmi.css.cornell.edu/Sludge/briefsummary.htm.

van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, *44*, 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Wasserman, J. C., de Oliveira Silva, L., de Pontes, G. C., & de Paiva Lima, E. (2018). Mercury contamination in the sludge of drinking water treatment plants dumping into a reservoir in Rio de Janeiro, Brazil. *Environmental Science and Pollution Research*, *25*(28), 28713–28724. https://doi.org/10.1007/s11356-018-2899-9

Zhao, Y., Liu, R., Awe, O. W., Yang, Y., & Shen, C. (2018). Acceptability of land application of alum-based water treatment residuals–an explicit and comprehensive review. *Chemical Engineering Journal*, *353*, 717–726. https://doi.org/10.1016/j.cej.2018.07.143

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Ribeiro, P. L., Bamberg, A. L., Pereira, I. d. S., Monteiro, A. B., Potes, M. d. L., & de Lima, C. L. R. (2022). Liming and co-application of water treatment residuals with biosolids for conditioning sandy soils. *Land Degradation & Development*, 1–13. https://doi.org/10.1002/ldr.4202