



BIOCHAR FROM WOOD WASTE AS A SUBSTRATE CONDITIONER FOR GREEN ROOF: EFFECT ON ELEMENT LEACHING

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Abstract

The use of biochar as an amendment in green roof substrates has been widely investigated due to its potential to reduce environmental impacts associated with urban runoff. This study evaluated the effect of wood waste-derived biochar applied at proportions of 3%, 5%, 14%, and 21% on the concentration of elements (Ca, K, Mg, P, B, Fe, Ni, Al, and Pb) in leachate. The experiment was conducted under controlled conditions using pot-based experimental units containing substrate with and without peanut grass (*Arachis repens*) under simulated acid rain. A reduction in the leachate concentrations of all macronutrients was observed in the biochar-amended samples, especially at 5% and 14% compared to the control (Ca: 71.0%; K: 80.4%; Mg: 82.3%; P: 84.5%), indicating an optimal range of biochar application for mitigating nutrient leaching. Among the evaluated micronutrients, Ni (~94%) and B (~81%) showed marked reductions associated with the presence of vegetation, which were maintained with biochar addition at 3%, 5%, and 14%. Pb also showed substantial reduction, particularly at 5% and 14% (~60–71%), highlighting the adsorptive potential of the conditioner for this potentially toxic element. These results demonstrate the potential of wood waste-derived biochar as a sustainable substrate conditioner for green roofs, in line with circular economy principles and SDGs 3, 6, 11, 12, 13, and 14.

Introduction

Rapid urbanization intensifies soil sealing, overloads drainage systems, and compromises rainwater quality. The predominance of impervious surfaces, such as asphalt and concrete, reduces infiltration and increases surface runoff, a problem that is even more critical in highly verticalized cities where green areas are limited (DIENER; AGOSTINETTO; SIEGLOCK, 2025; TUCCI, 2003).

In this context, green roofs emerge as a nature-based solution capable of retaining, delaying, and improving the quality of surface runoff. Water retention is one of the main attributes of these systems, as it allows for the storage and gradual release of rainwater, reducing peak flows and contributing to the rebalancing of the urban hydrological cycle (FRANCIS *et al.*, 2014; FLL, 2018; WERDIN *et al.*, 2021). In Brazil, public policies such as green property tax incentives have encouraged their adoption, especially in the South and Southeast regions (LIMA, 2023).

Despite these benefits, conventional substrates may act as diffuse sources of pollutants, releasing nutrients into receiving water bodies, particularly during the initial stages after installation (BUFFAM; BOCELLI, 2016; LIAO *et al.*, 2024). In urban environments, the occurrence of acid rain, with pH values ranging from 4.2 to 5.6, can further enhance the mobility of elements in the substrate, increasing the risk of leaching (ROCHA *et al.*, 2003).

Biochar, produced through the pyrolysis of organic residues, has been widely investigated as a substrate conditioner due to its high cation exchange capacity, potential to stabilize pH, and ability to retain nutrients (LEHMANN; JOSEPH, 2015; SHI *et al.*, 2023). Recent studies have shown that its application in green roofs can reduce the leaching of phosphorus, organic carbon, and suspended solids, with performance depending on both dosage and feedstock characteristics (LIAO *et al.*, 2022; GOLDSCHMIDT; BUFFAM, 2023).

The use of lignocellulosic residues for biochar production is aligned with circular economy principles and contributes to several Sustainable Development Goals (SDGs), including SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water).

Previous studies have demonstrated that incorporating wood waste-derived biochar into substrates cultivated with peanut grass (*Arachis repens*) promotes pH stabilization near neutrality, reduces electrical conductivity, and maintains water retention capacity without compromising the hydraulic performance of the system (LIMA; FUNGARO, 2025).

Therefore, this study aims to evaluate the influence of wood waste-derived biochar addition on the leaching of macronutrients (Ca, K, Mg, and P), micronutrients (B, Fe, and Ni), and potentially toxic elements (Al and Pb) in green roof substrate systems, contributing to the improvement of environmental quality in urban settings.

Materials and Methods

Materials

All reagents used were of analytical grade, and all solutions were prepared with deionized water. Peanut grass (*Arachis repens*)



was used in the experiments, as it is a species commonly applied in green roof systems due to its adaptation to shallow substrates and its ability to provide good vegetation cover. The commercial substrate used in this study was developed for application in slabs and green roof systems and is suitable for different types of vegetation. The material was supplied by the company ECRA Urban Sustainability. The biochar was produced from sawdust derived from timber management in the region of Sinop (MT), Brazil. The production process was carried out by slow pyrolysis in a batch reactor at approximately 450 °C, with a residence time of 40 min. The material was produced by the Brazilian Agricultural Research Corporation (Embrapa), Sinop/MT unit, and provided for this study by researcher Dr. Fabiana Abreu de Rezende. The physicochemical characterization of the biochar and substrate is described in Lima et al. (2025) and Lima (2023).

Methods

Pot leaching test

The experiment was conducted using 18 PET bottles, arranged into six samples in triplicate (Table 1). The selected biochar proportions represent different levels of incorporation into the substrate. The proportions (3%, 5%, 14%, and 21%) were defined based on previous studies reporting commonly applied ranges in green roof substrates, as well as on prior experimental results obtained by the authors, in which intermediate proportions showed greater efficiency in nutrient retention. The inclusion of the 21% proportion aimed to evaluate possible saturation effects of adsorption sites at higher dosages, allowing the assessment of system behavior under conditions of biochar excess. The samples were irrigated with potable water three times per week for 45 days (January–March 2025) to promote the rooting of peanut grass seedlings. Subsequently, they were subjected to 0.33 L of simulated acid rain (HNO_3 and H_2SO_4 , $10^{-5} \text{ mol L}^{-1}$ each, $\text{pH} \approx 4.5$), corresponding to the average annual rainfall of 2022 at the Barueri/SP station (INMET). The collected leachates were analyzed for macronutrients, micronutrients, and elements, and the results are expressed as mean $\pm$ standard deviation ($n = 3$) (ROCHA *et al.*, 2003).

Table 1 – Mass proportions of substrate and biochar in each treatment.

Treatment	Vegetation	Substrate (g)	Biochar (g)
SUB (control)	No	100	0
SUBP	Yes	100	0
SBC3%P	Yes	97	3
SBC5%P	Yes	95	5
SBC14%P	Yes	86	14
SBC21%P	Yes	79	21

Determination of element concentrations in leachate

The concentrations of Ca, K, Mg, P, B, Fe, Ni, Al, and Pb were determined by inductively coupled plasma optical emission spectrometry (ICP-OES) using a Spectro Arcos instrument (axial plasma configuration, CCD detector, ORCA system, and two holographic diffraction gratings). All analyses were performed in triplicate. The data were subjected to analysis of variance (ANOVA) and, when significant ($p < 0.05$), to Tukey's test at the 5% significance level. Nonlinear regression analysis was performed using Origin 2018 software, applying an asymptotic decreasing exponential model. Model fit was evaluated using the adjusted R^2 . The graphs include standard error bars ($\pm$), and different letters indicate statistically significant differences between samples (Tukey, $p < 0.05$).

Results and Discussion

Determination of macronutrients (Ca, K, Mg and P) in leachate

The mean concentrations of macronutrients in the leachates are presented in Table 2 and Figures 1 and 2. The comparison between SUB and SUBP showed significant reductions of 61.4% (Ca), 64.7% (K), 77.3% (Mg), and 66.1% (P), indicating active nutrient uptake by peanut grass, a leguminous species with a stoloniferous root system and high demand for Ca^{2+} , K^+ , Mg^{2+} , and H_2PO_4^- (FRANCIS *et al.*, 2014).

Table 2 – Mean concentrations of macronutrients in leachate as a function of biochar proportion ($\pm$ standard deviation)

Sample	Ca (mg L^{-1})	K (mg L^{-1})	Mg (mg L^{-1})	P (mg L^{-1})
SUB	15.81 $\pm$ 12.92 a	31.58 $\pm$ 26.80 a	31.84 $\pm$ 34.65 a	12.03 $\pm$ 4.66 a
SUBP	6.11 $\pm$ 0.28 a	11.16 $\pm$ 0.70 a	7.24 $\pm$ 0.46 a	4.08 $\pm$ 1.03 b
SBC3%P	4.90 $\pm$ 0.43 a	7.66 $\pm$ 0.36 a	5.94 $\pm$ 0.40 a	2.91 $\pm$ 0.53 b
SBC5%P	4.09 $\pm$ 0.30 a	7.05 $\pm$ 1.30 a	5.17 $\pm$ 0.52 a	2.32 $\pm$ 0.39 b
SBC14%P	4.59 $\pm$ 1.69 a	6.20 $\pm$ 0.50 a	5.64 $\pm$ 1.52 a	1.87 $\pm$ 0.22 b
SBC21%P	6.91 $\pm$ 2.49 a	14.99 $\pm$ 6.03 a	9.88 $\pm$ 3.40 a	4.36 $\pm$ 1.11 b

¹ Letters refer to Tukey's test ($p < 0.05$) applied to phosphorus (P), which was the only macronutrient showing statistically significant differences in ANOVA results ($p = 0.0005$).

For calcium (Ca) and magnesium (Mg), biochar treatments promoted a progressive reduction trend up to SBC5%P (74.1% for Ca and 83.8% for Mg), although without statistically significant differences according to ANOVA ($p > 0.05$). The high variability



of the SUB treatment, due to the heterogeneity of the commercial substrate, limited the statistical sensitivity of the analysis. Nevertheless, the observed retention trend is supported by well-established mechanisms. The high cation exchange capacity of lignocellulosic biochar favors the retention of Ca^{2+} and Mg^{2+} in carboxylic and phenolic functional groups, which are predominant in materials produced at approximately 450 °C (LEHMANN; JOSEPH, 2015; RODRIGUES *et al.*, 2017).

Potassium (K) showed the greatest proportional reduction up to the addition of 14% biochar (80.4%), also without statistical significance according to ANOVA ($p = 0.122$), due to the same high variability observed in the SUB treatment.

Phosphorus (P) was the only macronutrient with statistically significant differences by ANOVA ($p = 0.0005$), differing from all other treatments according to Tukey's test ($p < 0.05$), with the lowest value observed at SBC14%P (84.5% reduction). Phosphate adsorption involves precipitation with surface Ca^{2+} and Mg^{2+} and the formation of Ca–P and Mg–P complexes under near-neutral pH conditions (SHI *et al.*, 2023).

The results of the nonlinear regression analysis (Table 3 and Figures 3 and 4) confirmed that the asymptotic decreasing exponential function provided an excellent fit for K (adjusted $R^2 = 0.9944$) and P (adjusted $R^2 = 0.9969$), and a moderate fit for Ca (adjusted $R^2 = 0.6748$) and Mg (adjusted $R^2 = 0.7335$), within the range of 0% to 14% biochar. The SBC21%P treatment was excluded from the regression analysis because it showed behavior divergent from the trend observed in the other proportions, with increased concentrations in the leachate. This behavior suggests saturation of biochar adsorption sites at higher dosages, resulting in reduced retention efficiency and, consequently, increased element mobility. Including this point would compromise the fit of the proposed exponential model, which adequately describes the dose–response relationship up to 14% biochar.

These results complement the analysis of variance. For Ca, K, and Mg, whose reductions were not statistically significant by ANOVA due to the high variability of the SUB treatment, regression analysis revealed a consistent dose–response pattern. This interpretation should be considered with caution, given the lack of statistical significance ($p > 0.05$). Nevertheless, the asymptote of the curve, reached between 5% and 14%, represents the minimum estimated leaching value for the substrate–plant system, indicating a potentially optimal range of biochar application.

Table 3 – Nonlinear regression parameters for macronutrients (asymptotic decreasing exponential function).

Item	Adjusted equation (*)	R ²	R ² Adjusted
Ca	$y = 4.389 - 1.736 \cdot cx$	0.8916	0.6748
K	$y = 6.222 - 4.926 \cdot cx$	0.9982	0.9944
Mg	$y = 5.445 - 1.808 \cdot cx$	0.9112	0.7335
P	$y = 1.830 - 2.776 \cdot cx$	0.9990	0.9969

(*) $y = a - b \cdot c^x$, where x = biochar proportion (%); y = leachate concentration (mg L^{-1}); a = asymptote (estimated minimum concentration); b = decay amplitude; and c = exponential decay rate, indicating the rate of concentration reduction as a function of biochar proportion.

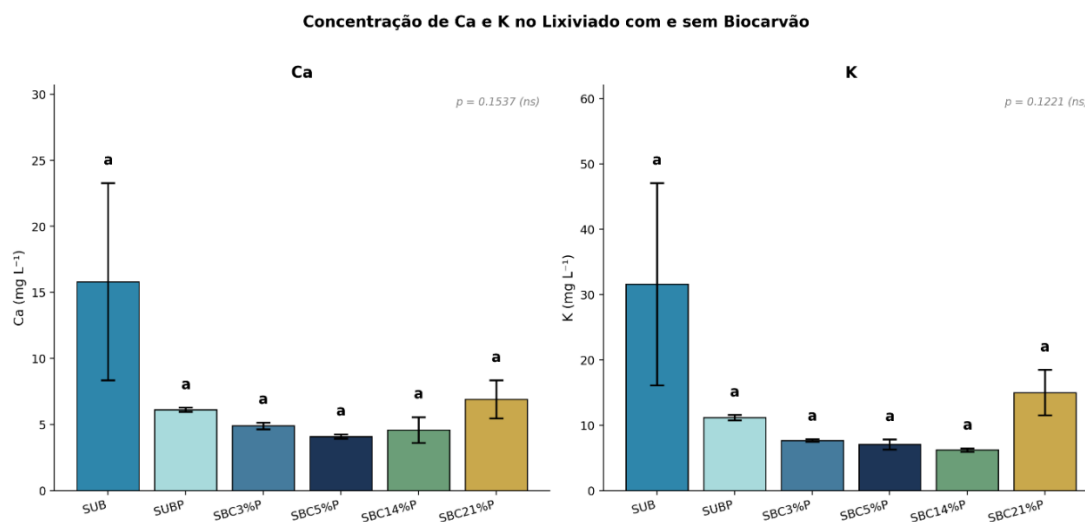


Figure 1 - Concentration of Ca and K in leachate with and without biochar. Error bars represent the standard error (n = 3). Equal letters indicate no significant difference (ANOVA, $p > 0.05$).



Concentração de Mg e P no Lixiviado com e sem Biocarbvão

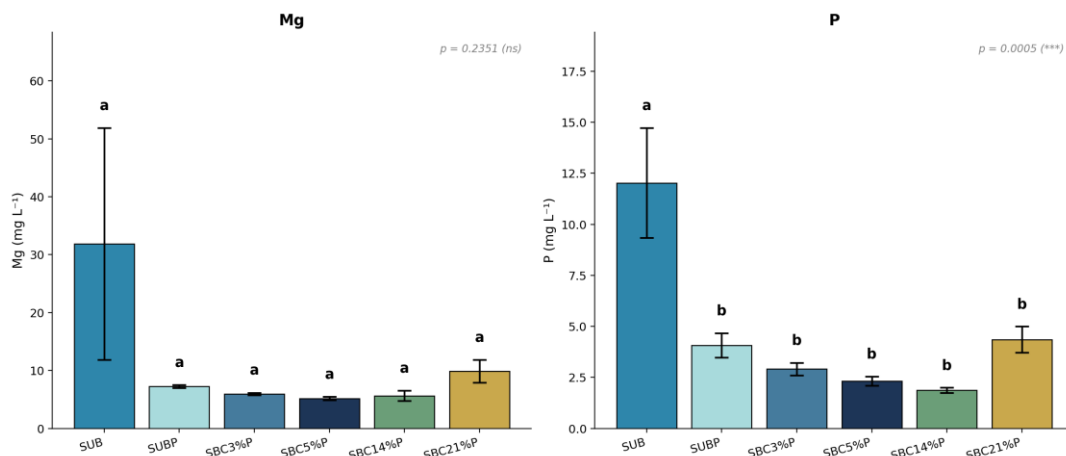


Figure 2 - Concentration of Mg and P in leachate with and without biochar. Error bars represent the standard error (n = 3). Equal letters indicate no significant difference (ANOVA, $p > 0.05$).

Análise de Regressão — Ca e K

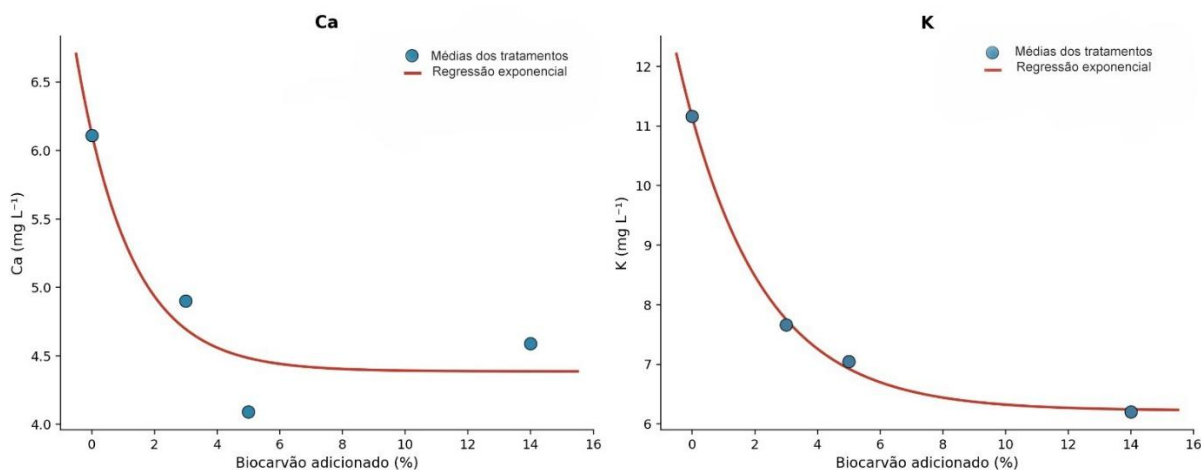


Figure 3 - Nonlinear regression analysis (asymptotic decreasing exponential model) for Ca and K. Points represent the means of the SUBP, SBC3%P, SBC5%P, and SBC14%P treatments ($x \in [0\%, 14\%]$).

Análise de Regressão — Mg e P

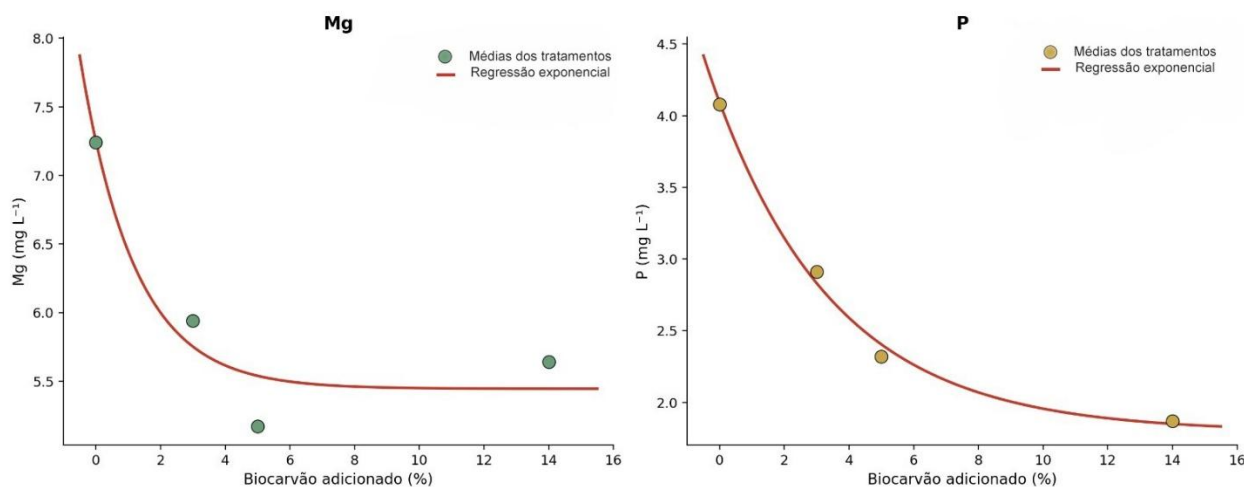


Figure 4 - Nonlinear regression analysis (asymptotic decreasing exponential model) for Mg and P. Points represent the means of the SUBP, SBC3%P, SBC5%P, and SBC14%P treatments ($x \in [0\%, 14\%]$).



Determination of micronutrients and elements (Al, B, Fe, Ni, and Pb) in leachate

The mean concentrations of micronutrients and elements (Al, B, Fe, Ni, and Pb) in the leachate are presented in Table 4 and Figures 5-7. The addition of biochar and the presence of vegetation influenced the concentrations of each element differently, with variable responses depending on the proportion applied and the physicochemical characteristics of each constituent.

Table 4 – Mean concentrations ($\pm$ standard deviation) of micronutrients and elements in leachate with and without biochar.

Sample	Al (mg L ⁻¹)	B (mg L ⁻¹)	Fe (mg L ⁻¹)	Ni (mg L ⁻¹)	Pb (mg L ⁻¹)
SUB	0.223 $\pm$ 0.031 a	0.052 $\pm$ 0.039 a	0.078 $\pm$ 0.021 b	0.248 $\pm$ 0.349 a	0.035 $\pm$ 0.013 a
SUBP	0.320 $\pm$ 0.056 a	0.010 $\pm$ 0.000 a	0.170 $\pm$ 0.018 a	0.034 $\pm$ 0.002 a	0.033 $\pm$ 0.006 a
SBC3%P	0.270 $\pm$ 0.036 a	0.010 $\pm$ 0.000 a	0.162 $\pm$ 0.017 a	0.015 $\pm$ 0.008 a	0.025 $\pm$ 0.001 a
SBC5%P	0.299 $\pm$ 0.044 a	0.010 $\pm$ 0.000 a	0.181 $\pm$ 0.032 a	0.014 $\pm$ 0.007 a	0.014 $\pm$ 0.007 b
SBC14%P	0.340 $\pm$ 0.079 a	0.010 $\pm$ 0.000 a	0.193 $\pm$ 0.063 a	0.015 $\pm$ 0.009 a	0.010 $\pm$ 0.000 b
SBC21%P	0.210 $\pm$ 0.053 a	0.034 $\pm$ 0.005 a	0.078 $\pm$ 0.022 b	0.036 $\pm$ 0.034 a	0.020 $\pm$ 0.009 a

Concentração de Al e B no Lixiviado com e sem Biocarvão

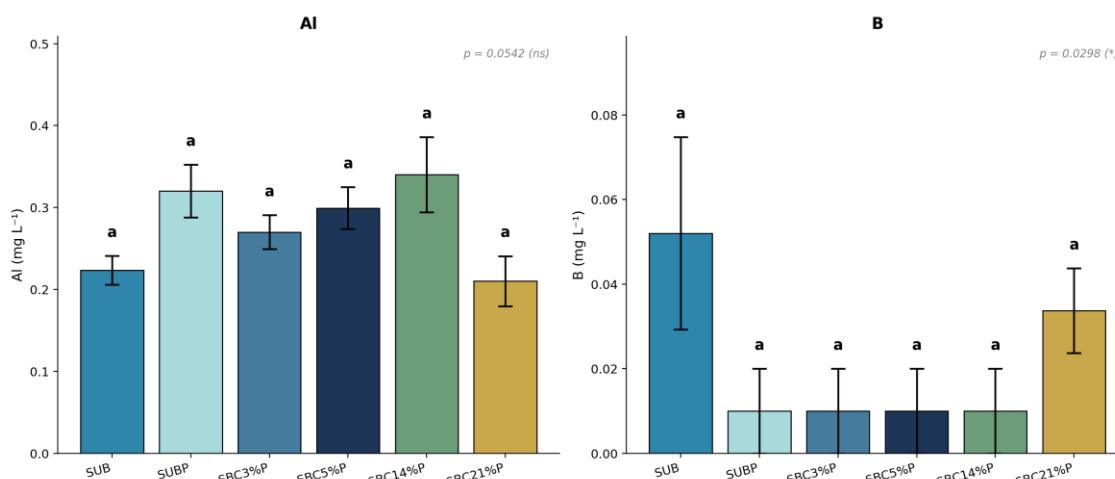


Figure 5 - Concentration of Al and B in leachate with and without biochar. Error bars represent the standard error (n = 3)*. Means followed by different letters indicate significant differences (Tukey, p < 0.05).

Concentração de Fe e Ni no Lixiviado com e sem Biocarvão

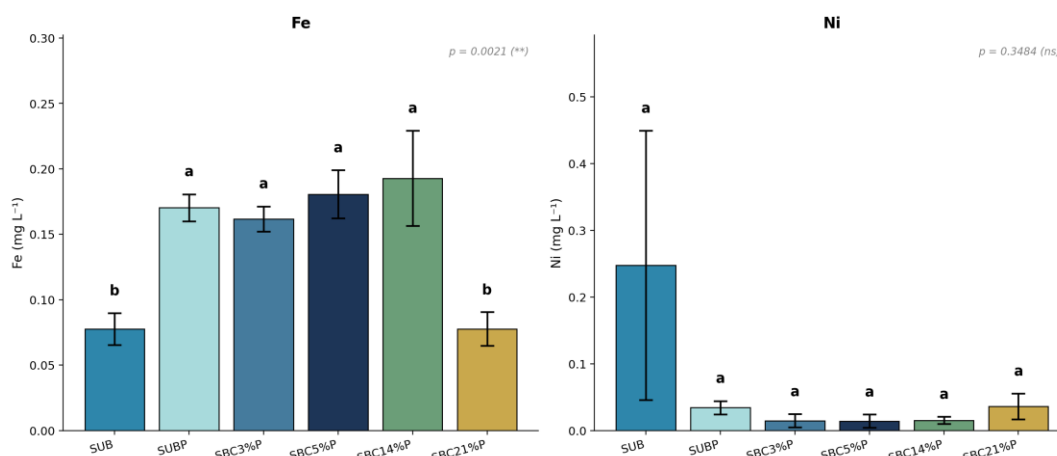


Figure 6 - Concentration of Fe and Ni in leachate with and without biochar. Error bars represent the standard error (n = 3)*. Means followed by different letters indicate significant differences (Tukey, p < 0.05).



Concentração de Pb no Lixiviado com e sem Biocarvão

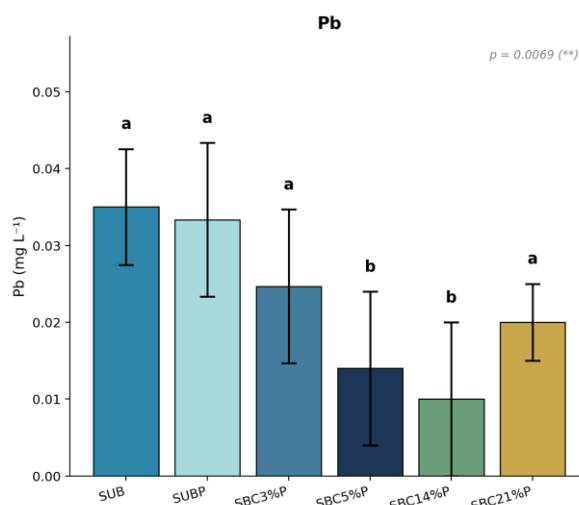


Figure 7 - Concentration of Pb in leachate with and without biochar. Error bars represent the standard error (n = 3)*. Means followed by different letters indicate significant differences (Tukey, $p < 0.05$).

(*) Error bars not visible in some treatments indicate a standard error close to zero (triplicates with values equal to the method detection limit, $LD \approx 0.02 \text{ mg L}^{-1}$). In these cases, the error bar corresponds to $LD/2$ as an estimate of minimum analytical uncertainty.

Al concentrations in the leachate ranged from 0.210 to 0.340 mg L^{-1} across all treatments, with no reduction pattern associated with biochar addition. The lowest value was observed in SBC21%P ($0.210 \pm 0.053 \text{ mg L}^{-1}$), while the other treatments showed slightly higher concentrations. This behavior is consistent with the pH conditions of the leachate (6.4 – 6.8), in which Al^{3+} tends to remain precipitated as low-solubility hydroxides and oxides, limiting its mobilization regardless of the proportion of biochar applied (LEHMANN; JOSEPH, 2015).

The concentration of B in the leachate was significantly reduced in the vegetated treatment ($\sim 81\%$) compared to the non-vegetated substrate (SUB: $0.052 \pm 0.039 \text{ mg L}^{-1}$), reflecting high uptake by peanut grass. No changes were observed with increasing biochar proportions, except at 21%, where the concentration increased.

The behavior of Fe differed from that of the other elements. The SUB ($0.078 \pm 0.021 \text{ mg L}^{-1}$) and SBC21%P ($0.078 \pm 0.022 \text{ mg L}^{-1}$) treatments showed similar concentrations, both lower than those observed in the intermediate treatments with vegetation and biochar (0.162 – 0.193 mg L^{-1}), indicating increased Fe mobility associated with biochar addition and root activity. This behavior may be associated with rhizosolubilization, in which root biological activity enhances Fe mobilization in the substrate (RODRIGUES *et al.*, 2017).

For Pb, the lowest concentrations were observed in SBC5%P and SBC14%P (0.014 and 0.010 mg L^{-1} , respectively), representing reductions of approximately 60–71% compared to SUB (0.035 mg L^{-1}) and SUBP (0.033 mg L^{-1}). These results suggest that, at these proportions, biochar acts as a Pb^{2+} adsorbent through interactions with surface functional groups. This finding is environmentally relevant, reinforcing the potential of lignocellulosic biochar as an adsorbent for potentially toxic elements.

The concentration of Ni in the leachate was significantly higher in the non-vegetated substrate (SUB: $0.248 \pm 0.349 \text{ mg L}^{-1}$) compared to all other treatments. The SBC3%P, SBC5%P, and SBC14%P treatments showed the greatest reductions ($\sim 94\%$ compared to SUB), while SBC21%P showed an increase (0.036 mg L^{-1}) relative to the intermediate proportions, indicating possible saturation of adsorption sites at this dosage.

Final considerations

Wood waste-derived biochar added to the substrate significantly reduced the concentrations of macronutrients (Ca, K, Mg, and P) in the leachate at proportions of 5% and 14%, with evidence of adsorption site saturation at 21%. The decreasing exponential function showed an excellent fit for K (adjusted $R^2 = 0.9944$) and P (adjusted $R^2 = 0.9969$), confirming a well-defined dose–response relationship.

The presence of vegetation played an important role in reducing the leaching of B and Ni, highlighting the contribution of plant uptake. The proportions of 5% and 14% biochar were the most efficient in mitigating Ni and Pb concentrations in the leachate, consistent with the behavior observed for macronutrients. Fe and Al generally showed higher concentrations in the biochar-amended treatments, except at 21%, indicating distinct behavior compared to the other evaluated elements. Pb showed a substantial reduction (~ 60 – 71%) specifically at 5% and 14%, representing an environmentally relevant result given its toxic potential.

From a circular economy perspective, the use of native wood sawdust transforms an abundant waste material in Brazil into a high-value input for sustainable construction, aligning with SDG 12. The results also demonstrate direct connections with other SDGs: nutrient reduction in leachate contributes to the protection of water bodies (SDGs 6 and 14) and reduces human exposure



to diffuse pollutants (SDG 3); carbon sequestration by biochar and mitigation of urban heat islands by green roofs support SDG 13; and the promotion of resilient green infrastructure reinforces SDG 11. Further full-scale and long-term studies are recommended to confirm these benefits over multiple hydrological cycles.

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