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Maize grown in soil contaminated by mining tailings shows reduced growth and yield

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ABSTRACT. The 2015 Samarco dam collapse in Mariana, Brazil, resulted in the widespread deposition of mining tailings across agricultural lands in the Rio Doce Basin. This study was carried out in the municipality of Rio Casca, where a single maize variety was cultivated simultaneously in two comparable areas: one contaminated by mining tailings and one uncontaminated control area. Plants were of the same age and grown under similar climatic conditions, minimizing environmental variation. Soil and plant samples were analysed for physical and chemical properties, including nutrient and heavy metal content. The contaminated area showed reduced base saturation, lower effective cation exchange capacity, higher concentrations of Na, Fe, and Cu, and lower Mg concentration. Maize grown in contaminated soil exhibited reduced nitrogen balance index and chlorophyll content, thinner and broader leaves. Significant reductions in plant height, stem diameter, and overall biomass were also recorded for plants grown in the area exposed to mining tailings. Grain analysis further confirmed the negative effects of the mining tailings, with reductions in essential nutrients, like Ca, Mg, and N, and an increase in Na content, which can impair water uptake and cause ion toxicity. These findings show that maize grown in soil contaminated by mining tailings accumulates nutrients differently in leaves, roots, and grains, and has lower chlorophyll content, growth, and yield. Despite identical fertilization and climatic conditions, the lower fertility and altered composition of the contaminated soil limited crop performance. These results underscore the lasting impact of tailings on soil function and maize productivity, reinforcing the need for targeted management in affected areas of the Rio Doce Basin.

Keywords: dam breach; environmental impact; heavy metals; maize productivity; Samarco mining disaster.

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Introduction

Mining is essential to economic development, yet it frequently results in severe environmental impacts. One of the most critical issues is the production of tailings, which can contaminate soils and water bodies. The breach of Samarco's Fundão dam in Mariana, Brazil, in 2015, serves as a clear example of this problem. This event released approximately 43.8 million cubic meters of mining tailings, which swept across extensive agricultural areas and eventually reached the Atlantic Ocean (Marta-Almeida et al., 2016). The original riverbank soil along the Rio Doce was overlain by an irregular, poorly structured layer of mining tailings whose variable thickness increased bulk density and, consequently, reduced porosity, permeability, and the soil's capacity to store and supply water and nutrients (Guerra et al., 2017). Furthermore, the affected soil, already deficient in organic matter, exhibits elevated concentrations of metals such as Fe and Mn from the tailing mass, which impair not only agricultural productivity but also compromise water quality (Guerra et al., 2017; AECOM, 2020; Araújo et al., 2022). Hence, these environmental changes may have compromised the sustainability of economic activities and the food security of local communities along the entire impacted stretch of the river, which is approximately 668 km (Fernandes et al., 2016; Carmo et al., 2017).

Some plant species are able to absorb heavy metals from the environment, accumulating them in their edible parts. This substantial accumulation of elements in plants represents a critical entry point into the food chain, with the potential to affect the broader food web and human health (Zhou et al., 2016; Gupta et al., 2022; Araujo et al., 2022). Studies have shown that arugula and radishes grown in Samarco mining tailings displayed high concentrations of essential elements such as iron (Fe), manganese (Mn), and sodium (Na) (Almeida et al., 2022). However, the concentrations reported were still below the maximum permissible limits for human consumption (Almeida et al., 2022). Furthermore, a comprehensive study assessed the risks associated with consuming agricultural products grown in areas impacted by tailings from Samarco's dam (AECOM, 2020). The analysis highlighted the potential dangers of ingesting contaminants across various food groups, including fruits, vegetables, grains, milk, eggs, meats, and offal produced in the affected area (AECOM, 2020). Notably, bananas and oranges exhibited high concentrations of lead (Pb), potassium (K), Mn, and magnesium (Mg), while beans exceeded safe limits for barium (Ba), copper (Cu), zinc (Zn), nickel (Ni), Mn, and Mg (AECOM, 2020). Milk, whether from cows or goats, contained high concentrations of arsenic (As), Pb, chromium (Cr), and Mg, elements that are potentially harmful at elevated levels (AECOM, 2020). Root vegetables and tubers, such as sweet potatoes and cassava, also recorded significant concentrations of Cr and Pb, indicating serious contamination (AECOM, 2020). These risks are particularly concerning for children and adolescents, who consume these products in greater proportion (AECOM, 2020). Interestingly, many of these elements were also found in products from neighboring areas not directly affected by the tailings, suggesting a broader, historical contamination across the basin (AECOM, 2020). These impacts are not limited to agriculture and human health, but also promote profound changes in the structure and diversity of native plant communities in the forest remnants of the Rio Doce basin (Fernandes et al., 2025).

The bioaccumulation of heavy metals in terrestrial ecosystems, particularly through local food chains, is an escalating concern for both environmental and human health (Wang et al., 2014). Recent studies, such as those by Coelho et al. (2020), have shown that both the roots and leaves of *Brachiaria decumbens* collected from areas affected by Samarco's dam breach exhibited elevated Fe concentrations. Similarly, the forage species *Stylosanthes guianensis*, used as cattle feed, showed increased Fe levels throughout its tissues, while *Saccharum officinarum* accumulated high concentrations of Mn in the stems and Cu in both leaves and stems (Coelho et al., 2020). This represents a risk to humans via the consumption of contaminated meat and dairy products. Indeed, high concentrations of aluminum (Al), arsenic (As), mercury (Hg), and nickel (Ni) have been detected in the blood of individuals living in these contaminated areas (Vormittag et al., 2021; Cavalheiro Paulelli et al., 2022). Consequently, the development of effective risk management strategies and ongoing monitoring of food quality in areas affected by mining tailings are essential to safeguard local communities and downstream consumers.

Attention has typically focused on the contamination of food sources by mining tailings; however, the impacts on agricultural productivity are equally critical but have received less consideration. Mining tailings can affect plant morphology and compromise photosynthetic performance, as reflected in reduced pigment content, CO_2 assimilation, and the maximum quantum yield of photosystem II (Esteves et al., 2020; Almeida et al., 2022; da Silva et al., 2022). These changes result in serious consequences for plant growth (Ashraf et al., 2011; Singh et al., 2016). For instance, the high concentrations of Fe and Mn found in the tailings from the disaster region are linked to physiological alterations that impair the performance of various species, ultimately hindering ecosystem recovery in impacted areas (Cruz et al., 2020; Araujo et al., 2022; da Silva et al., 2022; Freitas et al., 2023). In native species, these alterations include reductions in plant height, leaf area, biomass accumulation, and chlorophyll content, even under adequate macronutrient conditions (Cruz et al., 2022). Furthermore, disruptions in photosynthetic parameters, such as the quantum yield of photosystem I, along with micronutrient imbalances—particularly toxic levels of boron and arsenic—have been shown to impair reproductive processes, notably reducing pollen viability (Gudin et al., 2024). Together, these physiological disruptions highlight the multifaceted impact of tailings on both vegetative development and reproductive success, underscoring the need for further investigation into how these changes affect agricultural species cultivated in contaminated soils.

The goal of this study was to assess the productivity and elemental composition of maize grown on soils impacted by the deposition of mining tailings from Samarco's dam rupture, six years after the disaster. As a staple food and a major component of animal feed, maize is integral to local livelihoods and the broader agricultural economy. Its widespread cultivation across the Rio Doce basin (field observations) makes it a representative crop for evaluating the agricultural consequences of soil contamination. Specifically, we aimed to address the following questions: 1) Does the soil in the area contaminated by Samarco's tailings exhibit significant alterations in chemical and physical properties, such as nutrient availability, pH, cation exchange capacity, and texture, compared to uncontaminated soil, potentially affecting its suitability for agriculture?

2) Does maize growth with its root system immersed in the tailings deposit layer lead to changes in productivity and the occurrence of plant nutritional disorders, as reflected by alterations in physiological indicators such as the Nitrogen Balance Index (NBI), chlorophyll content, specific leaf area (SLA), and flavonoid index? We hypothesized that soil contamination alters the availability of essential nutrients and their uptake by plants, resulting in reduced chlorophyll content and NBI. These physiological shifts reflect stress and nutritional imbalance, which are expected to negatively affect plant development and biomass accumulation. Furthermore, we hypothesized that maize grains produced under contaminated conditions would accumulate macro- and micronutrients in altered proportions, mirroring disruptions in nutrient availability and plant uptake dynamics due to the altered soil conditions.

Material and methods

Study area and plant species

The study was conducted in two areas with maize (*Zea mays* L.) plantations: one in a contaminated area heavily impacted by mining tailings, and one in an uncontaminated control area in the municipality of Rio Casca, Minas Gerais, Brazil, located within the Rio Doce basin. Throughout this study, these areas will be referred to as 'impacted' and 'control', respectively. The site contaminated by mining tailings is located just 5 m from the Doce riverbank (20°5'51.3"S; 42°45'29.5"W) and has been directly exposed to the tailings from Samarco's dam rupture (Figure S1a, see supplementary material available at https://doi.org/10.5281/zenodo.16921240). In contrast, the control site is located 1,250 meters away (20°5'53.9"S; 42°44'54.9"W), providing a comparative baseline for evaluating the environmental impact of the contamination. This region predominantly features agricultural land uses, with approximately 78.96% of the area devoted to farming activities (including both pasture and crops) and 18.57% covered by forest remnants (Ramos et al., 2024). The area's climate is classified under the Köppen system as subtropical with dry winters and hot summers (Cwa) and tropical with dry winters and rainy summers (Figure S1; Alvares et al., 2013).

To assess the impact of soil changes on agricultural productivity, we randomly selected and marked 20 plants in each area (impacted and control), ensuring a minimum distance of ten meters between each plant. Both plantations consisted of the LG 6036 maize variety (Limagrain). At the time of data collection, the maize plants were approximately 90 days post-planting. Most of the sampled plants had uniformly developed ears, with kernels in the R6 stage, characterized by a hard, yellow texture indicative of physiological maturity (Figure S2).

Physical-chemical analysis of soils

Soil samples were collected from five points in each area (impacted and control). The five samples from each area were combined to form a composite sample, from which physicochemical attributes were analysed in three replicates per area. All physical and chemical analyses were performed according to the official procedures and quality standards recommended by the Brazilian Agricultural Research Corporation (EMBRAPA), the national reference for soil analysis in Brazil. For physical parameters, we analysed the content of total sand, coarse and fine sand (kg kg^{-1}) was analysed using the sieving method, while the particle density (g cm^{-3}) was analysed using the volumetric flask method. Additionally, the content of silt (kg kg^{-1}) and clay (kg kg^{-1}) were analysed using the slow agitation pipette method. We extracted the contents of Fe, Zn, Mn, Cu, cadmium (Cd), Pb, Ni, and Cr using a 0.05 mol L^{-1} HCl solution and a 0.025 mol L^{-1} H_2SO_4 solution (Mehlich^{-1}). Phosphorus (P) was extracted with 0.05 mol L^{-1} HCl and 0.025 mol L^{-1} H_2SO_4 (Mehlich^{-1}) and determined by colorimetry in the presence of ascorbic acid; K was extracted with 0.05 mol L^{-1} HCl at a ratio of 1:10 and measured by flame photometry; calcium (Ca) and Mg were extracted with 1 mol L^{-1} KCl in the proportion 1:20 and measured by atomic absorption. Additionally, Al concentration was determined by titration with 0.025 mol L^{-1} NaOH. The pH was determined by the H_2O method (1:2.5) and exchangeable acidity (H+Al) by 0.5 mol L^{-1} calcium acetate at pH 7.0. We calculated the exchangeable bases (sum of Ca, Mg, Na, and K) in $cmol_c$ dm^{-3} and the cation exchange capacity (T) at pH 7.0 by adding the exchangeable bases to the exchangeable acidity (H+Al). Furthermore, we determined the base saturation (V), aluminum saturation (m), and effective cation exchange capacity (t), which is the sum of the exchangeable bases plus exchangeable Al^{+3}.

Nitrogen Balance Index (NBI), chlorophyll content, flavonoids index, plant development and biomass assessment

To evaluate the impact of mining tailings on the physiology of maize we assessed the NBI, chlorophyll content, flavonoid index and SLA of each of the 20 individuals per treatment. We, non-destructively, measured the NBI along with chlorophyll content and flavonoid index using the Dualex® 4.5 Scientific meter. For each of these measurements, we sampled four leaves per plant across 20 individuals for each treatment. Measurements were taken on both the left and right sides of the midrib on the adaxial leaf surface. The NBI was calculated as the ratio of chlorophyll to flavonoid index, which reflects the carbon/nitrogen ratio in the leaves (Perea et al., 2021; Maia et al., 2023). The Dualex device provides chlorophyll readings in μg cm^{-2}, while flavonoids are expressed as relative, unitless indices based on epidermal absorbance.

To assess plant development, we measured plant height (cm) and stem diameter (measured 10 cm above the soil surface). As indicators of productivity, we also recorded the number of maize ears per plant. To determine total biomass, each plant was carefully uprooted and thoroughly washed to remove all soil residues. Plants were then separated into their main components—ears, husks, leaves, stems, and roots—which were dried in a forced-air oven at 60 °C until constant mass was achieved. All parts were individually weighed using an analytical balance with 0.001 g precision. The total biomass of each plant was calculated as the sum of the dry weights of all components.

Productivity and nutritional analysis

To assess the impact of mining tailings on maize productivity, we measured several parameters: number of ears, ear length (cm), number of grains per ear, total grain weight (g), and average grain weight (g) (20 individuals per treatment). To evaluate the nutrient composition of the plants, we compared the macro- and micronutrient contents in the grains, leaves, and roots of plants grown in contaminated and uncontaminated areas (10 randomly selected individuals per treatment). For all three plant organs, we extracted Ca and Mg using a 1 mol L^{-1} KCl solution in a 1:20 ratio, and measured these elements by atomic absorption spectroscopy. Sodium (Na) and P were extracted using a 0.05 mol L^{-1} HCl and 0.025 mol L^{-1} H_2SO_4 solution (Mehlich^{-1}) and determined by colorimetry in the presence of ascorbic acid. Potassium (K) was extracted with 0.05 mol L^{-1} HCl at a ratio of 1:10 and measured by flame photometry. Nitrogen (N) concentration was determined following acidic digestion, diffusion, and titration of NH_3 with 0.01 N H_2SO_4. Additionally, Al concentration was determined by titration with 0.025 mol L^{-1} NaOH. We also extracted and quantified Zn, Cu, Fe, Mn, Ni, Co, Cd, Pb, and Cr using a 0.05 mol L^{-1} HCl and 0.025 mol L^{-1} H_2SO_4 solution (Mehlich^{-1}).

Data analysis

To compare quantitative variables between the impacted and control areas, we used statistical tests selected according to data distribution. The Student's t-test for independent samples was employed for normally distributed data, while the Mann-Whitney U test was applied for data that did not follow a normal distribution. We used the Spearman correlation test to examine relationships between developmental parameters and leaf nutrient composition. Correlation matrices were generated for each treatment, and correlograms were created to visually represent these relationships using the *ggcorrplot* package. Differences were considered significant at $P \leqslant 0.05$. All analyses and visualizations were performed using R software.

Results

No significant differences were found in the concentrations of key soil macronutrients such as P, K, and Ca between the impacted and control areas ($P > 0.05$; see Table 1). However, Mg concentration was approximately 4.7 times lower in the impacted than in the control areas ($P < 0.05$). Additionally, Na concentration and sodium saturation (n%) were twice as high in the impacted area compared to the control area ($P < 0.05$). Among the soil micronutrients, Fe and Cu were present at significantly higher concentrations in the impacted area, approximately 4.5 and 2.25 times higher, respectively, compared to the control area ($P < 0.05$; Table 1). In contrast, Mn and Zn concentrations did not differ significantly between the areas ($P > 0.05$). Notably, Ni was not detected in any samples from either area, suggesting concentrations below the detection limit of the analytical method or low availability in the soils studied. In addition, there were no differences in Al, exchangeable acidity (H+Al), aluminum saturation (m%), or total cation exchange capacity ($P > 0.05$) between the areas studied. However, S and base saturation percentage (V%) were 1.5 times lower in the impacted area compared to the control area (*P* < 0.05). The effective cation exchange capacity (t) was significantly higher in the control area than in the impacted area (*P* < 0.05). Physical characterization of the soils revealed that the impacted area contained higher concentrations of clay and silt, but lower amounts of coarse and fine sand, and a lower Flocculation Index compared to the control area (*P* < 0.05; Table 1). Taken together, these results demonstrate that the control area has more favorable soil nutritional and physical properties compared to the impacted area.

Table 1. Soil chemical and physical parameters in an area contaminated by mining tailings (impacted) resulting from Samarco's dam rupture in Mariana, and an uncontaminated area (control), Rio Casca, Minas Gerais, Brazil.

Soil parameters	Impacted			Control			*t*	W	p-value	test
pH H_2O	4.943	±	0.007	5.027	±	0.145	-0.470		0.68	*t*-test
P mg dm^{-3}	18.000	±	1.247	17.000	±	0.471	0.61		0.59	*t*-test
K mg dm^{-3}	25.667	±	0.720	18.667	±	1.785	2.96		0.069	*t*-test
Na $cmol_c$ dm^{-3}	0.020	±	0.000	0.010	±	0.000			0.04	Mann-Whitney
Ca $cmol_c$ dm^{-3}	3.433	±	0.054	3.567	±	0.119	-0.83		0.46	*t*-test
Mg $cmol_c$ dm^{-3}	0.433	±	0.191	2.067	±	0.233	-4.43		0.01	*t*-test
Al $cmol_c$ dm^{-3}	0.300	±	0.125	0.300	±	0.125		4.5	1	Mann-Whitney
H+Al $cmol_c$ dm^{-3}	6.217	±	0.251	5.613	±	0.205	1.51		0.205	*t*-test
S $cmol_c$ dm^{-3}	3.950	±	0.135	5.690	±	0.259	-4.86		0.016	*t*-test
T $cmol_c$ dm^{-3}	10.163	±	0.321	11.303	±	0.163	-2.58		0.082	*t*-test
V%	38.667	±	1.089	50.333	±	1.963	-4.24		0.022	*t*-test
m%	6.740	±	2.848	4.667	±	1.915	0.49		0.651	*t*-test
n%	0.167	±	0.012	0.090	±	0.000	5.27		0.030	*t*-test
t $cmol_c$ dm^{-3}	4.250	±	0.210	5.990	±	0.379	-3.28		0.043	*t*-test
Fe mg dm^{-3}	452.443	±	14.582	94.463	±	6.474	18.32		0.005	*t*-test
Cu mg dm^{-3}	8.033	±	0.267	3.563	±	0.068	13		0.003	*t*-test
Mn mg dm^{-3}	101.217	±	8.993	175.173	±	23.600	-2.39		0.111	*t*-test
Zn mg dm^{-3}	9.163	±	0.677	8.597	±	0.235	0.645		0.573	*t*-test
Ni mg dm^{-3}	0.000	±	0.000	0.000	±	0.000	-	-	-	-
Natural clay	22.667	±	0.544	13.000	±	0.000	14.5		0.004	*t*-test
Total clay	46.333	±	0.720	38.667	±	1.186	4.51		0.016	*t*-test
Total sand	15.333	±	1.089	45.667	±	1.440	-13.79		0.0002	*t*-test
Coarse sand	5.333	±	1.089	20.667	±	0.720	-9.59		0.001	*t*-test
Fine sand	10.000	±	0.000	25.000	±	2.055	-5.96		0.027	*t*-test
Silt	38.333	±	1.785	15.667	±	0.981	9.086		0.002	*t*-test
Flocculation Index	51.000	±	0.816	65.333	±	1.089	-8.6		0.001	*t*-test

H+Al: potential acidity, S: sum of exchangeable bases, T: total cation exchange capacity (CEC Total), V%: base saturation, m%: aluminum saturation, n%: sodium saturation and t: effective cation exchange capacity (CEC effective).

Maize cultivated in the impacted area exhibited significantly reduced NBI and chlorophyll content, with decreases of 46% and 27%, respectively, compared to the control area (*P* < 0.05; Figure 1a, b; Table S1). Furthermore, these plants developed leaves that were notably thinner yet broader, resulting in a substantially increased SLA (*P* < 0.05; Figure 1c). However, no statistical differences were observed in the flavonoid index of maize leaves between the two areas (*P* > 0.05; Figure 1d). Growth parameters, including height, stem diameter, and biomass, were reduced by at least 50% in maize cultivated in the impacted area compared to those grown in the control area (*P* < 0.05; Figure 1e, f, g; Table S1). Notably, the root-to-shoot ratio remained unchanged between treatments (*P* > 0.05; Figure 1h).

Maize plants grown in the impacted area exhibited statistically significant decreases in several important yield factors compared to those grown in the control area. Specifically, the number of ears per plant was reduced by 50%, ear length by 22%, the number of grains per ear by 35%, the total grain weight by 65%, and the average grain weight by 50% in maize plants grown in the impacted area compared to the control area (*P* < 0.05; Figure 2a-d; Table S1).

Maize grown in the impacted area exhibited significant alterations in mineral composition compared to the control (Figure 3), including a marked accumulation of Na. For instance, Na concentration in the grains from the impacted area was 54% higher than that in the control samples (*P* < 0.05). In contrast, substantial reductions were observed for essential nutrients such as Ca, Mg, and N, which decreased by 30%, 33%, and 42%, respectively (*P* < 0.05). No traces of Cu, Ni, or Al were detected in grains from either treatment (*P* > 0.05). Furthermore, the concentrations of K, P, Zn, Fe, Mn, and Co in maize grains did not differ statistically between the impacted area and the control area (*P* > 0.05).

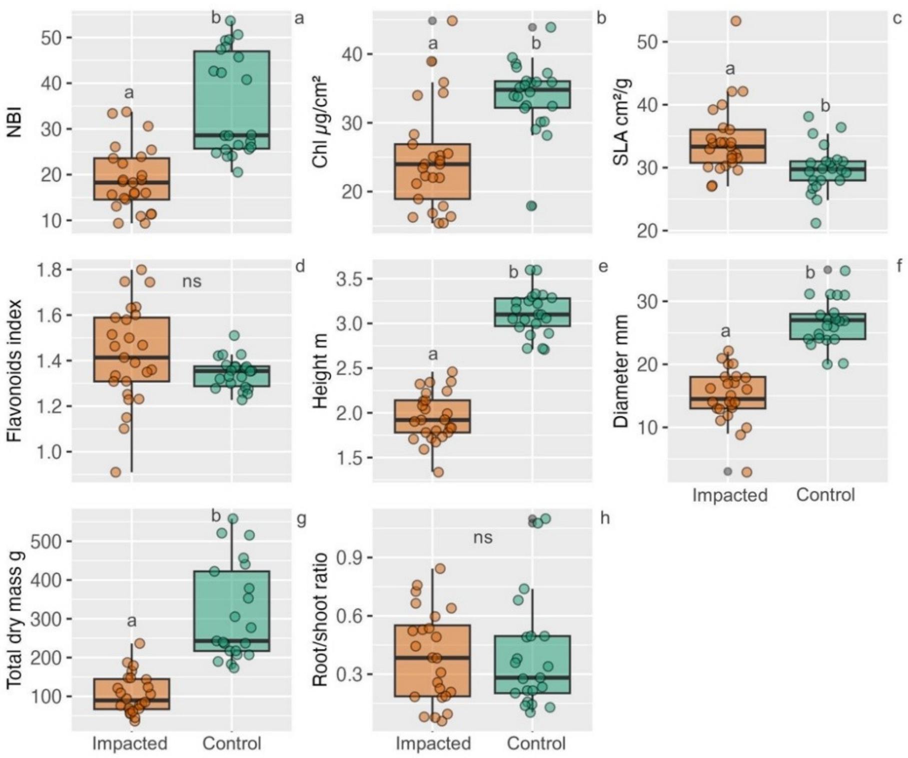

Figure 1. Developmental parameters in maize cultivated in an area contaminated (impacted) by mining tailings resulting from Samarco's dam rupture in Mariana, Brazil, and in an uncontaminated area (control). (a) Nitrogen Balance Index (NBI), (b) chlorophyll content (Chl), (c) specific leaf area (SLA), (d) flavonoid index, (e) height, (f) diameter, (g) total dry mass and (h) root/shoot ratio. The central line in each boxplot represents the median. Lowercase letters indicate statistically significant differences between the two treatments according to the one-tailed Mann–Whitney U test at the 0.05 significance level.

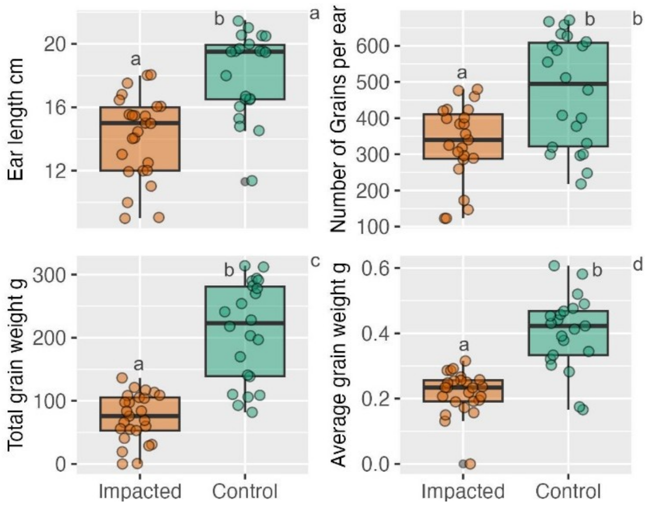

Figure 2. Productivity parameters in maize cultivated in an area contaminated (impacted) by mining tailings resulting from Samarco's dam rupture in Mariana, Brazil, and in an uncontaminated area (control). (a) Ear length, (b) number of grains per ear, (c) total grain weight, and (d) average grain weight. The central line in each boxplot represents the median. Lowercase letters indicate statistically significant differences between the two treatments according to the one-tailed Mann–Whitney U test at the 0.05 significance level.

Regarding maize leaves, significant reductions in the concentrations of several essential minerals were observed in the impacted area (Figure 3). Specifically, the concentrations of Ca, Mg, N, K, Mn, Zn, and Cu were all significantly reduced in leaves from plants cultivated in the impacted area compared to those cultivated in the control area ($P < 0.05$). Reductions exceeded 20% for N and K, with the most pronounced decline observed in Cu concentration, which fell by approximately 54% compared to the control area. Additionally, maize leaves grown in the impacted area showed no significant differences in the concentrations of Na, P, Fe, and Co compared to those grown in the control area ($P > 0.05$). Ni and Al were undetectable in maize leaves from both the impacted and control areas.

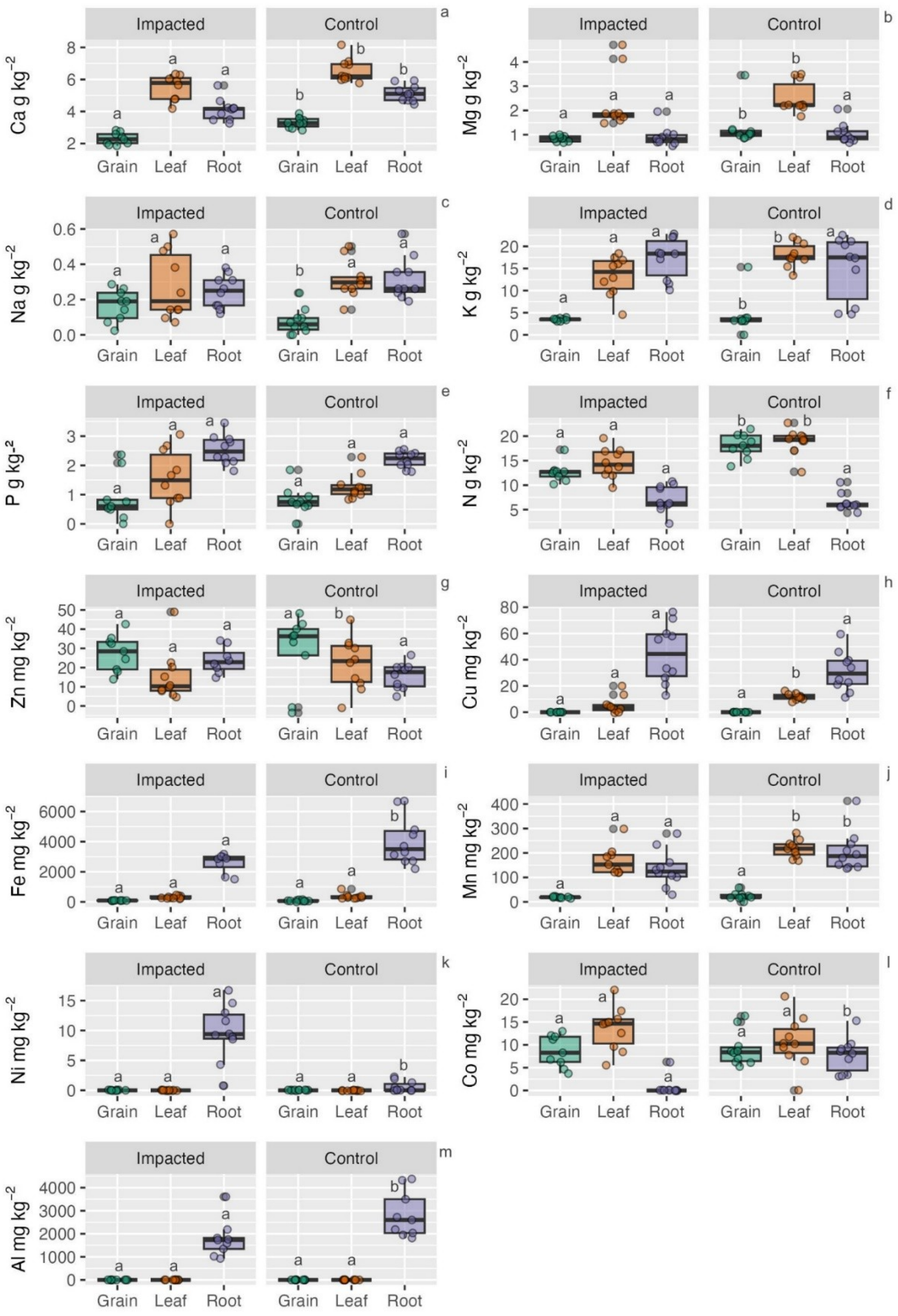

Figure 3. Accumulation of nutrients in grains, leaves, and roots of maize cultivated in an area contaminated (impacted) by mining tailings resulting from Samarco's dam rupture in Mariana, Brazil, and in an uncontaminated area (control). The central line in each boxplot represents the median. Lowercase letters indicate statistically significant differences for grains, leaves, and roots between the two treatments, as determined by the two-tailed Mann–Whitney U test at the 0.05 significance level.

In the roots of maize plants cultivated in the impacted area, significant alterations in mineral concentrations were observed compared to those from the control area (Figure 3). Specifically, clear reductions were found in Ca and Fe, both decreasing by less than 10% in the impacted area, whereas Mn and Al showed more pronounced decreases, exceeding 30% ($P < 0.05$). Cobalt exhibited a particularly substantial decrease, with concentrations 90% lower compared to roots from the control area ($P < 0.05$). Conversely, Ni concentration in the roots of maize plants from the impacted area was markedly increased, showing a 93% elevation relative to plants from the control area ($P < 0.05$). However, no significant differences were detected in the concentrations of Mg, Na, K, P, Zn, Cu, or N in the roots of maize grown in the impacted area compared to those grown in the control area ($P > 0.05$).

In maize plants cultivated in the impacted area, NBI and chlorophyll content were negatively correlated with elevated concentrations of Ca, Mg, Fe, Mn, Cu, Zn, and Co in the leaves (Figure 4a). Additionally, SLA was negatively correlated with Co, chlorophyll, and N concentrations. Productivity parameters also suffered from high concentrations of Ca, Mg, Na, Fe, and flavonoids in the leaves. Furthermore, K and N concentrations showed strong negative correlations with other nutrients, such as Ca, Mg, Na, Mn, Fe, Zn, and Cu. In contrast, height and total dry mass gain were positively correlated with the concentrations of Fe and Co in the leaves. Plant height and total biomass were also positively correlated with productivity measures, including the number of grains and total grain weight. For maize grown in the control area, we observed strong positive correlations between developmental parameters, such as height and total dry mass, and productivity parameters, such as grain number and total grain weight. Additionally, there was a positive correlation between the nutrient concentrations of Ca and Mg with chlorophyll content and NBI. Interestingly, in the control area, no significant negative correlations were observed that would indicate competition or antagonism among the analysed nutrients, which is characteristic of well-balanced and uncontaminated soils (Figure 4b).

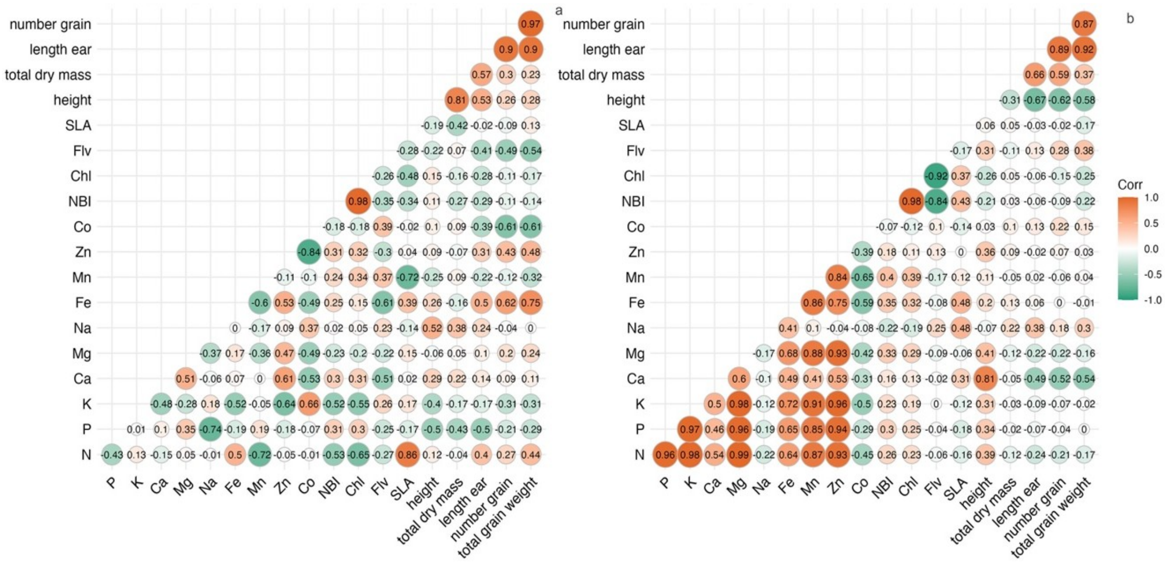

Figure 4. Correlations between foliar nutrient concentrations and developmental and productivity parameters in maize grown in (a) an area contaminated (impacted) by tailings resulting from Samarco's dam rupture in Mariana, Brazil, and (b) an uncontaminated area (control).

Discussion

Our study revealed that, despite intensive fertilization efforts by local farmers, maize grown in contaminated soils exhibited a lower nutrient balance. The contaminated soil showed no difference in P and K concentrations compared to the control area, likely due to these fertilization practices aimed at restoring productivity after the disaster. However, a significant reduction in base saturation was observed, indicating a diminished capacity of the soil to retain essential basic cations such as Ca, Mg, K, and Na. This limitation may be associated with the lower concentration of organic matter, which is known to improve nutrient retention (Sumner & Miller, 1996). Additionally, the effective cation exchange capacity (t) was significantly lower in the contaminated area, indicating a general decrease in the soil's ability to bind and exchange nutrients, which is essential for soil health and fertility (Alloway, 2013). In contrast to previous findings from controlled laboratory studies, such as Esteves et al. (2020), who reported no significant effects of Samarco dam tailings on the germination and early growth of maize (*Zea mays*, DKB390), sorghum (*Sorghum bicolor*, BRS 332), and millet (*Pennisetum glaucum*, BRS 1502), our field results revealed a markedly different scenario for maize. This discrepancy may be explained by the more complex and chronic stress conditions present in the field, where multiple soil degradation processes interact simultaneously.

Although annual fertilization can improve soil fertility over time (Havlin & Tisdale, 2014), our results showed that Mg concentration in the contaminated area remained low, whereas Na and heavy metals such as Fe and Cu remained elevated. The higher concentrations of Na, Fe, and Cu in contaminated soils can be attributed to the composition of the mining tailings. For example, Na is used in the iron ore flotation process and has been detected in high quantities in the soil along the Rio Doce Basin (18 a 150 mg kg^{-1}) (Araujo et al., 2005; Filippov et al., 2014; Santos et al., 2019). This elevated Na not only causes osmotic stress (Zhu, 2001; Ahmed et al., 2024) and negatively affects soil microbial communities (Santos et al., 2019; Scotti et al., 2020; Gomes et al., 2021), but also disrupt soil structure. In particular, Na ions disperse soil colloids by weakening the electrostatic attraction between particles, which reduces soil aggregation and lowers the flocculation index (Qadir & Schubert, 2002). This effect can occur even in the presence of adequate concentration of Ca, a known flocculating agent, because Na^{+} competes with Ca^{2+} for exchange sites on clay particles, leading to increased dispersion. Thus, the reduced flocculation index observed in the contaminated area, despite similar Ca concentrations, can be explained by the disproportionately higher Na concentration derived from the tailings. In addition to these chemical constraints, physical degradation of the contaminated soil also plays a critical role in limiting plant development. Soil compaction and the increase in clay and silt fractions altered soil texture and porosity, impairing aeration and water retention, two factors essential for healthy root growth and functioning (Horn et al., 1995; Lipiec et al., 2003).These physical alterations likely contributed to the stunted growth and reduced productivity observed in our study, highlighting the urgent need for integrated soil management practices that address both chemical remediation and physical restoration.

The chemical imbalance observed in contaminated soil was also reflected in the nutrient composition of maize roots. In particular, maize plants grown under contaminated conditions exhibited significantly higher concentrations of Ni in their root tissues. This element is known to adsorb strongly to key functional sites on the root surface, where it can disrupt membrane integrity, impair enzymatic processes, and interfere with the uptake and translocation of essential resources such as water and nutrients (Wu et al., 2006; Testa et al., 2023). However, this elevated concentration should be interpreted with caution, as the roots were not washed prior to analysis. Therefore, it is possible that a portion of the detected Ni reflects external adhesion to the root surface rather than true internal accumulation. In the specific case of Fe, despite its higher concentration in contaminated soil, lower accumulation was observed in maize roots. This may be related to the limited bioavailability of Fe, which depends not only on its total content but also on its chemical form and interactions with other elements in the soil matrix (Alloway, 2013).

The reduction in foliar concentrations of essential nutrients such as Ca, Mg, K, N, Zn, Cu, and Mn in maize plants cultivated in the contaminated area is consistent with the observed declines in growth and productivity. These nutrients are fundamental for key physiological processes, including cell wall stability (Ca), chlorophyll synthesis and enzymatic activation (Mg and Mn), osmoregulation and stomatal function (K), protein and nucleic acid synthesis (N), and redox balance and photosynthetic efficiency (Zn and Cu) (Marschner, 2012; Cakmak & Kirkby, 2008). Their deficiency likely compromises metabolic integrity, leading to impaired photosynthesis, reduced biomass accumulation, and lower grain production. Consistent with these deficiencies, maize plants from the contaminated area also exhibited significantly lower NBI and chlorophyll content, both of which are reliable indicators of nutritional status and photosynthetic capacity. The reduction in NBI reflects a limitation in nitrogen assimilation, while decreased chlorophyll indicates impaired light-harvesting and energy conversion efficiency (Maxwell & Johnson, 2000). Concurrently, the increase in SLA suggests an acclimation strategy aimed at maximising light capture under stress but is often associated with reduced tissue robustness and efficiency. At the same time, an increase in flavonoid index was observed in these plants, suggesting the activation of photoprotective and antioxidant pathways in response to physiological stress. Flavonoids are often upregulated in response to nutrient deficiency and oxidative stress, where they function as ROS scavengers and help stabilise cellular components (Gill & Tuteja, 2010; Shomali et al., 2022). This set of responses reveals an integrated stress syndrome in maize under contaminated conditions, in which nutrient limitations, disrupted primary metabolism, and activation of secondary defence compounds jointly contribute to reduced growth and yield.

In maize grown in the control area, strong positive correlations were observed between developmental parameters, such as height and biomass, and productivity parameters, such as the number of grains and total grain weight. This highlights the direct association between plant growth and higher grain yield. Additionally, the positive correlation between nutrient concentrations, such as Ca and Mg, with chlorophyll content and the NBI suggests that adequate nutrition promotes photosynthetic health and plant vigour. Studies demonstrate that Mg is essential for photosynthesis as it is a central component of the chlorophyll molecule and activates enzymes involved in energy metabolism (Cakmak & Kirkby, 2008; Chen et al., 2018). Calcium, on the other hand, plays a crucial role in the stability of cell membranes and in cellular signalling, contributing to photosynthetic efficiency and stress resistance (Cakmak & Kirkby, 2008; Chen et al., 2018). Taken together, these data indicate that in the control area, plants were cultivated under stable and favourable conditions, while such positive correlations were not detected under contaminated conditions. However, in maize leaves grown in contaminated soil, the presence of Ca, Mg, Fe, Mn, Cu, Zn, and Co negatively affected NBI and chlorophyll content, indicating that nutrient imbalances and stress conditions may impair chlorophyll synthesis and nitrogen status, thereby adversely affecting plant health.

Beyond the observed reduction in productivity, maize grains from the contaminated area also exhibited significant alterations in elemental composition. Reductions in Ca, Mg, and N, elements essential for human nutrition and structural functions (Chen et al., 2018), highlight the nutritional imbalance and reduced quality of agricultural products grown in contaminated soils in the Rio Doce Basin. The high Na concentration in grains from the contaminated area reflects increased soil salinity, which can severely compromise germination and early seedling development. Elevated Na increases the osmotic potential around seeds, reducing water uptake required to initiate germination (Munns & Tester, 2008). It competes with essential ions such as K, Ca, and Mg, leading to nutritional deficiencies and impaired cell development (Zhu, 2001). This ionic imbalance can impair seedling establishment. Furthermore, excess Na can cause direct toxicity by inducing oxidative stress, damaging cellular components such as DNA, proteins, and lipids, and ultimately reducing seed viability (Sharma et al., 2012; Ma et al., 2022). These physiological disturbances suggest that increased Na accumulation in maize grains from contaminated soils may compromise the reproductive success and regenerative capacity of the species. Even minor alterations in seed elemental composition may influence food quality and ecological interactions, especially in regions where maize is a key resource. Similar physiological and nutritional imbalances may also affect native plant species growing in contaminated soils. Altered nutrient uptake, reduced chlorophyll and N levels, and increased oxidative stress responses, as observed in maize, could compromise growth, reproduction, and seed viability in native flora. This may have broader consequences for community dynamics and ecosystem recovery. Future studies should investigate whether native species in the Rio Doce Basin exhibit comparable responses, particularly those important for ecological succession and habitat restoration.

Conclusion

This study demonstrates that maize cultivated in soils contaminated by Samarco dam tailings exhibited altered nutrient accumulation in both leaves and grains, along with marked reductions in growth and productivity. The lower fertility of the contaminated soils led to limited nutrient availability and disrupted uptake dynamics. Despite identical fertilization and climatic conditions, the lower fertility and altered composition of the contaminated soil limited crop performance. These results underscore the lasting impact of tailings on soil function and maize productivity, reinforcing the need for targeted management in affected areas of the Rio Doce Basin.

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