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Phytoextraction of heavy metals in soil contaminated by oil activity in the Amazon, Ecuador

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ABSTRACT: Oil activity in Ecuador is one of the main causes of soil contamination and represents a significant threat to the environment and human health. This study addresses the evaluation of the phytoextraction of heavy metals from the Amazonian Region in the province of Orellana in the Flor del Pantano Community with three grass species for tropical climates for three months: Guinea (*Panicum maximum*), Marandú (*Brachiaria brizantha*) and Mombaza (*Panicum maximum*), previously a soil analysis of cadmium, lead, cobalt, mercury and total chromium concentrations was performed, a one-way ANOVA experimental design was applied for the phytoextraction of heavy metals. In the result of the soil analysis of heavy metals, total chromium does not meet the permissible values of the Ministerial Agreement 097 anexo 2 book VI of Ecuador; the three species were evaluated against the control especially the concentrations of total chromium (Cr), where the extraction capacity in the different tests against the control showed the highest extractive capacity is Marandú, reaching an average of 12.65 mg kg^{-1} of Cr, almost twice as much as other species studied. This could be attributed to its adaptation to adverse conditions, such as acid soils with pH 5, Marandú's physiological response, and its effectiveness in phytoextraction. Highlighting the importance of the use of grass species, it is essential to consider the specific characteristics of the species in future research, such as incorporating organic matter to promote microorganisms and improve the effectiveness of grasses.
Keywords: phytoextraction; heavy metals; grasses; oil activity; plant biotechnology; sustainable environmental management.

Fitoextracção de metais pesados em solos contaminados por actividades petrolíferas na Amazónia, Equador

RESUMO: A atividade petrolífera no Equador é uma das principais causas de contaminação do solo e representa uma ameaça significativa ao meio ambiente e à saúde humana. Este estudo aborda a avaliação da fitoextracção de metais pesados da Região Amazónica na província de Orellana na Comunidade Flor del Pantano com três espécies de gramíneas para climas tropicais durante três meses: Guiné (Panicum maximun), Marandú (Brachiaria brizantha) e Mombaza (Panicum maximun), previamente foi realizada uma análise de solo das concentrações de cádmio, chumbo, cobalto, mercúrio e cromo total, foi aplicado o delineamento experimental ANOVA one-way para a fitoextração de metais pesados. No resultado da análise do solo de metais pesados, o crómio total não cumpre os valores admissíveis do Acordo Ministerial 097 anexos 2 livro VI do Equador, as três espécies foram avaliadas contra o controlo, especialmente as concentrações de crómio total (Cr), onde a capacidade de extração nos diferentes testes contra o controlo mostrou que a maior capacidade extractiva é Marandú, atingindo uma média de 12,65 mg/kg Cr, quase o dobro das outras espécies estudadas. Isso pode ser atribuído à sua adaptação a condições adversas, como solos ácidos com pH 5, à resposta fisiológica do Marandú e à sua eficiência na fitoextração, destacando a importância do uso de espécies de gramíneas, é essencial considerar as caraterísticas específicas a utilização de espécies de plantas em futuras investigações, tais como a incorporação de matéria orgânica para promover os microrganismos e melhorar a eficácia das gramíneas.
Palavras chave: fitoextracção; metais pesados; gramíneas; atividade oleosa; biotecnologia vegetal; gestão ambiental sustentável.

1. INTRODUCTION

The oil industry generates a large amount of stone waste and sludge rich in heavy metals that are deposited on the surface of the environment soil is the most static medium, retains pollutants for extended periods, and permanence is especially serious in the case of inorganic pollutants such as heavy metals, which can not be degraded (SEG, 2020). Soil contamination is internationally recognized as a major threat to soil health, affecting safe food production and food security; about 65% of the world's energy production comes from the combustion of fossil fuels (coal, natural gas and oil), which are major environmental pollutants (SHANSHAN; YANQING, 2020). It is important to address this issue because of the detrimental effects that heavy metal contamination in soil can have on both human health and the environment, as the presence of these metals in soil can negatively affect water quality, biodiversity and human health (DELGADILLO-LÓPEZ et al., 2011).

This environmental and health problem has generated the need to seek effective and sustainable solutions for the remediation of contaminated soils (SEPÚLVEDA et al., 2012). In Ecuador, the Amazon region has the largest oil exploitation sites (Diaz Valencia, 2019) and, therefore higher concentrations of heavy metals in the soil (SILVA; MONZÓN, 2018)

Phytoextraction is an environmental remediation technique that uses plants to extract metals and other contaminants from soil and water. This process is based on the natural ability of some plants to absorb and accumulate heavy metals (BELTRÁN-PINEDA; GÓMEZ-RODRÍGUEZ, 2016). Most plants are phyto-accumulators and can mobilize high levels of heavy metals in their tissues (RONG et al., 2017). Ideal phytoremediation plants should have a high capacity to absorb and accumulate in root cells (phytostabilization), translocate to the shoot (phytoextraction), as well as rapid growth and high biomass production (FLORES ROMERO, 2022).

Panicum maximum, commonly known as Guinea, is recognized for its high productivity and resistance to adverse conditions such as drought and poor soil nutrients and adapts to tropical and humid subtropical climates (NENNING et al., 2022). This grass has shown promising abilities for the phytoextraction of heavy metals, making it an attractive option for the remediation of contaminated soils (RODRÍGUEZ HERNÁNDEZ et al., 2019).

Urochloa brizantha, also known as Marandú, is a grass widely used in grazing and livestock systems, largely due to its high productivity and adaptability to diverse environmental conditions (TORRES LÓPEZ, 2022). Marandú has a high potential for soil phytoremediation, taking into account its characteristics to recover soil (BARBARO et al., 2018). Mombaza is among the most used forages in the Amazonian production system, as they are a viable option due to the local soil and climatic conditions and management (TIAN et al., 2021). Heavy metals are the main pollutants found: cadmium, lead, cobalt, mercury, and total chromium, representing a serious environmental risk (BECERRIL et al., 2007).

The objective of this research is to evaluate the effectiveness of phytoextraction using Guinea grass species (*Panicum maximum),* Marandú *(Brachiaria brizantha)* and Mombaza *(Panicum maximum)* in reducing chromium concentration in soils contaminated by oil activity, guaranteeing compliance with Ecuadorian environmental regulations (ÁLVAREZ-VÁZQUEZ et al., 2022).

2. MATERIALS AND METHODS

2.1. Area of study

The focus of the present research on phytoextraction with Gramineae plants was developed in the Flor del Pantano Community located in the province of Orellana, in the Ecuadorian Amazon; this area was an oil or petroleum waste disposal area for 10 years, approximately 3 and a half million of toxic water has been spilled, which has caused a high level of acidity and loss of organic matter in the soil. This type of contaminated soil harbors a variety of heavy metals that can alter the microbiological capacity of the soil and affect people's health (Da Silva et al., 2021); the main heavy metals include (Stumpf et al., 2016): lead (Pb), cadmium (Cd), mercury (Hg), chrome (Cr), and cobalt (Co) (ALAPE; GARCÍA, 2020).

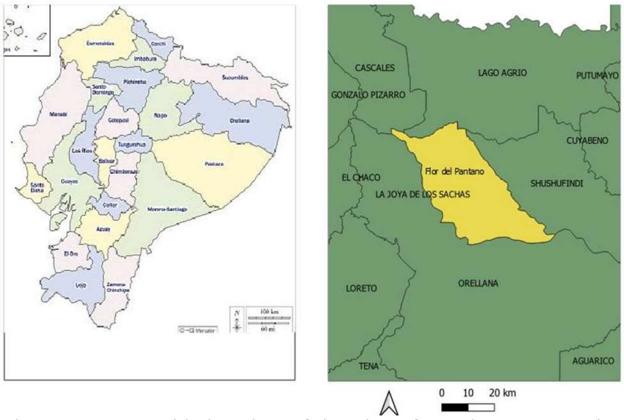

Figure 1. Geographic location of the Flor of Pantáno Community.
Figura 1. Localização geográfica da Comunidade Flor do Pantáno.

2.2. Sampling techniques

Equipment such as atomic absorption spectrometers, sampling tools, preservation supplies, and personal protective equipment were prepared to identify and quantify the contamination and concentration of heavy metals. Soil samples were collected using a systematic diagonal sampling technique, following the protocol for representative sampling (ARIAS ZAPATA, 2020).

Samples were taken from each plot at two initial times (without grass species) and at the end after three months (with grass species). Sampling was carried out using standardized procedures using a drill to a depth of 0.3 m; immediately, the samples were collected in a plastic container, together with sub-samples, extracted from the experimental plots to homogenize the sample, from which one kilogram per plot was obtained to guarantee the results.

A simple sampling method was used to obtain the samples; this method helped estimate the number of samples depending on the area. For each plot, a total of 5 simple samples were extracted, each weighing 1 kg. These samples were then combined following the homogeneous sampling method to produce a composite sample per plot Merino Torres; Pillaca Vilca (2019), per plot. All these procedures were applied to the various plots. A total of 12 homogeneous (combined) samples were sent to their respective laboratory analysis. Each sample is carefully identified and labeled with detailed information about the area; the samples are transported and stored under controlled conditions established in the sampling protocol by the laboratory (JARA ERAZO, 2018).

2.3. Laboratory techniques

The laboratory techniques used to determine the contamination levels of selected heavy metals - lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and cobalt (Co). Advanced analytical techniques were applied to the submitted samples. Such as air-acetylene flame atomic absorption spectroscopy, atomic absorption spectroscopy, hydride generator, and atomic absorption spectroscopy. (Goicochea-Trelles; Garcia-Lopez, 2023), Inductively coupled plasma mass spectrometry (ICP-MS), X-ray fluorescence spectroscopy (XRF) and optical spark emission spectroscopy (OES). These methodologies allow precise and quantitative detection of heavy metals. (Ríos et al., 2014)

2.4. Evaluation of heavy metals

The initial results of the concentration of heavy metals in the soil, such as lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and cobalt (Co), were compared to those of the Ministerial Agreement 097 annexes 2 books VI of Ecuador.

2.5. Phytoremediation species

To carry out this research, an area of 344 m^2 was delimited and affected by oil activity, considering the soil heterogeneity and the possible presence of heavy metals. In this area, we introduced three grass species Guinea (*Panicum maximum),* Marandú (*Urochloa brizantha*), and Mombaza (*Megathyrsus maximus)* with the best capacity for phytoextraction of heavy metals based on their hardiness and adaptive capacity to adverse conditions, capable of tolerating pH between 5.5 and 7, which ensures that they can incorporate nutrients to their system, thus trying to survive in the first instance and effectively produce cut grass along with the heavy metals of extractive interest.

2.5. Phytoremediation Area

The distribution executed in this area contemplated a Complete Randomized Design, evaluated under 12 total plots, each with a dimension of 5 m^2, and internal paths of 0.50 m were adopted. By applying a random distribution for each Gramineae species, 3 replications were assumed, and 9 plots were tested in their totality, where the phytoextraction capacity was analyzed. The remaining 3 plots were kept as control plots in a natural state without any intervention.

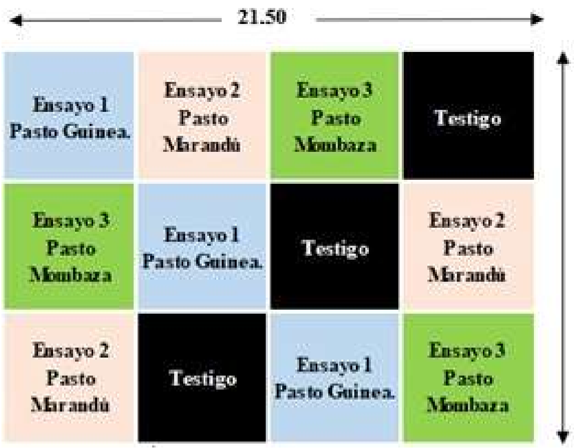

Figure 2. Distribution of Graminae by plot.
Figura 2. Distribuição de Gramíneas por parcelas.

2.6. Phytoremdiation evaluation

Once the heavy metals in the remediation process were identified, the phytoextraction was evaluated after three months of plant growth, considering the following variables: plant growth with fifteen-day intervals until the 90-day growth period was completed; the variations in growth between species allowed identifying if the degree of contamination by heavy metals directly affects its development. The observed growth rate provided an estimate of the contaminant load accumulation in the harvestable parts of the plant, impacting its biomass. After this period, the sprouting stage of tillers begins, signaling the grass-cutting season (RÍOS et al., 2014).

3. RESULTS

3.1. Presence of heavy metals

After analyzing the initial parameters of the study area, it was identified that cadmium (2.00 ± 0.00 mg kg^{-1}), cobalt (13.02 ± 1.11 mg kg^{-1}), mercury (0.05 ± 0.00 mg kg^{-1}) and lead (41.56 ± 5.36 mg kg^{-1}), comply with the maximum permissible values established in Ministerial Agreement N. 097-A, remediation criteria, unlike total chromium, which exceeds the permissible value. Chromium presents mean sum 112.93 mg kg^{-1}, CV 9.87%, median 115.5 mg kg^{-1}, range 35.7 mg kg^{-1}.

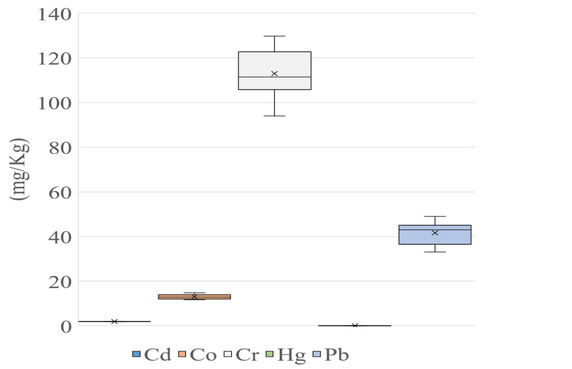

Figure 3. Amount of heavy metals in the study area.
Figura 3. Quantidade de metais pesados na área de estudo.

3.2. Plant growth

The growth of the species Guinea (Panicum maximum), Marandú (*Brachiaria brizantha*) and Mombaza (*Panicum maximum*) was affected by the concentration of total chromium in the soil, as shown in Figure 4.

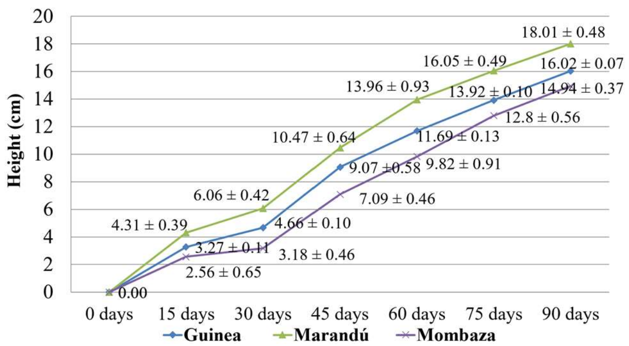

Figure 4. Species growth dynamics.
Figura 4. Dinâmica de crescimento das espécies.

In the analysis of variance (ANOVA) of the growth of grass plants, which was performed with a randomized block design, where the analysis factor is the type of species (control, Guinea, Marandú and Mombaza) and the blocking factor is the days (15, 30, 45, 60, 57 and 90). It should be mentioned that the plant height data comply with the assumptions of normality, homoscedasticity and independence. The analysis variable is significant in the ANOVA since the p-value is less than 5%, so there is a difference in the growth of the grass species in Table 1.

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Table 1. ANOVA analysis of grass species growth at 90 days.
Tabela 1. Análise ANOVA do crescimento das espécies de grama aos 90 dias.

Source	level of freedom	Sum of Square	Means Squares	Value F	p-value
Gramineous species	2	28.54	14.269	78.16	0.000
Days	5	405.69	81.139	444.42	0.000
Error	10	1.83	0.183		
Total	17	436.06			

The analysis of the difference of means between the grass species using Tukey's test (5%) determined three groups of species development at 90 days; Marandú achieved the greatest height (Figure 5), followed by Guinea and Mombaza, under the condition of soils contaminated with chromium.

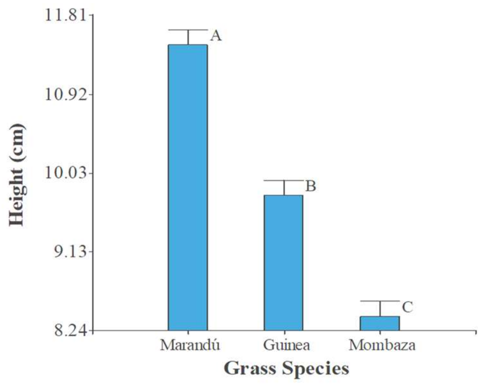

Figure 5. Tukey analysis of the growth of grass species. *This means that those who do not share a letter significantly differ, with 95% confidence.*
Figura 5. Análise de Tukey do crescimento das espécies de gramíneas. *Isto significa que aqueles que não partilham uma letra diferem significativamente, com 95% de confiança.*

3.3. Fitorremediation

The results generated by the laboratory analysis of the contaminated soil samples before and after the experimentation, using the three species of grasses and control, were the data that allowed to establish the variation of the results obtained in the percentage of chromium, here we can appreciate the extractive capacity of Cr of the Marandú grass with an average of 11.13 mg kg^{-1} far exceeds the averages extracted by Guinea with 6.46 mg kg^{-1}, Mombaza with 6.4 mg kg^{-1} and the control with 1.8 mg kg^{-1}.

In the general descriptive analysis of the data obtained for the variation of Chromium, the average is 6.45 mg kg^{-1} with a standard deviation of 4.16 mg kg^{-1} and a confidence interval of (3.80; 9.10) mg kg^{-1} for a reliability of 95%. It should be noted that there is an outlier value of 17.4 mg kg^{-1}, which is statistically acceptable for the analysis of this research.

The variation of the chromium content in the contaminated soil was analyzed using a one-factor ANOVA parametric statistical test, for which the assumptions of normality, homoscedasticity and independence were checked. The data did not comply with normality in the first instance, so a Johnson transformation was performed. The p-value equals 0.545, greater than 5% significance, complying with normality, as shown in Figure 6.

The result of the ANOVA test for the analysis factor, the type of grasses, is significant because the p-value is 0.001, which is less than 0.005. This establishes a difference between the species of grasses, Guinea, Marandú, and Mombaza, concerning the control used for the phytoextraction of the soil contaminated with Chromium, as shown in Table 2.

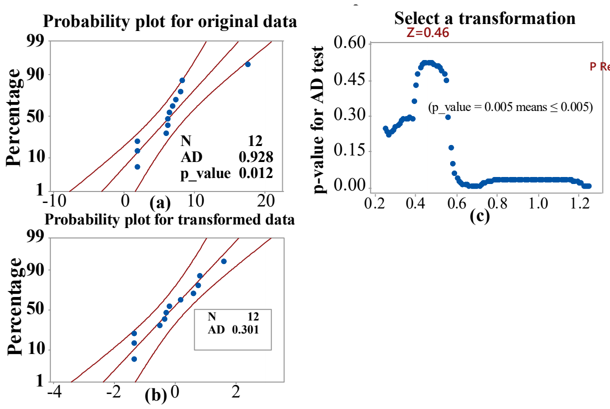

Figure 6. Johnson transformation for the Cr data, the table shows: (a) Normality Q-Q plot of the original data; (b) Normality Q-Q plot of the transformed data; (c) Selection plot of the transformation, the transformation function is -0.0615745 + 0.435148 × Asenh ((X - 6.45243) / 0.455488).
Figura 6. Transformação de Johnson para os dados de Cr, a tabela mostra: (a) Gráfico Q-Q de normalidade dos dados originais; (b) Gráfico Q-Q de normalidade dos dados transformados; (c) Gráfico de seleção da transformação, a função de transformação é -0.0615745 + 0.435148 × Asinh ((X – 6.45243) / 0.455488).

Table 2. ANOVA analysis of the variation of Chromium. The data used are the transformed data.
Tabela 2. Análise ANOVA da variação do crómio. Os dados utilizados são os transformados.

Source	Leve lof freedom (gl)	Sum of Square(SC)	Means Squares (MC)	Value F	p-value
Gramineous species	3	1.116	0.372	17.29	0.001
Error	8	0.172	0.022		
Total	11	1.289			

Since there is a significant difference in the ANOVA analysis of the variation of the percentage of chromium among the species of grasses, a comparison of means was made using Tukey's statistic. The Mombaza and Guinea grasses are statistically equal because the p-value is greater than 5%. On the other hand, there is a significant difference when comparing the Marandú, Guinea and Mombaza grasses concerning the control because the p-value is less than 5%, as shown in Figure 7.

The Tukey test shows that the Marandú grass species are statistically significant at 5% compared to the control to reduce the chromium content in the contaminated soil in the Amazon region in the province of Orellana in the Flor del Pantano Community (Figure 8).

To verify the assumptions of the ANOVA model and guarantee the validity of the results obtained, the analysis of the residuals of the transformed data applied to the selected statistical model was carried out, resulting in the normal probability graph, where the standardized residuals comply with normality because the p-value is greater than 0.1 with a significance of 5%, which is corroborated by the histogram. Regarding the plot of residuals vs. fits, the data are homoscedastic since they do not have an established shape. Finally, in the plot of residuals vs. order, the data are in random form, indicating independence, as shown in Figure 9. Hence, the ANOVA analysis and its interpretations are statistically reliable.

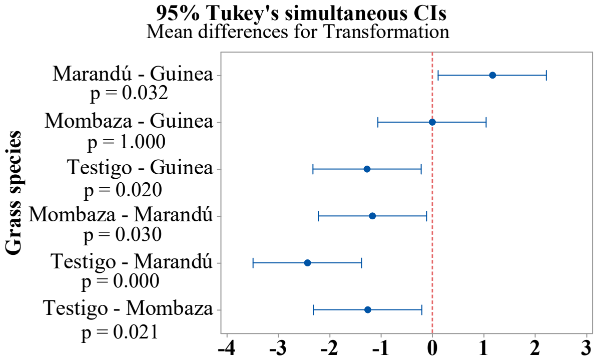

Figure 7. Comparison of means test for chromium content. The corresponding means are significantly different if an interval does not contain zero.
Figura 7. Teste de comparação de médias para o teor de crómio. Se um intervalo não contiver zero, as médias correspondentes são significativamente diferentes.

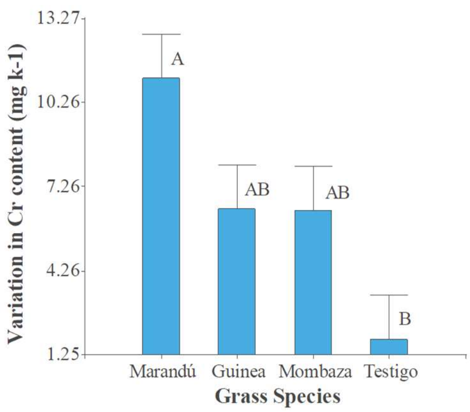

Figure 8. Tukey analysis of Chromium variation. This means that those who do not share a letter significantly differ, with 95% confidence.
Figura 8. Análise de Tukey da variação do Crómio. Análise de Tukey da variação do Crómio. As médias que não partilham uma letra são significativamente diferentes, com 95% de confiança.

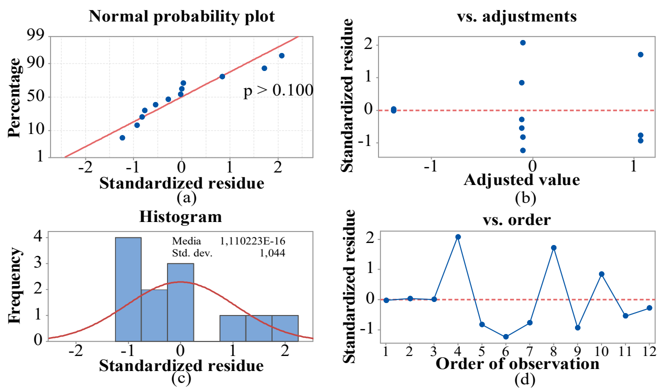

Figure 9. Plots of the residuals, the table shows: (a) Normality Q-Q plot; (b) Plot of the standardized residuals vs. adjustment (Homoscedasticity); (c) Histogram of the residuals; (d) Plot of the standardized residuals vs. order of observation (Independence).
Figura 9. Gráficos dos resíduos, a tabela mostra: (a) Gráfico Q-Q de normalidade; (b) Gráfico dos resíduos padronizados vs. ajuste (Homocedasticidade); (c) Histograma dos resíduos; (d) Gráfico dos resíduos padronizados vs. ordem de observação (Independência).

4. DISCUSSION

Contamination by heavy metals in the soil is a problem in eastern Ecuador. These metals, such as lead, cadmium and mercury, can accumulate in the soil due to various human activities, such as mining, intensive agriculture and industry (RIVERA et al., 2021). When crops are grown in contaminated soils, they can absorb these metals, which affects their quality and food safety. In addition, the presence of heavy metals can alter soil properties and hinder plant growth. Addressing this issue is essential to protect human health and the environment (MEDINA-BUENO et al., 2023).

The study focused on the phytoextraction of heavy metals, particularly chromium (Cr), in soils contaminated by oil activity in Flor del Pantano, Orellana Province, Ecuador. The grasses used revealed different extractive capacities, including the Marandú grass, where a greater difference was found in the amount of Cr with 12.65 mg kg-1 on average, practically doubling the extractive capacity with the other species studied. This is possibly due to its ability to adapt to the difficult conditions that contaminated soils provide to plant species, as it is known that this grass can develop successfully in acid soils. Initial results showed that the presence of hydrocarbons in the soil was associated with the accumulation of heavy metals, highlighting the need to address this environmental problem, as indicated by Diaz Valencia in his work on Phytoextraction of chromium in plants (RIOS LOZANO; SÁNCHEZ NAJAR, 2022).

The three species of grasses evaluated (Guinea, Marandú and Mombaza) were selected for their specific characteristics, such as resistance to adverse conditions and adapting to the tropical climate. Technically, in the case of the Marandú grass, whose average growth reaches 1.5 m, with a lanceolate leaf type that provides it with a leaf surface with a greater photosynthetic work capacity and, therefore, with higher evapotranspiration rates that allow extracting nutrients for its maintenance and, in this physiological process, absorbs heavy metals, specifically the (BENAVIDES et al., 2024). The results indicated that these grasses showed variability in their ability to extract heavy metals, highlighting the importance of carefully selecting species to optimize phytoextraction in soils contaminated with heavy metals derived from petroleum activity (GARRIDO et al., 2023).

The analysis of the concentration of heavy metals, especially chromium, revealed that phytoextraction with the three grass species had a significant impact on reducing the chromium content in the soil, particularly with Marandú, which after the extraction analysis showed 11.13 mg kg^{-1}, as opposed to Mombaza and Guinea with 6.4 and 6.46 mg kg^{-1}, respectively. In other words, twice the amount of Cr was extracted.

In this sense, we observed that the species used, as a subsistence measure, by not differentiating nutrients, but cations and anions with weights and molecular masses similar to those they feed on, carry with them in their physiological processes, heavy metals, specifically in our case Cr. However, it was observed that chromium did not comply with the permissible limits established by the environmental regulations of Ministerial Agreement 097 Annexes 2 Book VI of Ecuador, suggesting that additional strategies or adjustments in the phytoextraction process were required to comply with the standards. (LÁZARO, 2009).

The variation in grass growth over time and the comparison with control without intervention made it

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possible to evaluate the direct impact of the presence of heavy metals on plant development. The results indicated significant differences among the grass species, especially in the case of Marandú, which excelled in the phytoextraction of chromium.

The physiological response of Marandú within an adverse substrate is around pH 5 values, which puts them at the limit of their ability to survive; however, unlike the other species, the species in question has responded, with values exceeding 11 mg kg^{-1} depending on the conditions where it has developed its root system and the conditions of the rhizosphere to the almost null presence of biome that interacts with the ability to absorb nutrients. (OJEDA-MORALES et al., 2023).

Marandú grass (Brachiaria brizantha) has demonstrated certain physiological and adaptive traits that give it advantages over other grasses, such as Guinea (*Panicum maximum)* and Mombaza (*Megathyrsus maximum*). These traits include tolerance to poor, acidic and nutrient-poor soils, which allows it to grow in a wide variety of soil and climatic conditions, including drought-tolerant conditions compared to Guinea and Mombaza. (LÓPEZ VELÁSQUEZ, 2022).

The physiological features such as photosynthesis, respiration, transpiration, absorption and transport of water and nutrients, synthesis of biochemical compounds, response to environmental stimuli, growth and development are not affected since chromium does not interfere in the assimilation of other essential nutrients for plants of the minerals necessary for a plant to live, chromium is not antagonistic to any of them; consequently, Marandú develops normally (NÚÑEZ SOLÍS, 2018).

Marandú's deep roots and ability to store water allow it to maintain growth according to its genetics. It has a high regrowth capacity and can grow at a wide range of altitudes, from low to high. It is known for its rapid growth and ability to produce high-forage biomass. These specific physiological and adaptive traits make Marandú grass thrive in the hostile conditions of contaminated soils (LÓPEZ-VIGOA et al., 2019).

A key feature is its deep and extensive root system, which allows it to reach and extract water from deeper soil layers. The roots of this species can form specialized structures such as root villi or absorptive hairs, which increase the surface area for water and nutrient absorption. This ability to explore and extract water from the soil contributes to its resistance to drought conditions and its ability to survive in hostile environments (NEAMAN et al., 2021).

Increasing the planting density of Marandú is a strategy to improve the extraction of chromium from contaminated soil combined with an integrated approach such as nutrient application to improve the plant's ability to absorb and accumulate chromium while adjusting the pH of oil-contaminated soil could influence the availability of chromium in the plant whose concentration in the biomass would vary according to the growth stage of the plant. A higher planting density would invariably lead to competition for light, water, and nutrients, increasing the competition for survival and thus accelerating the process of mineral extraction, including chromium, releasing this heavy metal from the contaminated soil in a shorter time. (MACEDO, 2020).

As mentioned, chromium is not an antagonist element of other minerals on which the plants feed; in this sense, if we consider increasing the planting density and reducing competition for space, nutrients and water, we would increase the survival capacity of Marandú and thus enhance its ability to extract chromium from contaminated soil. Marandú grass responds well to fertilization with nitrogen (N), phosphorus (p) and potassium (K), as well as other nutrients such as sulfur (S), calcium (Ca) and magnesium (Mg). The application of fertilizers in the initial stage could include phosphorus and potassium, which are important for initial root development and vegetative growth during the growth cycle; nitrogen can be applied to promote vigorous growth and increased forage production, which is important to clarify is not suitable for animal consumption (MENDOZA, 2018).

Regarding soil pH adjustment, Marandú generally grows in slightly acidic to neutral soils, with a pH range between 5.5 and 7.0. If petroleum-contaminated soil has a pH outside this range, measures can be taken to correct it. A common practice to increase soil pH is the application of agricultural lime (calcium carbonate). This application helps neutralize the soil's acidity and increase its pH. That is, the addition of organic matter, in the case of an alkaline pH, would reduce the alkalinity of the soil; on the contrary, the addition of carbonates would bring an acid soil to achieve a pH close to neutrality, in both cases, depending on the amounts used. It is important to remember that the neutral pH of crude oil does not directly influence the pH of oil-contaminated soil since its composition and environmental conditions determine its pH.

Considering its neutrality, oil contamination would not affect soil pH; however, it would affect soil texture and structure. In general, at the moment of degradation of petroleum products, once established in the soil, they tend to acidify it. Therefore, in many cases, it will be necessary to perform soil analysis to correct and adjust the pH of the contaminated soil to adjust fertilization levels and improve the availability of nutrients for the benefit of the pigeon pea crop under these special conditions of soil contaminated by hydro carbides (LÁZARO, 2009).

The initial effectiveness of phytoextraction in reducing chromium levels is a promising step in rehabilitating contaminated soils. It is crucial to consider long-term sustainability because Marandú is a perennial grass; i.e., it requires mowing, the first mowing occurring at 90 to 120 days; after that, mowing occurs every thirty days. The possible environmental implications for maintaining the effectiveness of phytoextraction over time lie in the management of the grass itself, as the cuttings will not be used for cattle feed, this foliage can be chopped and taken to composting, to incorporate it into the soil, In this way, organic matter is provided which would provide the adequate conditions for the development of beneficial microorganisms for the soil, such as endophytic bacteria of the rhizobium genus, specialized in fixing nitrogen in the soil, an element that is vital for the growth of pastures such as Marandú (ÁLVAREZ-VÁZQUEZ et al., 2022).

As for the possible environmental implications of the continuous extraction of heavy metals through the use of Marandú, they are practically null since this pasture is not destined for animal consumption, but, as mentioned, through treatments such as pica and compost, practices that promote the activity of microbial consortiums such as arbuscular mycorrhizae of the genus glomus. These associations help in the absorption of nutrients such as phosphorus. Also, Azospirillum and gramineae such as Marandú, Azospirillum is a bacterium that promotes their growth through biological nitrogen fixation and the production of plant hormones. We will also mention various species of bacteria, such as some of the Pseudomonas genus, which can solubilize nutrients and stimulate plant growth through complex interactions with other soil microorganisms (DA SILVA et al., 2021).

While phytoextraction may be promising, it is important to recognize that there are other remediation techniques available that may be equally effective or even more appropriate in certain contexts; for example, the replacement of contaminated soil with clean soil is a remediation technique that involves excavating and removing contaminated soil from the affected area and replacing it with clean soil that is free of contaminants. This process seeks to physically eliminate the source of contamination by removing the contaminated soil and replacing it with clean material that can adequately support plant growth or other forms of subsequent land use. The costs associated with this technique can vary significantly depending on how much soil is removed. Costs associated with site restoration and rehabilitation after remediation should be considered. This technique can be effective in specific, limited areas where contamination has not spread deep into the subsoil and where replacement with clean soil is technically and economically feasible.

The use of chemical products to decompose or neutralize contaminants accelerates the decontamination process; in this group, we have oxidizing products such as hydrogen peroxide (hydrogen peroxide) or potassium permanganate, which can oxidize persistent organic compounds in soil or water. Reducers such as iron or ferrous sulfate can reduce inorganic contaminants such as heavy metals and precipitate or volatilize them. Surfactants, such as surfactants or emulsifying agents, can help disperse and solubilize contaminants to facilitate their removal. Biosurfactants produced by microorganisms can enhance the biodegradation of organic contaminants.

The use of these active ingredients depends on the type of contaminant and the contaminated environment. The technique involves the controlled application of these chemicals to contaminated soil or water, followed by monitoring processes to evaluate the effectiveness of the treatment and the evolution of the treated contaminants. It is important to perform a detailed site analysis and consider the associated environmental and health risks before applying chemical treatment techniques. The addition of nutrients to stimulate natural microbial activity that aids in the breakdown of contaminants, using an approach known as nutrient bioremediation. This technique involves the controlled addition of nutrients to contaminated soil to promote the growth and activity of degrading microorganisms capable of naturally breaking down.

Some nutrient products commonly used in this technique are nitrogen, which can be supplied in the form of ammonium nitrate or urea; these promote the growth of decomposer microorganisms, and phosphorus, added in the form of phosphates to enhance the activity of enzymes involved in hydrocarbon degradation. Potassium is important for microbial growth and enzyme activity. Trace elements such as iron, manganese, and zinc are cofactors for many microbial enzymes involved in the degradation of organic compounds. These nutrients are applied and controlled to avoid soil imbalances and specifically promote the microbial activity responsible for oil degradation.

Nutrient-enhanced bioremediation is an environmentally friendly strategy that capitalizes on natural microbial degradation processes to clean up petroleum-contaminated soils. However, it is important to carefully design and monitor the process to ensure effectiveness and minimize unwanted environmental impacts. Another technique involves the installation of reactive subsurface barriers (RSBs) to treat and contain contaminants in affected soils by placing physical or chemical barriers in the soil that contain materials that react with contaminants to eliminate them or reduce their mobility. The materials used in these barriers can include, among the first ones, zero-valent iron (fe0), which can react with several contaminants, such as chlorinated organic compounds, to degrade them or transform them into less toxic forms.

Activated carbon is used to adsorb organic contaminants in the soil, thus reducing their mobility. Zeolites can adsorb contaminants such as heavy metals or organic ions. The general methodology involves the installation of these barriers in strategic areas of contaminated soil, such as, for example, between the source of contamination and a groundwater body or a sensitive area, when the contaminants come into contact with the barrier materials, chemical or physical processes occur that help to treat the contaminants. For example, in the case of zero-valent iron, it can react with chlorinated compounds, transferring electrons and decomposing them into non-toxic products. Activated carbon adsorbs organic molecules, trapping them in its porous structure. As in the previous cases, installing these reactive subsurface barriers requires careful design to ensure effective and durable placement. Also, as with the other alternatives, it is important to regularly monitor the effectiveness of the barriers and maintain them properly to achieve optimal results in remediating contaminated soil (GARRIDO et al., 2023).

5. CONCLUSIONS

Phytoextraction with grasses showed promising results in reducing chromium concentration in soils contaminated by oil activity in Flor del Pantano, Orellana, Ecuador. Marandú extracted on average 12.65 mg kg^{-1}. Mombaza and Guinea reported similar values, 6.4 and 6.46 mg kg^{-1}, respectively. The selection of grass species played a crucial role in the phytoextraction efficiency, and was observed that Marandú was particularly effective in chromium extraction.

Despite the reduction in chromium concentration, it was necessary to address the persistence of certain levels that did not comply with the limits established by environmental regulations. However, the results supported the feasibility of phytoextraction as an environmental remediation strategy and suggested the need for adjustments and continuous monitoring to ensure compliance with environmental standards. One of the measures that would contribute to the phytoextraction response would be the increase in planting density because, in this particular case, it consists of taking advantage of the first instances of seed growth so that the initial seed vigor allows more voluminous extractions.

Possible future research directions were highlighted, such as the optimization of the growth conditions of grasses, the exploration of other plant species, the evaluation of phytoextraction in different types of contaminated soil, and the association of species. We know that their germination occurs at different times; therefore, the seeds that germinate first would improve the conditions of the seeds that germinate later, providing a combined strategy to improve the extraction of heavy metals from contaminated soils.

The study contributed to the understanding of phytoextraction as an effective tool in the remediation of soils contaminated by oil activity, highlighting the importance of considering specific factors of plant species in future research and environmental management practices, one of them, We are proposing another possibility within the joint actions from the agronomic point of view and the effectiveness of Gramineae species at the moment of acting as phytoextraction agents of heavy metals present due to the oil activity.

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