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Influence of Cadmium and Arbuscular Mycorrhizae on Growth and Chlorophyll Content in *Theobroma cacao* and *Theobroma grandiflorum* Plants

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ABSTRACT

Inoculation of arbuscular mycorrhizal fungi (AMF) has important benefits, not only for plant growth but also for reducing Cd absorption in *Theobroma* plants. This study aimed to investigate the influence of cadmium (Cd) and arbuscular mycorrhizae (AM) on growth and chlorophyll content (CC) in *Theobroma* plants. This experiment had a $3 \times 2 \times 2$ factorial design with species of *Theobroma cacao* and *Theobroma grandiflorum*, AMF inoculation (mycorrhizal control and AMF inoculation), and Cd addition (0, 1, and 3 $mgkg^{-1}$), arranged in a completely randomized design with three repetitions. The AMF inoculum consisted of applying 1500 units to each seedling. The results showed that the Cd content decreased in the stems with AMF treatment for *T. cacao* as well as in the soil, showing significant differences in both variables. However, a reduction of Cd could also be observed in *T. grandiflorum* stems without significant differences with Cd in the soil. The height, diameter, root biomass, and leaf area (LA) of the *Theobroma* plants increased in most of the treatments studied in comparison with treatments that received Cd, as did CC. The AMFs inoculated into *Theobroma* plants induced higher CC in leaves. Likewise, *T. cacao* presented a higher value in morphology and a lower Cd concentration in soil and shoots.

1 | Introduction

Soil contamination by heavy metals (HMs) caused by human activities has become one of the most critical environmental problems of global concern [1]. Cadmium (Cd) is a well-known and widespread HM in agricultural soils; its compounds are among the most hazardous substances indexed in the priority list of the Agency for Toxic Substances and Disease Registry. Moreover, Cd is a toxic HM that represents a threat to crop production and human health [2]. Many studies have investigated the toxicity of HMs in soil or water, as well as their effects on the local environment and plants of commercial interest such as cocoa.

As a recent review by Zhu et al. [3] reported the negative impact of Cd on different physiological behaviors of plants, starting from seed germination and seedling growth, in addition to photosynthesis and antioxidant system. Likewise, Cd directly or indirectly inhibits physiological processes such as respiration, photosynthesis, water movement, and gas exchange, which leads to impairment of plant metabolism [4] and plant chlorophyll synthesis [5]. Woody plants have proven to be an effective means of removing or stabilizing toxic metals from contaminated soils, with their high HM accumulation, perennial trait, high biomass production, and rapid growth [6, 7].

The Amazon rainforest is home to a large number of fruit-bearing woody plants, but many remain unexploited for commercial purposes, a clear example being the species belonging to the genus *Theobroma* [8]. *Theobroma grandiflorum* and *Theobroma bicolor* are recognized as nontimber forest species that thrive predominantly in humid soils, native to the Amazon basin, sharing similarities with *Theobroma cacao* [9]. *Theobroma cacao* is considered a moderate Cd accumulator, as the absorption potential can be conceived as quite high compared to other agricultural crops and more similar to woody species used for phytoextraction, such as willow and poplar [10].

Theobroma grandiflorum (Willd. Ex Spreng.) K. Schum. (Copoazú") belongs to the Malvaceae family. Its seeds can be used to extract vegetable oil and contain organic acids and phenolic and volatile compounds with antioxidant, antiglycemic, and anti-inflammatory properties. Due to these characteristics, *T. grandiflorum* has great potential for technological applications, mainly in food technology, where products and processes are developed based on extracts rich in bioactive compounds, as well as from its pulp or seeds [11]. Copoazú is one of the most important crops in the Peruvian Amazon; its seeds are used as raw material for copoazú chocolate production, in which roasting represents a critical step, as it promotes the development of the characteristic aroma, color, and flavor of chocolate [12].

International regulations require cocoa-derived products to be free of HM such as Cd. Arbuscular mycorrhizae (AM) contribute to reduce the content of HM in the plant, preventing their accumulation in the fruit and facilitating the rhizodeposition of HM through soil proteins related to glomalin [13]. Furthermore, AM fungi are important microbes that promote soil fertility and soil health and increase crop productivity [14]. The diversity of arbuscular mycorrhizal fungi (AMF) associated with cocoa plants could become a potential to immobilize Cd and improve morphological growth [15]; at the same time, the combination with compost has important synergistic benefits in decreasing absorption by cocoa grown in Cd-contaminated soil [16].

Cd contamination in agricultural soils poses a major threat to crop production and food security worldwide. Therefore, analyzing the influence of Cd and AM on growth and chlorophyll content (CC) in *Theobroma cacao* and *Theobroma grandiflorum* plants could be a strategy to reduce Cd accumulation in cocoa beans and is currently limited by the lack of understanding of Cd transfer pathways within different species of the genus *Theobroma*.

2 | Material and Methods

2.1 | Characteristics of the Soil Used in the Study

The agricultural soil used in the experiment came from agricultural fields in the locality of Lamas (San Martin region, Peru). The analytical characteristics of the soil were as follows: total nitrogen (N) 0.55 gkg^{-1}, available phosphorus (P) 3.18 $mgkg^{-1}$, available potassium (K) 18.0 $mgkg^{-1}$, organic matter 10.3 gkg^{-1}, total Cd 0.1 $mgkg^{-1}$, pH 6.75, and electrical conductivity (EC) 0.16 dS/m. For treatments with Cd addition, an aqueous solution of $CdCl_2$ (1 and 3 mgL^{-1}) was used in each pot containing 3 kg of substrate. To help stabilize the contaminant, the Cd-containing soil was allowed to air dry for a total of 2 months and shaken every 15 days for a total of four times.

2.2 | Experimental Procedure

The growth substrate consisted of a mixture of river sand and soil (1:2, p:p), which was sterilized in autoclaving at 120 °C for 2 h. The grains of the two species of the genus *Theobroma* were disinfected with 2% (w/v) sodium hypochlorite, rinsed with sterilized water, and then seeded in sand previously autoclaved at 131 °C for 2 h. After 7 days, the germinated grains were transferred to individual pots (one per pot) filled with 3.0 kg of growth substrate. The experiment was conducted as a pot trial in a greenhouse located at the Universidad Nacional de San Martín (National University of San Martin) in Tarapoto (Peru) in February–May 2024 (Figure 1). During the experiment, the air temperature ranged from 25 to 34 °C.

2.3 | Experimental Design

The experiment for each species of the *Theobroma* genus (*Theobroma cacao*—TC and *Theobroma grandiflorum*—TG) had a

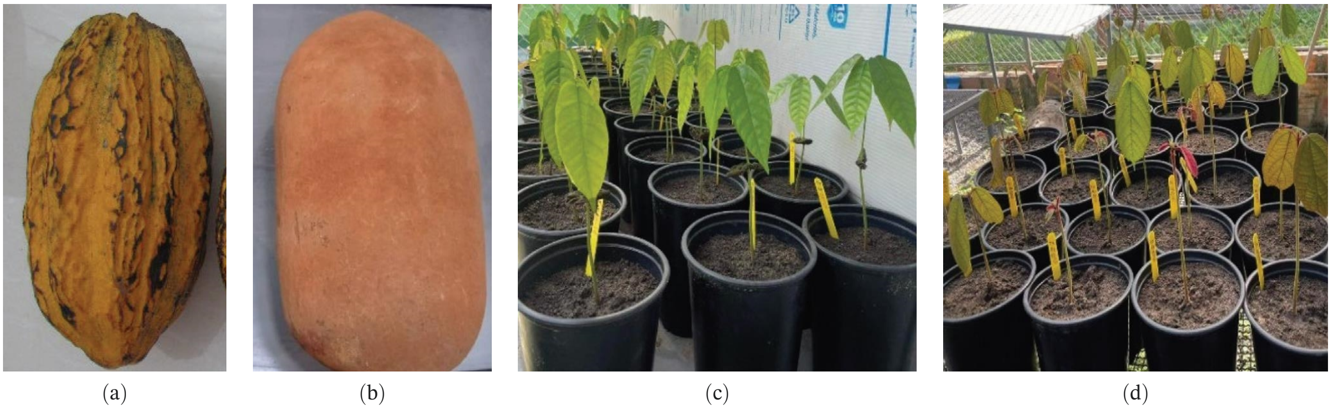

FIGURE 1 | Research process: (a) ripe fruit of *T. cacao*, (b) ripe fruit of *T. grandiflorum*, (b) development of *T. cacao* plants, and (d) development of *T. grandiflorum* plants.

factorial arrangement. Two types of AMF inoculation (mycorrhizal control—MC and inoculation—AMF) and three Cd concentrations (0, 1, and 3 $mg kg^{-1}$) were considered, arranged in a completely randomized design with three repetitions. The AMF inoculum consisted of 1500 AMF spores from the province of Lamas in the San Martin region, Peru, and was composed of a mixture of spores of the following AMF species: *Claroideoglomus* sp., *Acaulospora scrobiculata*, *Rhizoglomus* sp., *Diversispora aurantia, and Microkamienskia* sp. [15]. The following 12 combinations were used in the experimental configuration: TC-MC, TC-MC-1, TC-MC-3, TC-AMF, TC-AMF-1, TC-AMF-3, TG-MC, TG-MC-1, TG-MC-3, TG-AMF, TG-AMF-1, and TG-AMF-3. The response variables were colonization (Col), mycelium length (ML), spore number (SN), cadmium in soil (CdS), cadmium in bud (CdB), plant height (PH), plant diameter (PD), leaf area (LA), dry root biomass (DRB), and CC.

2.4 | Sampling and Measurements

After 3 months, the plants were collected by species (6 treatments × 3 repetitions). The plants, including the root system, were collected and placed in polyethylene bags for transport to the laboratory. There, fine roots were separated from the soil and briefly rinsed and then quickly dried on paper and subjected to morphological analysis. The PH was measured from the base to the highest leaf tip in cm. To determine the LA, all plant leaves were placed on a dark surface and photographed using ASSES software [17]. The chlorophyll concentration was determined using portable nondestructive measuring equipment (Konica Minolta SPAD 502) according to Solis et al. [18]. The roots were dried at 80 °C for 2 days in order to measure the dry weight. Arbuscular mycorrhizal Col was measured by the grid line intersection method after roots were flushed with 10% (w/v) KOH and stained as described by Phillips and Hayman [19]. ML per unit weight of soil was determined using the formula of [20]. Soil samples were collected for chemical analyses (pH, available P, and organic matter) and to determine Cd concentration (EPA 3050B). Stems were cut from each plant sample to quantify Cd concentration (digestion with HNO_3) through atomic absorption spectroscopy [21]. The pH was measured in an aqueous extract (1 : 5) using a pH meter. Available P was estimated according to Olsen's method [22]. The Walkley-Black method [23] was used to determine organic matter.

2.5 | Statistical Analysis

The effects of the factors and their interactions for each species were analyzed by analysis of variance. The Tukey's rank test was used for comparison between treatments ($p < 0.05$). Normality and homoscedasticity of the data were verified by the Shapiro–Wilk and Breush–Pagan tests ($p < 0.05$). Likewise, the response of the two species for the study variables was compared using the *T*-test for independent samples (0.05 < p). Finally, a correlation analysis was performed. The statistical procedures were performed using R Statistical software, version 4.0.2 [24].

3 | Results and Discussion

3.1 | Mycorrhizal Col, Extraradical Mycelium, and Number of Spores in Species of the Genus Theobroma

There were highly significant differences between treatments for the two species under study ($p < 0.05$). The AMF treatments showed the highest percentages of Col, extraradical mycelium, and number of spores. Their values decreased when the AMF were treated with Cd; TC-AMF-3 showed reductions of 23.50% in Col, 75.93% in ML, and 42.33% in SN compared to TC-AMF; meanwhile, TG-AMF-3 exhibited reductions of 37.78% in Col, 106.76% in ML, and 119.81% in SN relative to TG-AMF (Table 1). This response was expressed in both *Theobroma* genera, with *T. grandiflorun* showing greater tolerance to Cd, with higher values for Col, mycelium, and spores with respect to *T. cacao*, registering significant differences for the number of spores in concentrations of 1 $mg kg^{-1}$(Figure 2). High levels of Cd contamination can negatively affect AMF spore germination, extraradical

TABLE 1 | Analysis of mycorrhization in species of the genus *Theobroma* inoculated with cadmium.

Treatments	Col (%)	ML (cm)	SN
TC-AMF	68.00 ± 3.00a	4.75 ± 0.78a	309.33 ± 5.77a
TC-AMF-1	66.33 ± 5.51a	4.67 ± 0.48a	234.00 ± 27.78b
TC-AMF-3	55.33 ± 2.08b	2.70 ± 0.61b	217.33 ± 42.25b
CV	6.03	15.66	11.59
Sig.	*	*	*
TG-AMF	82.67 ± 4.73a	7.03 ± 1.95a	536.33 ± 67.99a
TG-AMF-1	70.67 ± 5.69a,b	4.95 ± 0.9a,b	296.00 ± 26.46 b
TG-AMF-3	60.00 ± 4.58b	3.40 ± 0.79b	244.00 ± 88.27b
CV	7.06	25.79	18.43
Sig	**	*	**

Note: Different letters present significant differences using the Tukey test ($p < 0.05$). SN, number of spores.
Abbreviations: Col, colonization; ML, mycelium length.
*: $p < 0.05$.
**: $p < 0.01$.

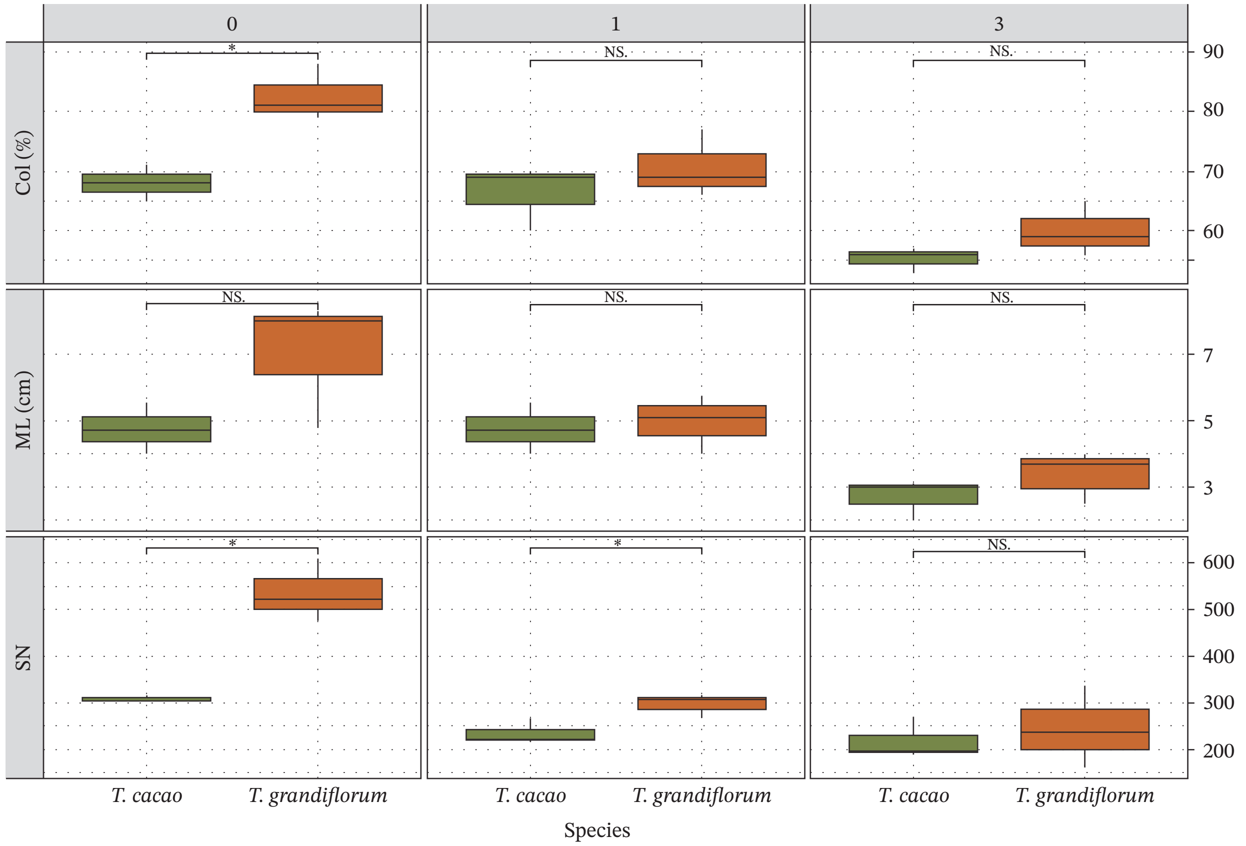

FIGURE 2 | Effect of mycorrhization on species of the genus *Theobroma* inoculated with cadmium. *: $p < 0.05$; NS: $p > 0.05$. Comparison of means using the *T*-test ($p < 0.05$).

TABLE 2 | Cadmium analysis in species of the genus *Theobroma*.

Treatments	CdS (mg kg^{-1})	CdB (mg kg^{-1})
TC-MC-1	0.42 ± 0.03a	0.63 ± 0.12b
TC-MC-3	0.45 ± 0.05a	1.13 ± 0.15a
TC- AMF-1	0.40 ± 0.01a	0.50 ± 0.20b
TC- AMF-3	0.43 ± 0.03a	0.86 ± 0.20a,b
CV	7.59	21.98
Sig	NS	**
TG-MC -1	0.55 ± 0.09a,b	0.85 ± 0.35b
TG-MC -3	0.67 ± 0.06a	1.85 ± 0.15a
TG-AMF -1	0.42 ± 0.03b	0.89 ± 0.10b
TG-AMF -3	0.53 ± 0.12a,b	1.06 ± 0.12b
CV	7.59	4.61
Sig	*	***

Note: NS: $p > 0.05$. Different letters present significant differences using the Tukey test ($p < 0.05$).
Abbreviations: CdB, cadmium in bud; CdS, cadmium in soils.
*: $p < 0.05$.
**: $p < 0.01$.
***: $p < 0.001$.

mycelial growth, and mycorrhizal Col [25]. HMs inhibit AMF spore germination and hyphal propagation, and, under controlled conditions, these contaminants have been found to reduce or suppress plant root growth and AMF Col [26]. In cocoa soils, naturally rich in Cd, Sandoval-Pineda et al. [27] found less abundance, richness, and diversity of AMF than in soils with low Cd levels. Therefore, high concentrations and availability of Cd generate a continuous stress on the AMF community, affecting mycorrhizal variables both Col and extraradical mycelium [16]. The addition of AMF (TC-AMF and TG-AMF) showed the best results in Col, mycelium, and the number of spores (Table 1).

3.2 | Effects of Cd on Species of the Genus Theobroma

The Cd content decreased in the stems with the AMF treatment for *T. grandiflorum*, as well as in the soil, showing significant differences in both variables as can be seen when comparing the treatments TG-MC-3 and TG-AMF-3 (Table 2 and Figure 3). A reduction of Cd was observed in the stems of *T. cacao* with the AMF treatment, with significant differences (TC-MC-3 vs. TC-AMF-3); however, soil Cd did not show significant differences; TC-AMF-3 displayed reductions of 4.65% in CdS and 31.40% CdB compared with TC-MC-3; whereas TG-AMF-3 showed reductions of 26.42% CdS and 74.53% CdB relative to TG-MC-3 (Table 2). The species of *T. grandiflorum* presented the highest levels of cd in the soil and shoots both in soil with and without mycorrhizae, with significant differences between the two species for the treatments (MC-3 of the soil and shoot and AMF-1 of the Borte, Figure 2). AMF inoculation can reduce the transfer of HMs to plants by acting as an exclusion barrier [15, 28] and by binding HMs to fungal structures such as hyphae [29]. The

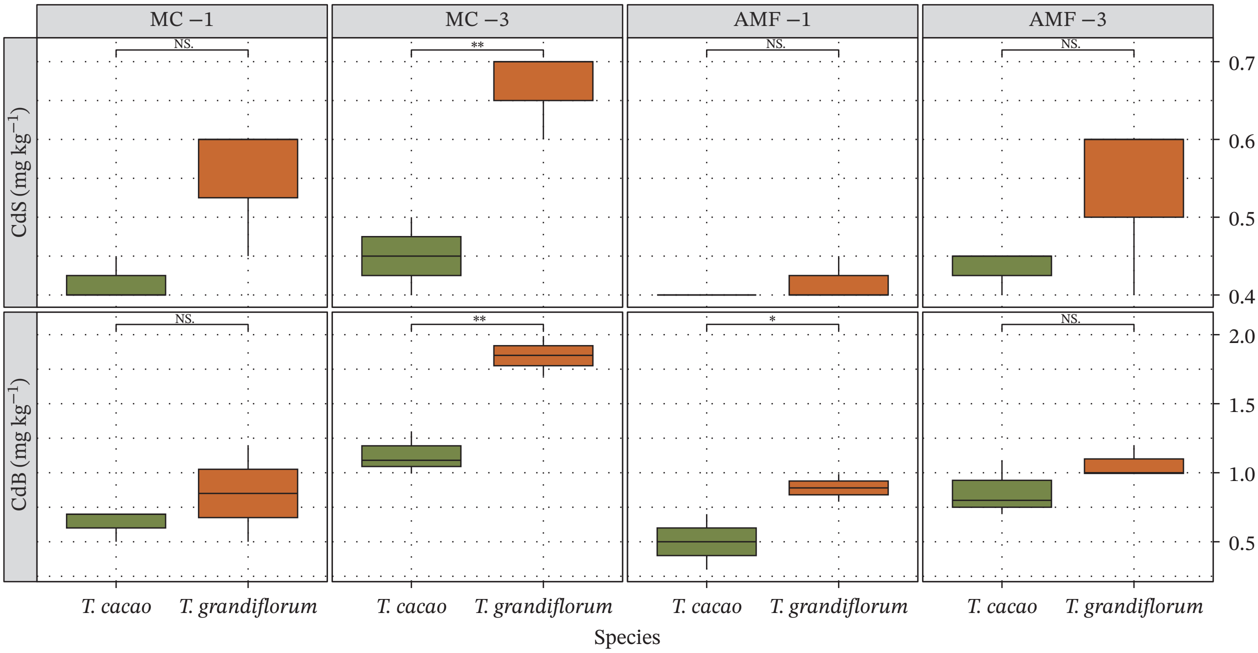

FIGURE 3 | Effect of mycorrhization on cadmium concentrations in the soil and shoots of species of the genus *Theobroma*. *: $p < 0.05$; **: $p < 0.01$, NS: $p > 0.05$. Comparison of means using the *T*-test ($p < 0.05$).

influence of AMF on metal absorption by plants varies with plant growth conditions, the associated fungus, metal concentrations, and soil pH [29]. By immobilizing metals on fungal structures, the AMFs have an impact on soil structure and Cd leaching [29]. In addition, it has been shown that the AMFs can decrease Cd concentration in plants by increasing their biomass, which can lead to dilution of the metal in the host plant [30]. In addition, that inoculation of plants with AMF protects host plants against biotic stressors [17].

On the other hand, numerous studies have indicated that the positive effects of AMF on plants under HM stress could be attributable, directly or indirectly, to improvements in the absorption of mineral nutrients, especially P, by plants [31]. This could be due to the formation of an extensive extraradical hyphal network that allows for enhanced P absorption [16]. Therefore, our results corroborate the beneficial effects of AMF in alleviating the stress suffered by plants of the genus *Theobroma* by translocating HMs such as Cd.

3.3 | Effect of Treatments on Morphological Variables in Species of the Genus Theobroma

The height, diameter, root biomass, and LA of *T. cacao* and *T. grandiflorum* plants were greater in most of the treatments studied that presented mycorrhizal fungi compared to the treatments that only received Cd; TC-AMF-3 showed increases of 0.87% in PH, 51.06% in PD, 60.33% in LA, and 20.45% in DRB compared with TC-MC-3; whereas TG-AMF-3 exhibited increases of 11.91% in PH, 52.27% in PD, 74.61% in LA, and 2.33% in DRB relative to TG-MC-3 (Table 3). Treatments TC-AMF and TG-AMF showed differences with treatments that received Cd (TC- AMF-1, TC-AMF-3, TG-AMF-1, and TG- AMF-3). Plant parameters were positively influenced by AMF, whereas they were negatively affected by Cd toxicity (Figure 4). AMF inoculation promotes host plant growth [32]. It can also positively influence plant growth and physiology [18] while reducing HM stress by enhancing nutrient and water absorption, osmotic adjustment, and photosynthetic and antioxidant activity [33, 34]. In agreement with our results, Zhang et al. [35] observed that the presence of AMF facilitated the growth of *Medicago sativa* plants by increasing plant biomass and retaining Cd in the soil–plant system. Together with our results, these studies evidenced that the AMFs play an important role in improving plant performance and tolerance in Cd-contaminated soils [30, 36, 37].

The AMF inoculation can reduce the transfer of HMs to plants by acting as an exclusion barrier [28] and by binding HMs to fungal structures such as hyphae [26, 38]. The influence of AMF on metal absorption by plants varies with plant growth conditions, the associated fungus, metal concentrations, and soil pH [28]. By immobilizing metals in fungal structures, the AMFs have an impact on soil structure and Cd leaching [29].

In addition, it has been shown that the AMFs can decrease the concentration of Cd in plants by increasing their biomass, which can lead to dilution of the metal in the host plant [30]. On the other hand, numerous studies have indicated that the positive effects of the AMFs on plants under HM stress could be attributable, directly or indirectly, to improvements in the absorption of mineral nutrients, especially P, by plants [31, 38]. This could be due to the formation of an extensive extraradical hyphal network that allows for enhanced P absorption [39]. Therefore, our results corroborate the beneficial effects of the AMFs in alleviating plant stress by translocating HMs such as Cd.

3.4 | Effect of Treatments on CC in Species of the Genus Theobroma

The CC was influenced by the inoculated AMF and the Cd levels in which *Theobroma* plants developed, this being the factor that showed significant differences in both *T. cacao* and

TABLE 3 | Morphology analysis of the *Theobroma* genus inoculated with cadmium.

Treatments	PH (cm)	PD (cm)	LA (cm^2)	DRB (g)
TC-MC	31.47 ± 1.69b	0.75 ± 0.05a,b	1539.98 ± 159.77a,b	7.27 ± 0.40a
TC-MC-1	28.95 ± 1.19b	0.57 ± 0.06b,c	1210.55 ± 166.4a,b	3.73 ± 0.49b
TC-MC-3	25.21 ± 3.24b	0.47 ± 0.12 c	877.86 ± 271.82 b	3.57 ± 0.06b
TC-AMF	42.89 ± 3.47a	0.94 ± 0.02a	1840.01 ± 384.63a	8.00 ± 0.75a
TC-AMF-1	28.76 ± 0.41b	0.78 ± 0.11a,b	1487.48 ± 127.33a,b	4.47 ± 0.60b
TC-AMF-3	25.43 ± 3.38b	0.71 ± 0.09 b	1407.43 ± 340.74a,b	4.3 ± 0.46b
CV	8.31	11.74	18.69	9.74
Sig.	***	***	*	***
TG-MC	27.38 ± 1.57a,b	0.64 ± 0.06b,c	873.53 ± 67.78a,b,c	3.73 ± 0.35a
TG-MC-1	23.93 ± 3.27b,c	0.60 ± 0.01b,c	621.92 ± 69.83c,d	2.20 ± 0.46c
TG-MC-3	20.91 ± 1.85c	0.44 ± 0.14c	431.20 ± 105.12d	2.57 ± 0.25c
TG-AMF	31.10 ± 2.04a	0.91 ± 0.04a	1069.97 ± 161.92a	3.93 ± 0.15a
TG-AMF-1	24.95 ± 0.91b,c	0.74 ± 0.12a,b	967.62 ± 79.84a,b	3.70 ± 0.26a,b
TG-AMF-3	23.40 ± 2.3b,c	0.67 ± 0.1a,b,c	752.93 ± 29.52b,c	2.63 ± 0.67b,c
CV	8.37	13.48	12.06	12.61
Sig.	***	***	***	***

Note: Different letters present significant differences using the Tukey test ($p < 0.05$).
Abbreviations: DRB, dry root biomass; LA, leaf area; PD, plant diameter; PH, plant height.
*: $p < 0.05$.
***: $p < 0.001$.

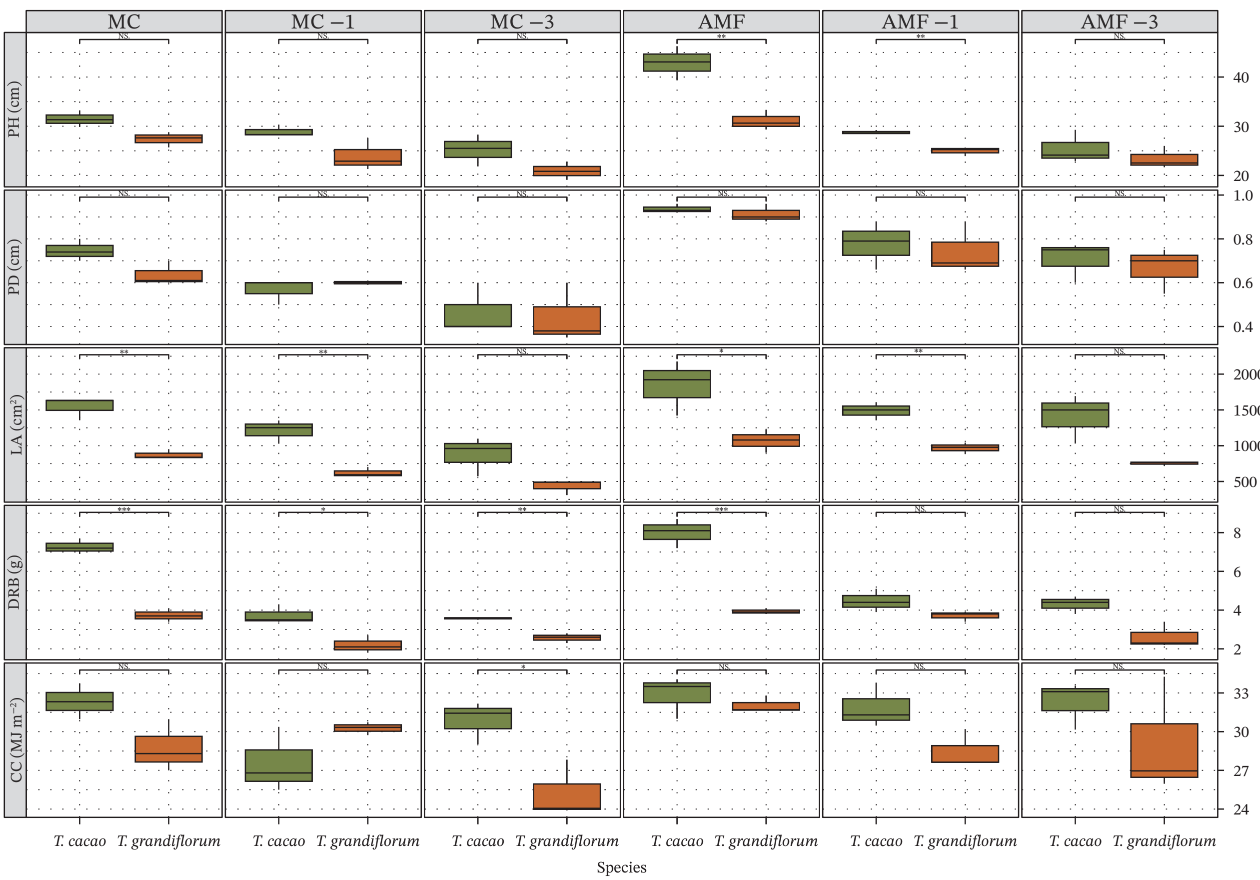

FIGURE 4 | Morphological analysis and chlorophyll content of the genus *Theobroma* inoculated with cadmium. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; NS: $p > 0.05$. Comparison of means using the *T*-test ($p < 0.05$).

TABLE 4 | Analysis of chlorophyll content in species of the genus *Theobroma* inoculated with cadmium.

Treatments	CC ($MJ\ m^{-2}$)
TC-MC	32.35 ± 1.39a,b
TC-MC-1	27.56 ± 2.52b
TC-MC-3	30.88 ± 1.64a,b
TC-AMF	32.85 ± 1.63a
TC-AMF-1	31.86 ± 1.73a,b
TC-AMF-3	32.27 ± 1.84a,b
CV	5.84
Sig.	*
TG-MC	28.76 ± 2.02a,b
TG-MC-1	30.26 ± 0.5a,b
TG-MC-3	25.26 ± 2.22 b
TG-AMF	32.04 ± 0.66a
TG-AMF-1	28.49 ± 1.48a,b
TG-AMF-3	29.06 ± 4.53a,b
CV	8.03
Sig.	*

Note: Different letters present significant differences using the Tukey test ($p < 0.05$).
Abbreviation: CC, chlorophyll content.
*: $p < 0.05$.

T. grandiflorum; TC-AMF-3 showed an increase of 4.50% in CC compared with TC-MC-3, whereas TG-AMF-3 exhibited an increase of 15.04% in CC relative to TG-MC-3 (Table 4). At the species level, significant differences were only reported in the MC-3 treatment, where *T. cacao* presented greater LA (Figure 4). Solis et al. [18] reported that coffee plants inoculated with AMF can positively influence plant physiology, while Vafadar et al. [40] suggested that higher CC influences the photosynthetic capacity of *Stevia rebaudiana*. Besides, in coffee plants, AMF inoculation increases photosynthetic rate and stomatal conductance [37]. These reports, complemented with the results of the present study, allow inferring that the increase of CC in *Theobroma* leaves due to AMF inoculation is related to a higher photosynthetic rate, positively affecting the physiology of *cocoa* and *grandiflorum* plants. In terms of relative CC, *Handroanthus serratifolius* (Vahl) plants treated with AMF had a chlorophyll index between 13 and 15, which was ~50% higher than the control [40]. Likewise, the addition of compost + AMF to Cd-contaminated *Oryza sativa* plants resulted in significant increases in PH, bud and root biomass, and CC [41], while AMF inoculation also increased the CC of *Zea mays* leaves under hydric stress [42].

3.5 | Analysis of the Relationship Among Hma, Cd, Morphological Parameters, and Chlorophyll

The correlation analysis showed that the higher the Col, ML, and number of spores, the more developed the plants were for both species. In the case of *Theobroma cacao*, the highest associations were between PD and SN with coefficients of 0.76 (Figure 5a). Regarding *Theobroma grandiflorum*, the greatest association was between PD with ML and Col, presenting coefficients of 0.78. It is also evident that when there were higher concentrations of Cd in the soil and buds, the plants showed less development for both species (Figure 5b). In accordance with our results, the presence of AMF facilitated the plant growth of *Medicago sativa* by increasing plant biomass and retaining the Cd in the soil–plant system [35, 46]. Therefore, the growth of Theobroma plants was significantly reduced with increasing Cd concentration, which agrees with what was indicated by Hassan et al. [43].

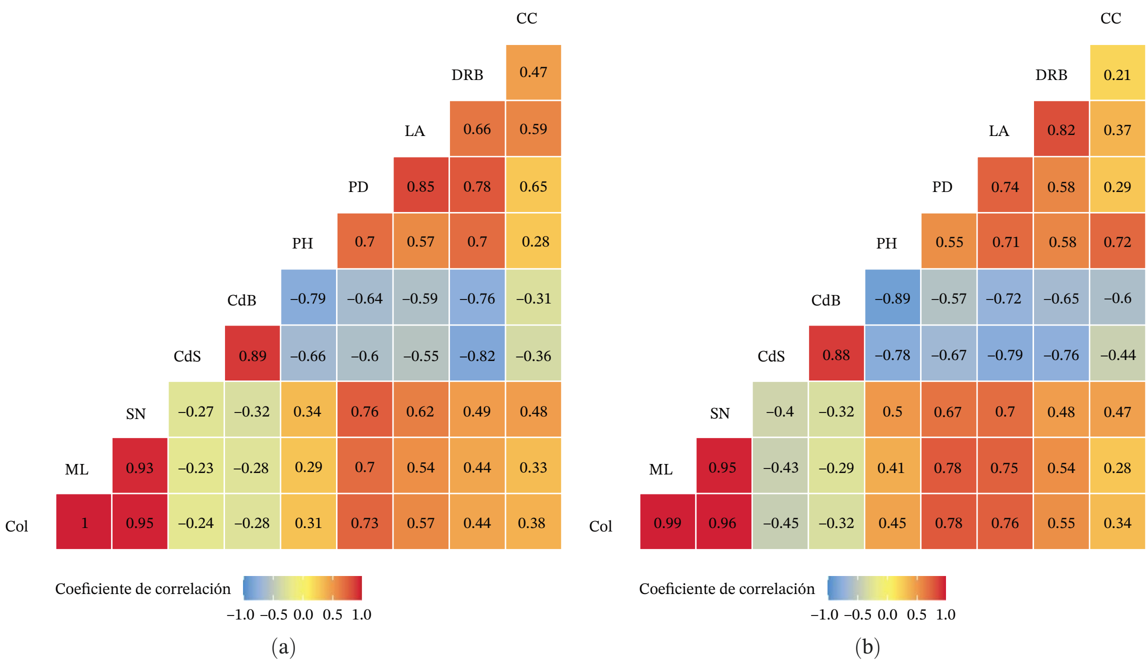

FIGURE 5 | Association among response variables of species of the genus *Theobroma* inoculated with cadmium. (a) *Theobroma cacao* and (b) *Theobroma grandiflorum*.

Coffee and cacao are high-value agricultural crops with strong productive potential in the Peruvian Amazon and are commonly associated with agroforestry systems that host a wide diversity of AMF [44, 45]. Therefore, AMF significantly increase glomalin content and the proportion of soil macroaggregates in Cd-contaminated soils [29]. However, inappropriate management practices focused on monoculture systems with a single host species may negatively affect local biodiversity. To fully understand the native biodiversity of AMF in *Theobroma* crops, we recommend further studies on their mycorrhizal potential for promoting plant growth and Cd immobilization in *Theobroma* plantations across the Peruvian Amazon. Such research could lead to evidence-based policy recommendations aimed at conserving soil microfauna and, consequently, reducing Cd presence in tropical soils.

4 | Conclusions

The AMF treatments showed the highest percentages of Col, extraradical mycelium, and number of spores; nevertheless, their values decreased when the AMFs were treated with Cd. *T. grandiflorun* fue el que absorbed mayor greater content of Cd, observing higher values in Col, mycelium, and spores with respect to *T. cacao*. Also, the height, diameter, root biomass, and LA of *T. cacao* and *T. grandiflorum* plants increased in most of the treatments studied compared to treatments that received Cd. The TC- MF and TG-MF treatments showed differences with the treatments that received Cd (TC- MF-1, TC- MF-3, TG-AMF-1, and TG-AMF-3). The CC was influenced by the AMFs inoculated in *Theobroma* plants, being this the factor that showed significant differences in both *T. cacao* and *T. grandiflorum*. Therefore, the AMFs inoculated into *Theobroma* plants induced higher CC in leaves, compared to plants that were not inoculated with AMF. At the same time, *T. cacao* presented higher value in morphology and lower cd concentration in soil and shoots. These results revealed that AMF played a functional role in reducing Cd concentration, positively influencing the growth and development of cacao plants. Therefore, these findings highlight AMF as a viable alternative to promote cadmium absorption in cacao plants, representing a sustainable strategy that contributes to food security and soil health in the Peruvian Amazon.

Author Contributions

Geomar Vallejos-Torres: writing – review and editing, conceptualization, methodology, validation, funding acquisition. **Noelia García-Vallejos:** formal analysis, investigation, data curation. **Nery Gaona-Jimenez:** methodology, validation. **Andi Lozano**: writing – original draft preparation. **Carlos M. Lozano-Carranza:** writing – review and editing. **Alberto Alva Arévalo:** conceptualization, validation. **Víctor Humberto Puicón Niño de Guzmán**: investigation, data curation. **Jorge Saavedra-Ramírez:** visualization, writing. **Juan C. Tuesta-Hidalgo:** formal analysis, data curation. **Oscar A. Tuesta-Hidalgo:** visualization, data curation. **Manuel Jesús Valdez-Andía**: writing – original draft preparation. **Karina M. Ordoñez-Ruiz:** conceptualization, formal analysis. **Juan R. Baselly-Villanueva:** conceptualization, validation.

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Disclosure

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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