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MITIGATION OF CADMIUM ACCUMULATION IN COCOA BEANS USING ARBUSCULAR MYCORRHIZAL FUNGI, BIOCHAR AND *Callisia repens*

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ABSTRACT

Cocoa beans serve as a vital raw material for chocolate production. However, the presence of cadmium (Cd) contamination poses a significant threat to cocoa crops and the chocolate industry due to its adverse effects on human health and cocoa quality. To reduce Cd concentration in cocoa beans, three mitigation strategies were evaluated: application of arbuscular mycorrhizal fungi (AMF), Callisia repens alone, the combined application of AMF and *C. repens*, and biochar at 1% and 2% w/w as an organic alternative. An untreated control was included for comparison. The field experiment was conducted in a mature cacao plantation (genotype CCN51) using a randomized complete block design with three replications in Huánuco, where the soil presents high total Cd levels (0.78 $mg.kg^{-1}$). Six months after experiment establishment, AMF and *C. repens* applied individually reduced Cd concentration in cocoa beans by 40.43% and 30.85% respectively, compared with the control. Total soil Cd remained unchanged across treatments; however, Cd availability decreases with the application of AMF, *C. repens*, their combination, and 2% biochar. These findings highlight the high potential of AMF and *C. repens* to reduce Cd availability in soil and consequently limit its accumulation in cocoa beans; however, Cd concentrations still exceed European Union limits. The short-term results of these findings highlight the need for further evaluation over multiple harvest cycles to confirm the effectiveness and stability of these mitigation strategies.

KEYWORDS: Heavy metals, food safety, soil remediation, comelina

MITIGACIÓN DE LA ACUMULACIÓN DE CADMIO EN GRANOS DE CACAO UTILIZANDO HONGOS MICORRIZÓRICOS ARBUSCULARES, BIOCARBÓN Y *Callisia repens*

RESUMEN

Los granos de cacao constituyen materia prima esencial para producción de chocolate. Sin embargo, contaminación por Cd representa una amenaza significativa para el cultivo de cacao e industria chocolatera, debido a efectos adversos sobre salud humana y calidad del producto. Con el objetivo de reducir concentración de Cd en granos, se evaluaron tres estrategias de mitigación: aplicación de consorcio de hongos micorrízicos arbusculares (HMA), *C. repens* solo, aplicación combinada de HMA y *C. repens*, y uso de biochar al 1% y 2% p/p como alternativa orgánica. Se incluyó un tratamiento control sin aplicación para comparación. El experimento de campo se realizó en una plantación de cacao en producción (genotipo CCN51), bajo un diseño de bloques completos al azar con tres repeticiones, en Huánuco, en un suelo con altos niveles de Cd total (0,78 $mg.kg^{-1}$). Seis meses después del establecimiento, aplicación individual de HMA y *C. repens* redujo contenido de Cd en granos en 40,43% y 30,85%, respectivamente, en comparación con el control. El contenido de Cd total en suelo no mostró variaciones entre tratamientos; sin embargo, fracción disponible disminuyó con aplicación de HMA, *C. repens*, su combinación y el biochar al 2%. Estos resultados evidencian potencial de HMA y *C. repens* para reducir disponibilidad de Cd en suelo y, en consecuencia, su acumulación en granos de cacao. Sin embargo, concentraciones de Cd aún superan límites establecidos por Unión Europea. Resultados obtenidos en un periodo corto resaltan la necesidad de evaluaciones durante varios ciclos de cosecha para confirmar estabilidad de estas estrategias de mitigación en el tiempo.

PALABRAS CLAVE: metales pesados, seguridad alimentaria, remediación de suelos, comelina.

INTRODUCTION

Cocoa (*Theobroma cacao* L.) is an indigenous tree species native to the Amazon region whose beans constitute the primary raw material for the chocolate industry. In recent years, chocolate consumption has increased substantially (Arévalo-Gardini *et al*., 2017), driving the production of fermented and dried beans. This growth responds to the increasing demand for beans with superior flavor and aroma characteristics (Bustamante *et al*., 2022).

One of the main problems of cocoa cultivation is the high levels of Cd present in the beans, due to its adverse impacts on human health and its detrimental effects on food quality (Lara *et al*., 2016). Consumption of products containing elevated levels of Cd poses severe health risks, including detrimental effects on bone health, kidney function, and the respiratory system. Furthermore, prolonged exposure to Cd has been linked to an increased risk of cancer development (World Health Organization, 2019). Recognizing this concern, the European Union (EU), which serves as the primary destination for Peruvian cocoa bean exports, has implemented more stringent guidelines specifying allowable Cd concentrations in cocoa products. These revised standards range from 0.1 to 0.8 $mg.kg^{-1}$ (Lara *et al*., 2016; The European Commission, 2014).The presence of high Cd concentrations in cocoa beans, particularly from the Amazonas, Piura and Tumbes regions, exceeds the maximum allowable limits under Peruvian and European legislation, affecting the export of cocoa beans (Arévalo-Gardini *et al*., 2017; Oliva *et al*., 2020).

Cd occurs naturally in soil through volcanic activity, atmospheric deposition, rock weathering, and biogenic processes (M.A. Khan *et al*., 2017; Maddela *et al*., 2020), but human activities such as mining, phosphate fertilizers, and industrial emissions also contribute to its accumulation (Maddela *et al*., 2020; Scaccabarozzi *et al*., 2020). Decomposing plant residues can further increase Cd in topsoil (Maddela *et al*., 2020). Due to its high mobility and bioaccumulation potential, Cd is readily absorbed by plant roots (Oliva *et al*., 2020; Rodríguez *et al*., 2019). Studies in South American cocoa plantations have shown a strong correlation between soil Cd and Cd concentration in cocoa beans. Soil pH plays a key role, as lower pH increases Cd availability and uptake (Argüello *et al*., 2023; Chavez *et al*., 2015; Ramtahal *et al*., 2019; Zug *et al*., 2019). In addition to soil properties (pH, organic matter, texture), Cd accumulation in cocoa is influenced by environmental Cd levels, production systems, genotype, and management practices (Chavez *et al*., 2015; Gramlich *et al*., 2017; K. Y. Khan *et al*., 2017; Maddela *et al*., 2020).

Biological strategies to reduce Cd uptake include the use of rhizosphere microorganisms (Cayotopa-Torres *et al*., 2021; Qiu-Yun *et al*., 2016; Harms *et al*., 2011). Certain fungi can transform, immobilize, or sequester metals, while AMF can mobilize or immobilize Cd in the mycosphere (Harms *et al*., 2011). Phytoremediation is another option, integrating companion plants that compete for Cd uptake. *C. repens*, an herbaceous species used in cocoa systems (Puertas, 2009) and tolerant to contaminated soils, was considered a potential Cd competitor.

In addition to biological approaches, organic amendments such as biochar can also reduce Cd availability by immobilizing it in soil through precipitation and surface interactions, thereby limiting plant uptake (Chen *et al*., 2020; Huaraca-Fernandez *et al*., 2020; Yuan *et al*., 2020).

The study evaluated the effectiveness of AMF and *Callisia repens* as biological strategies and biochar as an organic amendment to reduce Cd uptake in cocoa. The experiment was conducted in an eight-year-old cocoa plantation established on soil with high Cd levels, assessing

Cd concentrations in cocoa beans and total and available Cd in soil.

MATERIALS AND METHODS

The experiment was conducted in the Huamancoto (Pumahuasi) settlement, Daniel Alomía Robles district, Leoncio Prado province, Huánuco region. Geographically located at 9°12'25,07" S and 75°56'17,04" W, at an altitude of 671 meters above sea level. Pumahuasi is one of the main cocoa-producing communities in the Huánuco region and has favorable soil and climatic conditions for crop development, with temperatures ranging from 18 to 28 °C and an average annual precipitation of 3200 mm (Villanueva, 2019).

The study was in a plantation of the CCN51 cocoa genotype that had been established for eight years, on soil with elevated levels of soil Cd (0.78 $mg.kg^{-1}$) and high Cd concentration in cocoa beans (1.07 $mg.kg^{-1}$) (Villanueva, 2019). The farmer employed conventional management practices, including a plant spacing of 3 m x 3 m, annual maintenance pruning, and manual weed control. Fertilization management followed an annual substitution approach, a conventional farmer practice in absence of region-specific fertilization models for cocoa. The fertilization practiced is therefore yield-oriented, typically applying N–P–K at quantities of 84–35–160, split into up to three applications per year. The most common sources used are urea, rock phosphate, and potassium chloride (Florida, 2018).

The study population comprised 90 CCN51 cocoa trees established within an area of 648 m^2. The experiment was arranged in a randomized complete block design with three replications. Each block included 30 trees, and each experimental unit (36 m^2) consisted of five cacao trees; the central tree was selected for sampling. Although baseline data were not available for the individual plots, all treatments were managed uniformly. The treatments were randomly assigned, and blocks were established considering terrain variability; therefore, significant differences in initial Cd content among plots were not expected. Two concentrations of biochar (1% and 2%, w/w), *C. repens*, a consortium of AMF spores, and a combination of *C. repens* with AMF were investigated. Prior to application, the leaf litter covering the soil surface from the base of the stem to the canopy projection was removed. The biochar, produced from maize residues and pine pruning, through rotary pyrolysis at 500 °C, for 2 hours, had the following dry characteristics: organic matter 82.12%, ash 17.88%, carbon 26.28%, nitrogen 1.23%, P_2O_5 0.82%, potassium 4.42%. It was uniformly spread around the canopy projection area at rates equivalent to 8 $kg.plant^{-1}$ and 16 $kg.plant^{-1}$ for the 1% and 2% treatments, respectively. *C. repens* cuttings (10 kg fresh biomass per plant) were established to cover the soil surface from the trunk base to the canopy projection.

The propagated cuttings of *C. repens* showed vigorous growth, reflecting the species' high adaptability to diverse environmental conditions. The AMF consortium consisted of 1 kg of soil containing concentrated spores (1x105 $spores.g^{-1}$), obtained from cocoa rhizosphere soil. The inoculum was applied directly to the fine roots within the canopy projection area. The combined treatment of AMF + *C. repens* treatment followed the same procedures and application quantities used for individual treatments.

The control and all mitigation treatments received the farmer's conventional management practices, including fertilization based on target yield (due to the lack of regional fertilization models), conventional tillage, and preventive pesticide application.

Six months after treatment establishment, three cocoa pods per tree (one per main productive branch) were harvested and transported to the soil laboratory of the National Agrarian University La Selva.

Under aseptic laboratory conditions, cocoa beans were extracted from the pods. Mucilage removal was achieved through micro-fermentation for 7 days, followed by oven-drying at 60 °C until reaching 8% moisture content. The dried beans were then ground (Arévalo-Gardini *et al*., 2017). Cd extraction was performed using a digestion solution of HNO_3 (65%) and HCl_4 (98%), and Cd concentration was determined by atomic absorption spectrophotometer. The laboratory complies with national standards and is certified by the Instituto Nacional de Calidad (INACAL), Perú.

Soil samples (0-30 cm depth) were collected within the canopy projection area for each treatment. Surface vegetation was carefully removed prior to sampling. Eight soil cores per plant were randomly collected to obtain representative composite samples. Samples were dried naturally, crushed, and sieved (2 mm diameter).

Chemical analyses were carried out using standard procedures. Soil pH was measured potentiometrically in a 1:1 soil-to-water suspension. Texture was determined using the Bouyoucos hydrometer method. Calcium carbonate ($CaCO_3$) content was quantified by the gas-volumetric method. Extractable P was determined using a modified Olsen solution followed by colorimetry analysis. Soil organic carbon was measured using the Walkley and Black method. Total soil Cd was determined following the EPA-3050B digestion method and quantified by inductively coupled plasma optical emission spectrometry (ICP OES). Available Cd was extracted with 0.05M EDTA (pH 7.0) and measured using by atomic emission spectrophotometer (Beine, 2023). The transfer factor was calculated to evaluate Cd movement from soil to cocoa beans (Figure 1D).

Data normality was assessed using the Shapiro-Wilk test (α = 0.05), and homogeneity of variances was evaluated with Levene test (α = 0.05). Treatments were considered fixed effects. Analysis of variance (ANOVA) followed by the least significant difference (LSD) test (α = 0.05) was conducted using the easyanova package. Pearson correlation analysis among all variables was performed using the corrplot and PerformanceAnalytics packages in RStudio. All statistical analyses were carried out in R Studio statistical software, version 4.0.2 (R Core Team, n.d.).

RESULTS

Cd CONCENTRATION IN COCOA BEANS AND SOIL

The Cd concentration in cocoa beans decreased significantly with the *C. repens* and AMF treatments, whether applied alone or in combination, compared with the Control treatment (p-value < 0.01, C.V. = 12.41 %, Figure 1A). Inoculation with AMF reduced bean Cd concentration by 40.43% from 0.94 $mg.kg^{-1}$ in the Control to 0.56 $mg.kg^{-1}$. The use of *C. repens* as a bioremediator resulted in a 30.85% reduction, whereas the combined application of *C. repens* and AMF achieved a 24.47% decrease. Conversely, the application of biochar at 1% and 2% did not produce significant differences compared to the Control treatment. The treatments applied to cocoa cultivation significantly affected Cd concentration in cocoa beans (p-value < 0.001) (Figure 1B) but did not show any significant impact on the total Cd content in the soil (p-value = 0.19) (Figure 1C). AMF, *C. repens*, the combination of both (AMF + *C. repens*), and 2% biochar resulted in the lowest available Cd levels in the soil, with values of 0.19, 0.19, 0.21, and 0.19 $mg.kg^{-1}$, respectively.

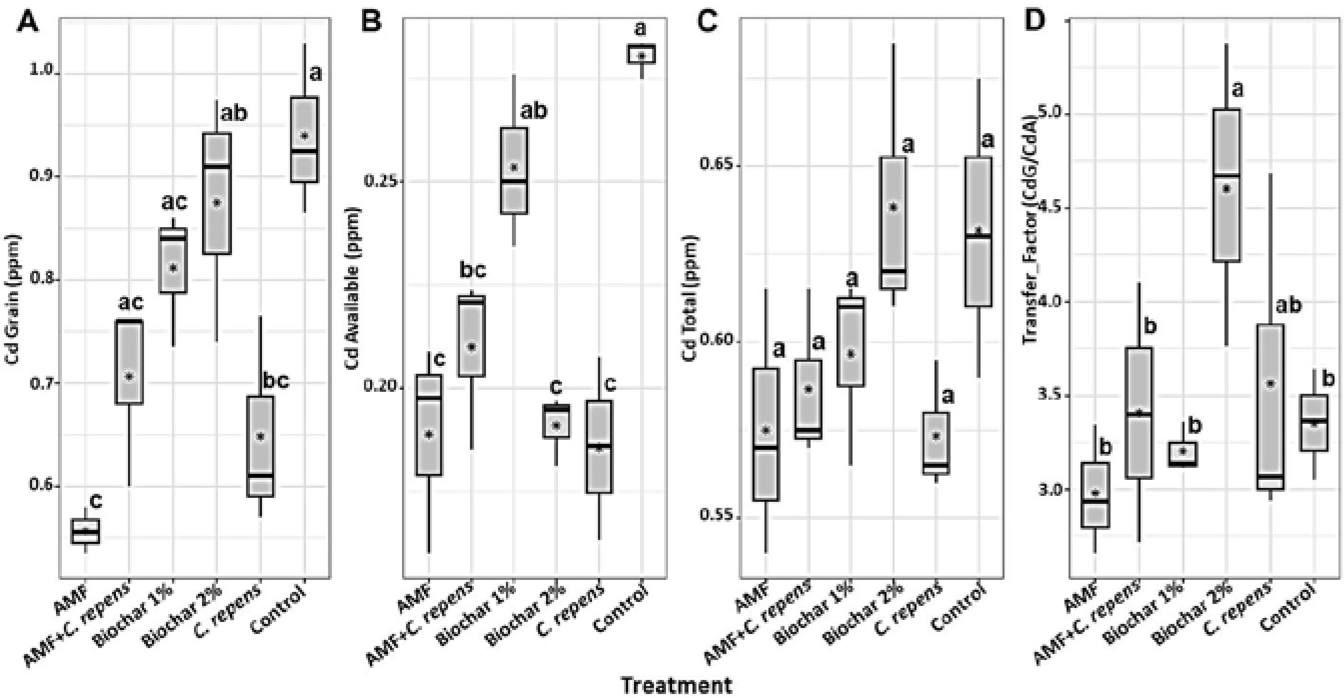

Figure 1. Cd concentration in cocoa beans (A), available fraction of Cd in the soil (B), and total Cd in the soil (C) and (D) transfer factor of Cd. Different letters indicate significant differences between treatments determined by the LSD test (p=0.05). The bars represent the lowest and highest value, the asterisk indicates the mean, and the line inside the boxes represents the median.

IMPACTS ON SOIL PHYSICOCHEMICAL CHARACTERISTICS

The applied treatments to the soil had an impact on the levels of soil organic matter (SOM) and extractable P (Figure 2A-B). Biochar application at 2% and 1% increased SOM, reaching mean values of 3.92% and 3.72% respectively. In contrast, treatments with AMF, *C. repens*, and their combination (AMF + *C. repens*) resulted in lower SOM values; however, only AMF treatment differed significantly from the control. Both 1% and 2% biochar application also enhanced extractable P. Soil pH did not differ significantly among treatments (Figure 2C), remaining near neutral (6.98-7.39). Likewise, soil texture (sand, silt, and clay) showed no significant variations across treatments (Figures 2D-G).

The Pearson correlation analysis revealed positive correlations between Cd concentration in cocoa beans and soil total Cd, soil available Cd, and SOM (Figure 3). Soil total Cd was also positively correlated with SOM. Notably, SOM exhibited a strong positive correlation with extractable P, whereas sand and silt were negatively correlated with these variables.

DISCUSSION

Cd CONCENTRATION IN COCOA BEANS AND SOIL

The results demonstrate that both AMF and *C. repens*, applied individually or in combination, effectively reduced Cd concentration in cocoa beans. However, biochar applied at 1% and 2% did not significantly decrease Cd levels in the cocoa beans. These findings highlight the capacity of AMF to mitigate heavy metal contamination in cocoa beans. As these microorganisms can reduce

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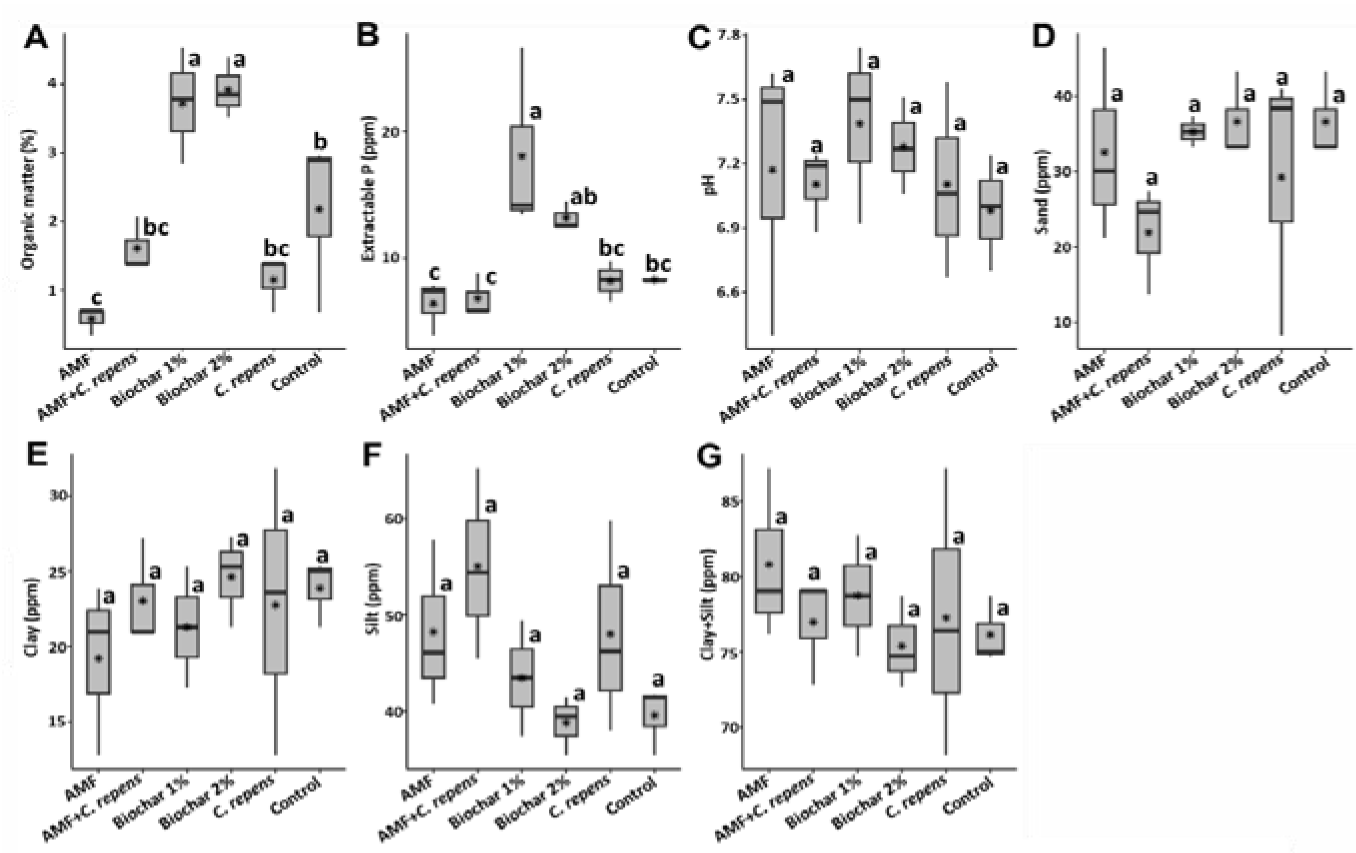

Figure 2. Effect of the treatments on SOM (A), extractable P (B), pH (p-value=0.86) (C), Sand (p-value=0.51) (D), Clay (p-value=0.82) (E), Silt (p-value=0.22) (F), and Clay+Silt (p-value=0.82) (G). Different letters indicate significant differences between treatments determined by the LSD test (p=0.05). The bars represent the lowest and highest value, the asterisk indicates the mean, and the line inside the boxes represents the median..

Cd availability and uptake by plants through immobilization processes and by altering the chemical of the metal in the soil (Sani *et al.*, 2025; L. Li *et al.*, 2024), a mechanism widely documented in previous studies. Certain fungal species have the capacity to chemically transform metals and sequester them within different cellular compartments or translocate them along fungal hyphae, thereby contributing to their redistribution within the soil-plant system (Liu & Wang, 2025; Salari *et al.*, 2024; Dinsley *et al.*, 2025). The mechanisms underlying this mitigation involve both immobilization and mobilization processes occurring in the mycosphere, where microorganisms such as AMF promote metal sorption onto fungal cell walls, biomineralization, and their accumulation within fungal cells, thereby reducing their bioavailability to plants (Liu & Wang, 2025; L. Li *et al.*, 2024; Dinsley *et al.*, 2025).

Additionally, W. Li *et al.* (2022) reported that AMF produce and secrete glomalin, a glycoprotein that facilitates the sequestration of heavy metals in soil, roots, and fungal hyphae. Through these mechanisms, plants colonized by AMF often exhibit increased tolerance to Cd and improved acquisition of essential nutrients without excessive uptake of heavy metals (Zare *et al.*, 2023; Boorboori & Zhang, 2022). Consequently, AMF may reduce the translocation of Cd to aerial plant tissues, thereby enhancing plant tolerance to

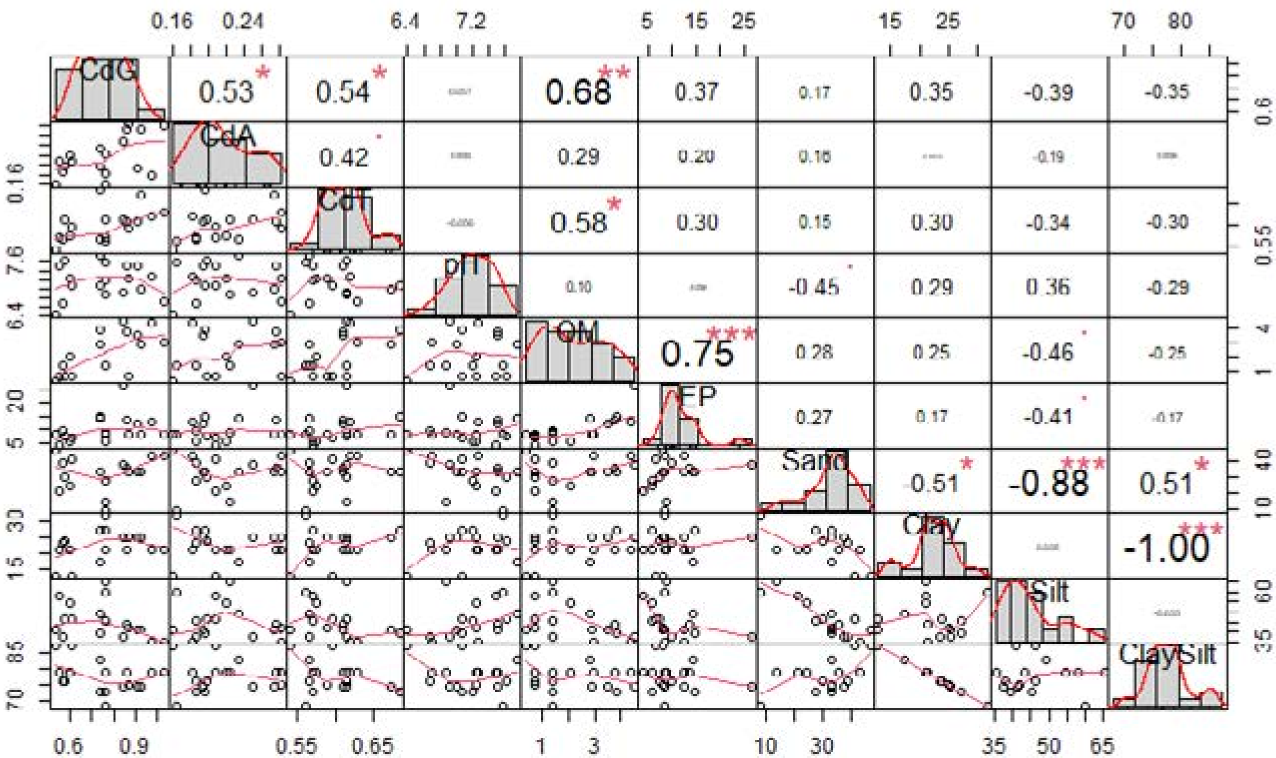

Figure 3. Pearson correlations between Cd concentration variables (Cd grain = CdG, Available Cd in Soil = CdA, Total Cd in Soil = CdT) and soil physicochemical characteristics (pH, Soil Organic Matter = OM, Extractable Phosphorus = EP, Sand, Clay, Silt, Clay+Silt = ClaySilt).

metal stress (Li *et al*., 2022; Wang *et al*., 2026). Consistent with these findings, González-Chávez *et al*. (2018) reported that the presence of *Acaulospora* sp. associated with *Jatropha curcas* significantly reduced Cd accumulation in foliage grown in mine-contaminated soils, with effects greater than those achieved through biochar application.

Our results that both AMF and *C. repens* may contribute to reducing Cd accumulation in cocoa beans. However, when both treatments were applied simultaneously, the reducing Cd accumulation was less pronounced than wen they were applied individually. This suggests a possible negative interaction between AMF and *C. repens*, potentially related to the to the colonization of *C. repens* roots by the AMF and subsequent changes in Cd dynamics within the system. It is important to note that this study did not quantify Cd accumulation in AMF structures or in *C. repens* tissues and AMF colonization levels were not evaluated in the treatments. Therefore, further studies are needed to clarify the mechanisms involved.

Although AMF and *C. repens* individually reduced Cd concentrations in cocoa beans, Cd levels still exceeded the maximum limits established by the European Union for cocoa and cocoa products (0.1-0.8 ppm) (European Commission, 2014). However, it should be considered that the treatments were evaluated after a relatively short period following application. Therefore, the mitigation effects could increase or decrease over longer periods. Another potential limitation is the possible release of heavy metals previously sequestered by AMF after fungal death and decomposition which could limit the long-term effectiveness of this mitigation strategy.

The reduction of Cd accumulation in cocoa beans and the decrease in Cd availability in soil observed with *C. repens* suggest its potential as a phytoremediation species. These findings indicate that *C. repens* could be a useful plant for mitigating Cd contamination in cocoa agroecosystems. However, further research is required to quantify Cd accumulation in different plant organs to confirm its potential as a natural Cd bioaccumulator.

The treatments significantly affected the available Cd content in the soil, whereas no significant changes were observed in total Cd content. Both AMF and *C. repens* reduced the availability of Cd in the soil, which may explain the lower Cd concentrations observed in cocoa beans.

This application of 2% biochar resulted in a 19% reduction in available Cd compared to the Control treatment. The biochar used in this study was produced from maize crop residues and pine pruning, with a carbon content exceeding 26%. This high carbon content likely increased the adsorption capacity of the soil, enabling greater retention of available Cd. Abbas *et al*. (2017) reported similar results using rice straw biochar pyrolyzed at 450 °C, which retained Cd in a sandy clay loam soil and reduced its accumulation in wheat grains. Likewise, biochar derived from tomato residues and poultry manure reduced Cd availability in soil (Khan *et al*., 2017).

The effectiveness of biochar in reducing Cd availability depends largely on its physicochemical properties, which are influenced by the feedstock used and the pyrolysis conditions during production. In addition, the application rate plays a crucial role. Chen *et al*. (2016) demonstrated that biochar applied at rates of 1% and 2% significantly immobilized Cd and Zn in soils. A review of 194 experiments published between 1980 and 2016 also indicated that biochar doses greater than 10 $mg.ha^{-1}$ (approximately 0.5%) significantly immobilized heavy metals in soils (Barrezueta *et al*., 2024).

The transfer factor results (Figure 1D) showed that treatments involving AMF presented lower Cd grain/Cd available ratios, likely due to the ability of AMF to retain available Cd within fungal structures. These mechanisms may represent a promising strategy for controlling Cd uptake by plants.

The average concentrations of available Cd and total Cd in the soil were 0.258 and 0.570 $mg.kg^{-1}$, respectively. Although these values indicate a relatively elevated Cd levels, they remain below the maximum concentration permitted for agricultural soils according to the Peruvian Ministry of Environment (MINAM), which is 1.46 $mg.kg^{-1}$ (OEFA, 2017). However, Cd concentrations in cocoa beans exceeded the limits established by EU Regulation 488/2014 (European Commission, 2014).

Cocoa is known for its high capacity to accumulate Cd in different plant organs, particularly in levels and roots, where concentrations can reach up to five times those found in the soil (Rodríguez *et al*., 2019; Oliva *et al*., 2020). Therefore, strategies aimed at reducing Cd bioavailability in soil are essential to prevent accumulation in harvestable cocoa beans.

A positive correlation was observed between Cd concentration in cocoa beans and soil total Cd, available Cd, and soil organic matter (SOM). This relationship suggests that Cd accumulation in beans is strongly influenced by the bioavailable fraction of Cd in the soil, which in turn depends on total Cd content and the mineralization of SOM.

Future studies should address some limitations of this preliminary research. These include evaluating the chemical forms of Cd released after AMF decomposition, assessing the potential desorption of Cd from biochar over time, and quantifying Cd accumulation in *C. repens*. In addition, future research should evaluate the economic feasibility of applying these strategies at larger scales in cocoa production systems.

EFFECT ON SOIL PHYSICOCHEMICAL CHARACTERISTICS

Biochar-treated plots showed higher levels of SOM and extractable phosphorus compared with the other treatments. This effect is likely related to the high organic carbon content of biochar, which contributes to carbon sequestration and improvements in soil physical properties such as porosity, water retention, and bulk density (Tian *et al*., 2024; Zhang *et al*., 2025). Previous studies have reported that biochar application can increase SOM and soil pH while reducing bulk density in soils subjected to long-term monoculture (Zhang *et al*., 2024).

The increases observed in SOM in the 1% and 2% biochar treatments can be attributed to the high organic matter (82.12%) and carbon content (26.28%) of the biochar used in this study. These applications contributed approximately 23 and 46 $t.ha^{-1}$ of organic matter, respectively. However, long-term monitoring is necessary to determine whether these increases in SOM can be sustained over time.

Biochar possesses a highly porous structure and large specific surface area with negatively charged functional groups, which can increase the soil cation exchange capacity (CEC) and enhance the retention of nutrients, including phosphorus, organic colloids, and water. Furthermore, biochar can function as a slow-release source of phosphorus in soils and may also supply basic cations such as calcium and magnesium, thereby contributing to improved soil fertility and greater nutrient availability for plant uptake (Ibrahim *et al*., 2024).

In treatments without biochar, extractable P concentrations were below the critical threshold of 10 $mg.kg^{-1}$ required for cocoa cultivation (Aikpokpodion, 2010). However, the incorporation of biochar at 1% and 2% increased extractable P above this threshold. In contrast, Farrell *et al*. (2014) reported no effect of biochar on P availability in calcareous soils after years, possibly due to the formation of Ca-P complexes.

Treatments involving AMF, and AMF combined with *C. repens* showed lower extractable P concentrations (< 7 $mg.kg^{-1}$). Nevertheless, AMF can enhance phosphorus uptake by plants through their extensive hyphal networks. Over the long term, improved P uptake may contribute to increased SOM through enhanced plant productivity and greater return of organic residues to the soil.

Soil pH and texture remained relatively stable across treatments, likely due to the short duration of the experiment (six months). However, longer-term studies may reveal changes in soil pH associated with biochar application (Yuan *et al*., 2025).

A relationship was also observed between soil total Cd and SOM, suggesting two possible hypotheses. Firstly, the recalcitrant (stable) fraction of SOM may act as a sink for Cd, limiting its uptake by plants. Second, SOM derived from cocoa residues may contribute to the cycling of Cd within the soil-plant system. In addition, a strong correlation between SOM and extractable P suggests that SOM mineralization may represent an important source of P in these soils

CONCLUSIONS

The biological alternatives tested, AMFs and *C. repens*, demonstrated a high potential for reducing Cd concentration in cocoa within a short-term period of six months. In addition, the application of biochar at a 2% dosage decreased the concentration of available Cd in the soil.

Cd concentration in cocoa beans was correlated with total soil Cd, available soil Cd, and SOM. Moreover, biochar application at these dosages increased SOM and extractable P levels, demonstrating its effectiveness as an organic amendment to enhance soil fertility.

Overall, the integration of AMF, *C. repens*, and biochar represents a promising strategy to reduce soil Cd availability, mitigate Cd accumulation in cocoa beans, and enhance soil fertility. Although Cd concentrations in cocoa beans decreased with these treatments, the levels still do not meet commercial standards. AMF and *C. repens* show potential as bioremediation strategies; however, their long-term effectiveness requires further evaluation.

These materials may also provide accessible and cost-effective alternatives for cocoa farmers facing Cd contamination in their fields. These results are from a preliminary short-term study and highlight the potential effectiveness of some mitigation strategies to reduce Cd contamination in cocoa beans. Further research is required to evaluate the long-term effectiveness and economic viability of these strategies. In addition, future studies should investigate the mechanisms that may promote the release of Cd from AMF and biochar over time. It is also important to assess appropriate management practices for *C. repens* once its life cycle is complete.

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