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Impact of drilling waste and sludge on eucalyptus growth and soil and water quality

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ABSTRACT

The Brazilian forestry sector stands out for its eucalyptus production and the reuse of industrial waste to improve soil fertility. However, environmental monitoring in planting areas is important to assess potential contamination risks, with a focus on soil and water quality. Thus, the objective of this study was to evaluate the initial development of eucalyptus plants and the impacts on soil and water quality, as a function of different doses of the combined application of drill cuttings and sewage sludge. The morphological variables and quality parameters evaluated were: height, shoot and root biomass, crown and stem diameter, chlorophyll index, and concentration of nutrients and heavy metals in the soil and water. The levels of Ca, Mg, K, P, and N in the waste favored the nutrition of eucalyptus plants, but if not managed properly, they can affect soil quality. The same occurs for some metals such as Ba and Pb, which were found in high concentrations in the waste and require care. The water quality results show that some heavy metals in the drained water did not exceed the limits of Brazilian regulations, with the exception of Cu, Mn, Ni, Pb and Ba, whose high levels can be attributed to the composition of the waste. The use of gravel and sludge promoted improvements in plant development, but requires monitoring to avoid risks of soil and water contamination, especially with regard to heavy metals.

Keywords: environmental quality, reuse of waste, water resources, well gravel.

Impacto do resíduo de perfuração e lodo no crescimento de eucalipto e na qualidade do solo e água

RESUMO

O setor florestal brasileiro se destaca pela produção de eucalipto e pelo reaproveitamento de resíduos industriais para a melhoria da fertilidade do solo. No entanto, é importante o monitoramento ambiental nas áreas de plantio para avaliar os potenciais riscos de contaminação, com foco na qualidade do solo e da água. Assim, o objetivo desse estudo foi avaliar o desenvolvimento inicial das plantas de eucalipto e os impactos na qualidade do solo e da água, em função de diferentes doses da aplicação combinada de cascalho de perfuração e lodo de esgoto. As variáveis morfológicas e parâmetros de qualidade avaliados foram: altura, biomassa da parte aérea e raiz, diâmetro de copa e caule, índice de clorofila e concentração de nutrientes e metais pesados no solo e na água. Os teores de Ca, Mg, K, P e N nos resíduos favoreceram a nutrição das plantas de eucalipto, mas, se não manejados adequadamente, podem afetar a qualidade do solo. O mesmo ocorre para alguns metais como o Ba e Pb que foram encontrados em alta concentração nos resíduos e exigem cuidados. Os resultados da qualidade da água mostram que alguns metais pesados na água drenada não ultrapassaram os limites da normativa brasileira, com exceção de Cu, Mn, Ni, Pb e Ba, cujos altos teores podem ser atribuídos à composição dos resíduos. O uso do cascalho e lodo promoveu melhorias no desenvolvimento das plantas, mas exige monitoramento para evitar riscos de contaminação do solo e da água, especialmente no tocante aos metais pesados.

Palavras-chave: cascalho de poços, qualidade ambiental, reaproveitamento de resíduo, recursos hídricos.

1. INTRODUCTION

The Brazilian forestry sector is one of the most important for the national economy, accounting for 9.9 million hectares of planted forests, of which 75% are used for eucalyptus cultivation (Ferreira *et al.*, 2024). In this scenario, the search for technologies that increase the productivity of this sector reinforces the need for practices that ensure soil and water conservation, essential resources for the efficiency of planting areas (Turchetto *et al.*, 2024).

Considering the high cost of mineral fertilizers, one of the alternatives that has been gaining prominence in eucalyptus planting areas is the reuse of industrial waste with the potential to promote improvements in soil fertility (Peng *et al.*, 2023). Among these, drill cuttings are an important mineral source of nutrients, with the potential to improve the chemical properties of the soil, especially increasing pH values and exchangeable bases (Agbogidi *et al.*, 2007). Another waste whose use is recognized due to its high organic matter content is sewage sludge, a byproduct of treatment plants in urban centers, which is capable of increasing the efficiency of the use of various elements in Brazilian soils (Meng *et al.*, 2019).

The integrated use of this waste represents a promising alternative, allowing for a more noble destination through its incorporation into the production chain. However, this waste contains some contaminants, such as heavy metals, salts, and other compounds that, if disposed of improperly, can cause environmental impacts, including contamination of soil and water resources (Chu *et al.*, 2023).

Monitoring the quality of planted areas managed with waste is essential to ensure environmental safety. Studies show that the application of sludge is effective in increasing the productivity of eucalyptus planted areas, with limited toxicity to the soil (Abreu-Junior *et al.*, 2020). However, the effects of this practice on water quality are still little known. In this context, the use of this waste should be associated with monitoring the increase, as well as the balance of macronutrient levels, with the aim of evaluating changes in soil fertility and plant nutrition, and the analysis of heavy metals to identify potential contamination risks at the site (Antonkiewicz *et al.*, 2019).

In this context, the objective of this study was to evaluate the response of the initial development of eucalyptus plants, as well as the impacts on the quality of the soil and water used in cultivation, as a function of different doses of the combined application of two residues (drilling gravel and sewage sludge).

2. MATERIAL AND METHODS

2.1. Chemical Characterization of Waste

Gravel samples from offshore oil well drilling in the post-salt layer of the Santos Basin at a depth of 3,400 meters were analyzed.

The total levels of macronutrients and heavy metals in the gravel were determined according to the EPA 3050B method (USEPA, 1996), and in the sludge, according to the EPA 3050 method (USEPA, 2008). The method proposed by Tedesco *et al.* (1995) was used to analyze the total nitrogen content.

2.2. Development of Eucalyptus Plants

A pot experiment was conducted in a randomized block design, arranged in a 3x4 factorial scheme, with samples from three soil classes and four fertilizer doses, and one treatment without fertilizer (control). Each soil was prepared with different proportions of gravel and sludge, aiming to equalize the amount of nutrients in relation to its natural characteristics. The fertilizer doses applied corresponded to 50%, 100% and 200% of the NPK recommendation for eucalyptus crops, according to Freire *et al.* (2013).

For each soil class, the amount of nutrient to be applied was determined. The N-P-K or NPK ratios of the different soil classes were, respectively: Planosol 1-4-3; Ferrasol 1-4-2; and Acrisol 1-4-3. Thus, the composition estimates for each soil were: Planosol (52.0% gravel and 48% sludge); Ferrasol (51.9% gravel and 48.1% silt); Acrisol (51.0% gravel and 49.0% silt).

Pots containing 20 liters of soil were used, in which seedlings of a clone of Eucalyptus urograndis, one month old, were planted. The experiment was conducted over a period of five months after planting. At the end, the height, stem and crown diameter, and biomass of the aerial part and root were evaluated. Chlorophyll content was measured using a portable chlorophyll meter (ClorofiLOG ® Falker), with evaluations being performed on leaves representing the lower, middle and upper sections of the plants.

2.3. Soil Quality

To determine the pseudototal contents of the metals Cd, Co, Cr, Cu, Mn, Ni, Pb and Ba in the soil samples, after the test, an opening (digestion) was carried out according to method 3050B, postulated by USEPA (1996). To assess the quality of soil analyses, samples of certified material SRM 2709ª San Joaquin Soil, USA (NIST, 2003), certified by the National Institute of Standards and Technology, were digested.

2.4. Water Quality

The experimental units consisted of 20L pots containing the treated soil and a eucalyptus plant. The applied water depth was 200 mm, equivalent to the average maximum rainfall recorded in the city of Rio de Janeiro, the place of origin of the waste used in the experiment. This value was chosen to simulate extreme weather conditions and represent the intensity of the maximum rainfall expected in the region, allowing an assessment of the behavior of the waste under these conditions and its interaction with the local environment.

To facilitate the collection of the drained water, the pots were placed on a 1.0 m high bench and the bottom of each pot was adapted with a layer of gravel. On the second day after the implementation of the experiment, a 200 mm rainfall was simulated, representing heavy rain over the planted area.

The drained water collected from the experimental units was analyzed to determine the levels of macronutrients and heavy metals, following the USEPA 3050 method.

2.5. Statistical analysis

The data were subjected to analysis of variance with application of the F test at 5%

(ANOVA) when the assumptions of normality and homogeneity were met and their means compared by the Tukey test at 5%.

3. RESULTS AND DISCUSSION

3.1. Chemical Characterization of Waste

The total levels of macronutrients and heavy metals determined via acid digestion are presented in Table 1.

Table 1. Total values of macronutrients and heavy metals in the gravel from the post-salt layer and sewage sludge.

Element	P	K	N	Ca	Mg	Al	Cu	Mn
	mg kg^{-1}							
Gravel	3115,0	4691,0	-	15102,8	4383,2	336,6	2,6	45,8
Sludge	6146,0	0,50	4340,0	32847,6	8423,8	3607,1	251,0	157,0
Element	Zn	Pb	Cd	Ni	Cr	Fe	Ba	Na
	mg kg^{-1}							
Gravel	18,8	0,8	0,1	106,2	86,0	2897,7	305,0	1077,0
Sludge	664,0	21,2	2,2	9,4	34,5	20311,4	9,3	1292,0

The levels of Ca, Mg, K, and P present in both residues and N in the sludge are important not only for plant nutrition, considering the nutritional requirements of most plants, but also for the sustainable management of environmental resources. When managed inappropriately, these elements can pose significant risks to water quality, contributing to processes such as eutrophication in water bodies and soil contamination. The values in this study are higher than those observed in the residues of Yadav *et al.* (2021) and Kwoczynski and Cmelik (2021), indicating a greater potential for environmental impact if not managed correctly.

The aluminum content found was high, but it is not in an extractable form, which reduces its potential risk to plants and the environment. The Al in this study originates from sewage sludge and the soils used, as also reported in other studies (Kolodiziej *et al.*, 2023). This fraction of Al, probably associated with unavailable forms, is only mobilized under extreme conditions, such as acid digestion. However, it is essential to consider that, if managed inappropriately, they can compromise soil quality. Regarding the levels of Fe and Al present in gravel, although they are naturally high in samples of this type of waste, their presence at high levels is not a cause for environmental concern, as they are common constituents of rocks and sediments (Costa *et al.*, 2023).

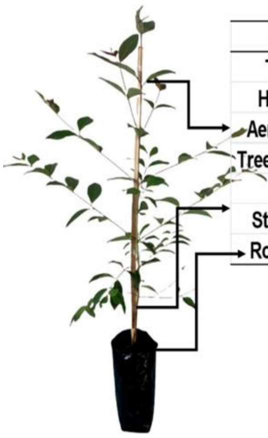
The greatest concern is with other metals present in gravel and sludge, such as Ba, Cd, Cr, Cu, Mn, Ni, Pb and Zn, which have a high contamination capacity. Although these metals are generally found in lower concentrations in these residues, their potential toxicity poses a significant risk to the environment if not managed properly (Li *et al.*, 2019).

In general, metal concentrations in sludge are below the maximum limits established by CONAMA Resolution 498 (CONAMA, 2020). For gravel, legislation such as IBAMA's IN 01/2018 recommends the analysis of metal ions after total digestion of the samples. However, this technique may overestimate the concentration of pollutant metals, since it releases metals trapped in silicates, which are generally not involved in the main transport mechanisms of aquatic pollutants (IBAMA, 2018).

It is observed that the gravel has a high barium content, and this result can be attributed to the addition of certain components, such as barytes ($BaSO_4$), which is incorporated into the drilling fluid to increase its density, and thus facilitate control during drilling operations (Guedes, 2014). Although the levels are high, the barium contained in the barytes is relatively immobile and not very bioavailable, due to its low solubility in water (Carvalho, 2013) and does not pose a risk of absorption by plants or mobility in the environment.

3.2. Initial Development of Eucalyptus Plants

During the initial growth of the plants, a significant difference was observed in both the treatments with application of fertilizer composed of residues and the control treatment (Figure 1). Regarding height, growth was observed for eucalyptus plants as the doses increased in all treatments with residue application, except in the control treatment. For Ferrasol and Acrisol, the highest height values were observed at the highest fertilizer dose. Furthermore, except in the treatment with 50% of the dose in Acrisol, the highest doses provided similar performances in all soils analyzed.



Soil Type	Planosol				Ferrasol				Acrisol			
Treatment	Control	50%	100%	200%	Control	50%	100%	200%	Control	50%	100%	200%
Height (Cm)	93,0 b	110,0 ab	108,0 ab	121,0 a	81,0 c	112,0 ba	105,0 bc	132,6 a	99 b	84,3 c	135,6 a	141,0 a
Aerial Biom (g)	71,8 c	99,7 b	112,0 ab	137,6 a	64,3 c	107,8 b	121,4 ab	151,5 a	75,0 c	119,1 b	137,0 a	147,4 a
Treetops D. (Cm)	60,0 b	57,3 c	61,0 b	83,3 a	62,0 bc	80,0 ab	70,7 b	95,7 a	80,0 b	80,3 b	84,7 ab	90,0 a
C.I	38,0 ns	41,6 ns	36,4 ns	37,8 ns	43,0 ns	42,0 ns	43,0 ns	42,0 ns	43,0 ns	43,0 ns	44,0 ns	44,0 ns
Stem D. (Cm)	15,0 a	13,3 b	14,6 ab	17,8 a	16,0 a	14,1 ab	14,5 ab	15,7 a	15,0 ab	16,1 a	16,7 a	16,8 a
Root Biom (g)	25,9 c	34,3 b	55,8 ab	66,1 a	25,0 b	83,5 ab	110,7 a	83,2 ab	36,0 b	38,5 b	54,1 a	57,6 a

Figure 1. Morphological and physiological parameters of eucalyptus plants in different soil types and fertilization based on gravel and sludge. Means followed by the same letter in the line did not differ at 5% probability by the Tukey test. Legend: Aerial biom: Biomass of the aerial part; root biom: Root biomass; Treetops D: Crown diameter; Stem D: Stem diameter; C.I: Chlorophyll index.

A significant increase in shoot biomass was observed in parallel with the increase in the fertilizer dose, with statistically significant values. This pattern was observed for all three soil classes, which may possibly be due to the addition of nutrients and organic matter from the two residues, promoting a positive effect on plant growth.

In addition, the highest shoot biomass was observed in the 200% treatment, in all soils, with statistically different values from the control, indicating that the addition of a greater quantity of residues resulted in a more significant increase in plant growth. This pattern may be due to the greater supply of nutrients and due to the improvement in soil properties.

For root biomass, the highest average values were observed for the Ferrasol, demonstrating the influence of soil texture. For root biomass, no uniform pattern was observed for the different soil classes. Again, values from treatments with the highest fertilizer doses stand out.

The crown and stem diameter values indicated that the integrated use of residues resulted in improved performance in the parameters evaluated, compared to the control. The highest fertilizer dose (200%) showed the highest values for both parameters. This pattern indicates the potential of using residues as an alternative to conventional fertilization for eucalyptus, contributing not only to increased plant growth but also to the appreciation of practices that promote environmental quality and stimulate the circular economy.

The results of this study are consistent with those observed by Delvaux *et al.* (2021), in which the authors evaluated the effects of various doses of a fertilizer derived from sugarcane filter cake (50%, 100%, 150%, and 200% of the recommended dose for cultivation), in addition to a control treatment without nutrient application. It was observed that the highest values of plant height, stem diameter, fresh and dry mass of leaves, stems and roots occurred when the intermediate doses of 50% and 100% were used.

Similar results were also observed by Waimer *et al.* (2022), with E. grandis plants. The authors found that plants grown in sludge presented the highest average biomass values, evidencing the responsiveness of the species to the increased availability of nutrients present in these residues. In the same sense, Abreu-Junior *et al.* (2020) observed that sludge-based fertilization can reduce phosphate use by 33% and eliminate the use of nitrogen fertilization, maintaining the productivity of E. urograndis, promoting waste recycling and reducing environmental impact.

Although no differences were observed in the chlorophyll index between the treatments and soils evaluated, the adequate use of NPK, present in gravel and sludge, can improve the chlorophyll concentration and photosynthetic efficiency of plants. This favors the production of biomass and the quality of eucalyptus plants, promoting more sustainable agricultural practices aligned with environmental preservation.

3.3. Heavy Metals in Soil

In Brazil, the limit level of contaminants in soil is regulated by CONAMA IN nº 498. Thus, the levels of metals detected in the three soil classes at the end of the test are presented in Table 2, and, in general, no levels of heavy metals were identified that exceeded the limits established by the Brazilian resolution (CONAMA, 2020).

Table 2. Values of heavy metals in soil in three soil classes and different fertilization treatments.

Treatment	Cd	Co	Cr	Cu	Mn	Ni	Pb	Ba
	mg.Kg^{-1}							
	Planosol							
Control	0,84	N.D	N.D	N.D	5,2	N.D	N.D	31,70
50%	0,88	N.D	N.D	1,05	5,51	N.D	N.D	42,1
100%	0,89	N.D	N.D	1,11	5,28	N.D	N.D	55,6
200%	0,90	N.D	N.D	1,11	5,25	0,75	N.D	58,46
	Ferrasol							
Control	0,50	N.D	N.D	N.D	52,53	4,00	N.D	111,39
50%	0,40	N.D	N.D	4,56	55,84	3,62	N.D	123,2
100%	0,38	N.D	N.D	5,20	54,06	6,06	N.D	133,9
200%	0,35	N.D	N.D	3,97	55,81	3,18	N.D	144,7
	Acrisol							
Control	0,30	N.D	11,85	11,80	55,58	5,42	N.D	96,48
50%	0,20	N.D	12,33	11,95	56,08	9,77	N.D	101,45
100%	0,36	N.D	14,15	11,70	58,68	5,60	N.D	104,03
200%	0,22	N.D	13,08	11,80	60,01	4,30	N.D	104,85
CONAMA MPL	1,3	25,0	75,0	60,0	N.E	70,0	72,0	300,0

CONAMA MPL: Maximum Permitted Limit for Soils. N.D: Not detected; N.E: Not specified

The analyzed metals of ecological interest remained below the maximum permitted limits, indicating compliance with environmental quality standards. In clayey soils, higher fertilizer doses (200%) reduced the availability of some heavy metals, possibly due to their adsorption or complexation by functional groups of organic matter. This process is reinforced by the interaction between organic carbon and metals, resulting in the formation of complexes that reduce their bioavailability. This dynamic can limit the absorption of metals by plants and influence their mobility in the soil, contributing to the maintenance of soil quality (Drábek *et al.*, 2015).

In clayey soils, higher Cd values were observed, while barium, despite being present in high concentrations, remained below the limit stipulated by legislation. The presence of Ba is associated with the baryte found in gravel. These results highlight the importance of monitoring metal levels in soils to preserve environmental quality and prevent potential impacts on water resources (Amaral Sobrinho *et al.*, 2020).

The low levels of some heavy metals in the soil can be explained by the lower concentrations in sewage sludge and gravel. Another factor that may contribute to this result is the limited amount of residue applied to the soil, given that fertilization was carried out only once during planting. However, more frequent applications and at higher doses may intensify the accumulation of these metals in the soil over time, which may affect environmental quality.

3.4. Nutrient Availability in Soil

Table 3 shows the values of pH, available P, exchangeable potassium, sodium, electrical conductivity calcium and magnesium in the different soil classes and applied doses of residues.

Table 3. Chemical attributes related to nutrients available in the soil.

Treatment	pH	Ca	Mg	Al	Na	H+Al	P	K	E.C
	1:2,5			Cmolc.dm^{-3}			mg.Kg^{-1}		dS.m
				Planosol					
Control	5,5 ns	0,8 ns	0,7 ns	0,03 ns	0,04 ns	1,5 ns	4,6 c	12,54 c	0,1a
50%	5,5 ns	0,8 ns	0,7 ns	0,03 ns	0,04 ns	1,3 ns	5,5 bc	12,54 c	0,1a
100%	5,3 ns	0,8 ns	0,5 ns	0,03 ns	0,03 ns	1,5 ns	5,6 b	13,18 b	0,1a
200%	5,4 ns	0,7 ns	0,5 ns	0,00 ns	0,05 ns	1,3 ns	6,8 ab	14,77 b	0,2 a
				Ferrasol					
Control	6,1 ns	2,5 ns	1,3 ns	0,00 ns	0,05 ns	1,6 b	2,97 b	30,0 ab	0,1 a
50%	6,1 ns	2,3 ns	1,0 ns	0,00 ns	0,06 ns	2,1ab	3,19 a	27,70 b	0,1 a
100%	6,2 ns	2,0 ns	1,4 ns	0,04 ns	0,06 ns	2,1ab	3,06 a	31,65 ab	0,1 a
200%	6,2 ns	2,2 ns	1,4 ns	0,1 ns	0,05 ns	2,9 a	3,00 ab	31,9 ab	0,1 a
				Acrisol					
Control	5,6 ns	2,3 ns	1,2 ns	0,00 ns	0,06 ns	1,7 b	2,41b	12, b	0,1 a
50%	5,5 ns	2,1 ns	1,3 ns	0,00 ns	0,06 ns	1,7 b	2,51b	14,14 ab	0,1 a
100%	5,4 ns	2,4 ns	1,4 ns	0,01 ns	0,05 ns	2,3 ab	4,33 a	15,09 ab	0,1 a
200%	5,4 ns	2,2 ns	1,5 ns	0,02 ns	0,05 ns	3,1 a	2,82 ab	16,82 a	0,1 a

The application of different doses of fertilization with residues did not result in significant differences in the values of pH, calcium, magnesium, aluminum and sodium in the three soil classes evaluated, even at the highest doses used. This pattern suggests that the absorption of these nutrients by eucalyptus plants may have been more efficient in the treatments using residues.

On the other hand, only the levels or contents of P and K were statistically significant differences observed. With the exception of the control treatment and the 50% dose, the mean values of these elements were similar among the other treatments. This uniformity can be attributed to the presence of P and K in the gravel and sludge residue (Table 1), highlighting the potential of these residues to supply these nutrients.

3.5. Heavy Metals in Water

Table 4 shows the values of some metals evaluated in the irrigation water drained from each treatment. Resolution No. 357/2005 establishes standards for the discharge of effluents and defines environmental guidelines for their classification.

Table 4. Maximum effluent discharge limits according to regulations of Brazilian environmental agencies.

Tratamento	Cd	Co	Cr	Cu	Mn	Ni	Pb	Ba
	mg.L^{-1}							
	Planosol							
Control	N.D	N.D	N.D	N.D	N.D	N.D	0,1	N.D
50%	N.D	N.D	0,04	0,01	0,02	0,30	0,30	1,20
100%	N.D	N.D	0,04	0,01	0,10	0,30	0,60	3,10
200%	N.D	N.D	0,04	0,01	0,10	0,40	0,90	6,30
	Ferrasol							
Control	N.D	N.D	0,01	N.D	N.D	N.D	0,30	N.D
50%	N.D	N.D	0,01	N.D	N.D	0,10	0,90	2,10
100%	N.D	N.D	0,01	N.D	0,02	0,10	0,80	3,20
200%	N.D	N.D	0,02	N.D	0,02	0,10	0,60	5,0
	Acrisol							
Control	N.D	N.D	0,00	N.D	N.D	N.D	0,10	N.D
50%	N.D	N.D	0,01	N.D	N.D	0,18	0,20	1,00
100%	N.D	N.D	0,01	N.D	0,01	0,20	0,50	4,00
200%	N.D	N.D	0,01	N.D	0,01	0,25	0,70	6,00
CONAMA 357	0,01	0,05	0,05	0,009	0,1	0,025	0,01	0,7

N.E: Not specified; *Maximum limit established by CONAMA Resolution No. 357/2005 (CONAMA, 2005).

The results indicate that the combined use of waste as fertilizer, even with a 200 mm layer, did not increase the levels of some heavy metals in the drained water, when compared to the regulatory standards in Brazil. For these elements, the pattern can be attributed to the low concentration already existing in the materials, to the adsorption capacity of the soils, especially those with a clayey texture, which limit the mobility of the metals, or even to the formation of complexes between the metals and the organic matter present in the waste.

Concentrations above the established standards were observed in the drained water from the Planosol treatment for Cu and Mn, as well as for Ni, Pb and Ba in all soil classes. The high levels of Ba are due to the presence of barytes in the drilling residue (Yang *et al.*, 2024). The values of Pb and Ni, on the other hand, are due to the sludge used. Some reports in the literature confirm the occurrence of high concentrations of these metals, such as Pb, in WWTP sludge (Molaey *et al.*, 2024), highlighting the importance of environmental monitoring when using these materials.

Although some metals did not exceed the limits stipulated by law, the results highlight the importance of continuous monitoring of soil and water quality when using this type of residue to fertilize eucalyptus. It is also necessary to monitor the available fractions of elements in the soil. Repeated applications or applications at higher doses can alter the dynamics of availability and mobility of metals over time, increasing the risk of accumulation in the soil and contamination of water resources.

4. CONCLUSION

Fertilization with waste improved soil quality and favored plant growth, but requires continuous monitoring to avoid risks to water quality due to heavy metals.

The use of this waste as fertilizer can increase the levels of heavy metals in drained water.

The combined use of gravel and sludge is a sustainable alternative for recycling nutrients, as long as they are applied with caution to mitigate environmental impacts, especially on water.

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6. REFERENCES

ABREU-JUNIOR, C. H.; OLIVEIRA, M. G. D.; CARDOSO, P. H. S.; MANDU, T. D. S.; FLORENTINO, A. L.; OLIVEIRA, F. C.; HE, Z. Sewage sludge application in Eucalyptus urograndis plantation: availability of phosphorus in soil and wood production. **Frontiers in Environmental Science**, v. 8, p. 116, 2020. https://doi.org/10.3389/fenvs.2020.00116

AGBOGIDI, O. M.; ERUOTOR, P. G.; AKPAROBI, S. O.; NNAJI, G. U. Evaluation of crude oil contaminated soil on the mineral nutrient elements of maize (*Zea mays* L.). **Journal of Agronomy,** v. 6, n. 1, p. 188, 2007.

AMARAL SOBRINHO, N. M. B.; CEDDIA, M. B.; ZONTA, E.; SOUZA, C. D. C. B. D.; LIMA, E. S. A. Barium and lead levels in sites for disposal of oil well waste. **Revista Caatinga**, v. 32, p. 1060-1068, 2020. https://doi.org/10.1590/1983-21252019v32n422rc.

ANTONKIEWICZ, J.; KOŁODZIEJ, B.; BIELIŃSKA, E. J.; GLEŃ-KAROLCZYK K. Research on the uptake and use of trace elements from municipal sewage sludge by multiflora rose and Virginia fanpetals. **Journal of Elementology**, v. 24, n. 3, p. 987-1005, 2019. https://doi.org/10.5601/jelem.2018.23.4.1757

CARVALHO, M. M. D. **Efeito da aplicação de resíduo de perfuração de poço de petróleo no desenvolvimento de cevada (Hordeum vulgare L.)**. 2013. Dissertação (Mestrado em Ciência do Solo) – Universidade Federal Rural do Rio de Janeiro, Rio de Janeiro, 2013.

CHU, S.; XIAN, L.; ZHAO, N.; LAI, C.; YANG, W.; WANG, J.; ZENG, S. Combined addition of bagasse and zeolite stabilizes potentially toxic elements in sewage sludge compost and improves Eucalyptus urophylla seedling growth. **Forest Ecology and Management**, n. 539, 2023. https://doi.org/10.1016/j.foreco.2023.121003

CONAMA (Brasil). Resolução nº 357 de 17 de março de 2005. Dispõe sobre a classificação dos corpos de água e diretrizes ambientais para o seu enquadramento, bem como estabelece as condições e padrões de lançamento de efluentes, e dá outras providências. **Diário Oficial [da] União**: seção 1, Brasília, DF, n. 053, p. 58-63, 18 mar. 2005.

CONAMA (Brasil). Resolução nº 498 de 19 de agosto de 2020. Define critérios e procedimentos para produção e aplicação de biossólido em solos, e dá outras providências. **Diário Oficial [da] União**: seção 1, Brasília, DF, n. 161, p. 265-269, 21 ago. 2020.

COSTA, L. C.; CARVALHO, C. F.; SOARES, A. S. F.; SOUZA, A. C. P.; BASTOS, E. F. T.; GUIMARÃES, E. C. B. T.; MARQUES, M. R. C. Physical and chemical characterization of drill cuttings: A review. **Marine Pollution Bulletin,** v. 194, p. 115342, 2023. https://doi.org/10.1016/j.marpolbul.2023.115342

DELVAUX, J. C.; CARMARGO, R.; LANA, R. M. Q., FRANCO, M. H. R.; STANGER, M. C.; GONCALVES, R. A.; MIGUEL, P. S. B. Soil quality bioindicators in initial eucalyptus growth under organomineral fertilization based on sugarcane filter cake. **Australian Journal of Crop Science**, v. 15, n. 4, p. 602-609, 2021.

DRÁBEK, O.; KIPLAGAT, I. K.; KOMAREK, M.; TEJNECKÝ, V.; BORŮVKA, L. Study of Interactions between Relevant Organic Acids and Aluminium in Model Solutions Using HPLC and IC. **Soil & Water Research,** v. 10, 2015. https://doi.org/10.17221/256/2014-SWR

FERREIRA, F. D. A. C.; FREITAS, L. C.; LEITE, E. S.; SANTOS, S. L. M.; LIMA, C. F. Technical and economic performance of a feller buncher in eucalyptus forests with different yields in Southern Bahia, Brazil. **Revista Caderno pedagógico**, v. 21, n. 8, 2024. https://doi.org/10.54033/cadpedv21n8-130

FREIRE, L. R.; BALIEIRO, F. C.; ZONTA, E.; ANJOS, L. H. C.; PEREIRA, M. G.; LIMA, E. *et al.* **Manual de calagem e adubação do Estado do Rio de Janeiro**. Brasília: EMBRAPA, 2013.

GUEDES, J. D. N. **Estratégias de manejo do cascalho oriundo da perfuração de poços de petróleo**. 2014. Tese (Doutorado em Agronomia-Ciência do Solo) - Universidade Federal Rural do Rio de Janeiro, Rio de Janeiro, 2014.

IBAMA (Brasil). Instrução Normativa 1, de 02 de janeiro de 2018. Define diretrizes que regulamentam as condições ambientais de uso e descarte de fluidos, cascalhos e pastas de cimento nas atividades de perfuração marítima de poços e produção de petróleo e gás, estabelece o Projeto de Monitoramento de Fluidos e Cascalhos, e dá outras providências. **Diário Oficial [da] União**: seção 1, Brasília, DF, p. 43, 05 fev. 2018.

KOŁODZIEJ, B.; ANTONKIEWICZ, J.; BIELIŃSKA, E. J.; WITKOWICZ, R.; DUBIS, B. Recovery of microelements from municipal sewage sludge by reed canary grass and giant miscanthus. **International Journal of Phytoremediation**, v. 25, n. 4, p. 441-454, 2023. https://doi.org/10.1080/15226514.2022.2090495

KWOCZYNSKI, Z.; ČMELÍK, J. Characterization of biomass wastes and its possibility of agriculture utilization due to biochar production by torrefaction process. **Journal of Cleaner Production**, v. 280, p. 124302, 2021. https://doi.org/10.1016/j.jclepro.2020.124302

LI, C.; ZHOU, K.; QIN, W.; TIAN, C.; QI, M.; YAN, X.; HAN, W. A review on heavy metals contamination in soil: effects, sources, and remediation techniques. **Soil and Sediment Contamination: An International Journal,** v. 28, n. 4, p. 380-394, 2019. https://doi.org/10.1080/15320383.2019.1592108

MENG, X.; HUANG, Q.; XU, J.; GAO, H.; YAN, J. A review of phosphorus recovery from different thermal treatment products of sewage sludge. **Waste Disposal & Sustainable Energy,** v. 1, n. 2, p. 99–115, 2019. https://doi.org/10.1007/s42768-019-00007-x

MOLAEY, R.; APPELS, L.; YESIL, H.; TUGTAS, A. E.; ÇALLI, B. Sustainable heavy metal removal from sewage sludge: A review of bioleaching and other emerging technologies. **Science of The Total Environment**, v. 2, p. 177020, 2024. https://doi.org/10.1016/j.scitotenv.2024.177020.

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (U.S.). **Standard Reference Materials - SRM 2709 - San Joaquin Soil. Baseline Trace Element Concentrations**. Gaithersburg, 18 July 2003.

PENG, X.; JIANG, Y.; CHEN, Z.; OSMAN, A. I.; FARGHALI, M.; ROONEY, D. W.; YAP, P. S. Recycling municipal, agricultural and industrial waste into energy, fertilizers, food and construction materials, and economic feasibility: a review. **Environmental Chemistry Letters**, v. 21, n. 2, p. 765-801, 2023. https://doi.org/10.1007/s10311-022-01551-5

TEDESCO, J. M.; GIANELLO, C.; BISSANI, C. A.; BOHNEM, H.; VOLKWEISS, S. J. **Análise de solo, plantas e outros materiais**. 2. ed. Porto Alegre: UFRS, 1995. 174p.

TURCHETTO, F.; SANTOS, B. M. S.; GRIEBELER, A. M.; ROS, C. O.; ARAUJO, M. M.; WAIMER, G. C.; BIESDORF, N. Organomineral fertilizer based on swine manure and Trichoderma harzianum improves the performance of *Eucalyptus grandis*. **Research Square**, 2024. https://doi.org/10.21203/rs.3.rs-3985590/v1

USEPA (U.S.). **Method 3050: Acid digestion of sediments, sludges, and soils**. Washington, DC, 2008. 14p.

USEPA (U.S.) **Method 3050B: Acid digestion of sediments, sludges, and soils**. Washington, DC, 1996. 12p.

WAIMER, G. C.; DOS SANTOS, B. M. S.; DA SILVA DENARDI, L.; ANDRIGUETTO, K. V.; JACHI, J. G.; GRIEBELER, A.; TURCHETTO, F. Efeito do uso de fertilizante a base de dejeto suíno no crescimento de plantas de *Eucalyptus grandis*. **9° Congresso Florestal Brasileiro**, v. 1, n. 1, p. 416-416, 2022. https://doi.org/10.55592/CFB.2022.8907291

YADAV, V. K.; YADAV, K. K.; CABRAL-PINTO, M. M.; CHOUDHARY, N.; GNANAMOORTHY, G.; TIRTH, V.; KHAN, N. A. O processamento de resíduos agrícolas e industriais ricos em cálcio para recuperação de carbonato de cálcio e óxido de cálcio e sua aplicação para limpeza ambiental: Uma revisão. **Ciências Aplicadas**, v. 11, n. 9, p. 4212, 2021. https://doi.org/10.3390/app11094212

YANG, L. L.; LIU, Z. Y.; WANG, S. B.; HE, X. B.; JIANG, G. C.; ZHANG, J. Chemical modification of barite for improving the performance of weighting materials for water-based drilling fluids. **Petroleum Science**, v. 21, n. 1, p. 551-566, 2024. https://doi.org/10.1016/j.petsci.2023.10.001