Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Iron mining tailings contamination increases manganese availability and uptake by maize and wheat and inhibits plant growth under different soil redox conditions

Giovanna Zanquetta Vitoria
Federal University of Lavras (ESAL-UFLA)
Arnon Afonso de Souza Cardoso
Federal University of Lavras (ESAL-UFLA)
Tamires Rodrigues dos Reis
Federal University of Lavras (ESAL-UFLA)
Aline Oliveira Silva
Federal University of Lavras (ESAL-UFLA)
Luiz Roberto Guimarães Guilherme
Federal University of Lavras (ESAL-UFLA)
Soraya Alvarenga Botelho
Federal University of Lavras (ESAL-UFLA)
Marco Aurélio Carbone Carneiro
marcocarbone@ufla.br

Federal University of Lavras (ESAL-UFLA)

Research Article

Keywords: Zea mays, Triticum aestivum, phytotoxicity, redox potential

Posted Date: November 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11223050/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

The release of potentially toxic elements, such as manganese (Mn), is a risk in soil contaminated with mining tailings, and waterlogging and redox conditions can exacerbate this risk. This study evaluated how different levels of impact from iron ore tailings deposition from the Fundão Dam (Mariana, Minas Gerais, Brazil), under different flooding conditions, affect Mn availability and the initial growth of maize (*Zea mays*) and wheat (*Triticum aestivum*). Soil samples were collected from areas with different impact levels (low, medium, and high impact, based on proximity to the Gualaxo do Norte River: 40, 20, and 0 m, respectively) and from a reference area without tailings deposition. Two experiments were conducted: (1) a soil incubation experiment, aiming to evaluate the effect of artificial flooding on Mn availability in the collected samples; and (2) a plant cultivation experiment, aiming to evaluate the growth and Mn uptake by maize and wheat cultivated in soil incubation samples. Manganese availability increased with both contamination and flooding. Tailings deposition increased available Mn up to 2.1-fold and Mn uptake up to 2.4-fold, and inhibited plant growth by up to 60% in maize and 39% in wheat. Flooding increased Mn availability by around 120% in the reference and 51% in the low-impact level, while in higher-impact areas, Mn is already available without flooding. Overall, the results indicate that tailings contamination and flooding can increase Mn bioavailability in soils contaminated with iron mining tailings from Fundão Dam.

1 Introduction

Iron mining is an economically important activity in Brazil, but it generates tailings that can contaminate soils and water bodies with potentially toxic elements, such as manganese (Mn). The collapse of the Fundão Dam in Mariana (Minas Gerais, Brazil) exemplifies this impact, affecting the Doce River watershed for around 660 km (Kütter et al. 2023). Manganese toxicity is the second most important factor limiting plant growth in acidic soils, after aluminum toxicity (Kochian et al. 2004), and Mn commonly occurs in iron-mining tailings at high concentrations because it associates with iron formations, initially in poorly soluble forms (Queiroz et al. 2021; A. P. V. Silva et al. 2024).

However, changes in environmental conditions may increase Mn solubility and environmental risk. Manganese availability in soil is mainly controlled by soil redox potential (Eh) and active acidity (pH) (Z. Zhang et al. 2025). Under flooded soil conditions, Eh tends to decrease, favoring the reduction of Mn^{4+} to Mn^{2+}, the main Mn ionic form absorbable by plants (L. Zhang et al. 2025). Although essential for plants, excess Mn can cause phytotoxicity, reducing plant growth and crop production (White and Brown 2010). Although previous studies have addressed these factors separately, the interaction between tailings contamination and flooding remains poorly understood.

Because seasonal variations in precipitation and water levels induce redox oscillations that can alter Mn availability in soils and water bodies contaminated with Fundão Dam tailings (Queiroz et al. 2021), we hypothesized that artificial flooding would increase Mn phytotoxicity in tailings-contaminated soils. Accordingly, this study investigated the effects of artificial flooding on Mn availability, Mn uptake, and the

growth of maize and wheat plants cultivated in soil samples collected along the Gualaxo do Norte River, in an area of the Doce River watershed contaminated by Fundão Dam tailings.

2 Materials and methods

2.1 Study area and soil sampling

The soil samples were collected in 2020 in the Paracatu de Baixo community, Mariana, Minas Gerais State, Brazil, a region affected by the collapse of the Fundão Dam. Two areas were selected: a reference area, consisting of a non-impacted forest fragment, and an impacted area in the alluvial plain of the Gualaxo do Norte River, characterized by tailings deposition (Reis et al. 2025). In each area, a sampling grid with nine points (20 m spacing) was established, and soil samples were collected from the 0–20 cm layer (Figure S1). In the impacted area, sampling points were classified as low-impact, medium-impact, or high-impact based on their proximity to the river (40, 20, and 0 m, respectively) and the extent of tailings deposition. Soil samples were chemically and physically characterized (Silva 2009), with results presented in Table S1.

2.2 Soil incubation experiment

In the incubation experiment, treatments consisted of the combination of four impact levels of tailings deposition in the soil (reference, low-impact, medium-impact, and high-impact) and two artificial flooding conditions (air-dried and flooded), arranged in a completely randomized design in a factorial scheme (4 × 2) with eight combinations and six replicates. The control treatment consisted of the air-dried reference sample combination. Soil samples (0.6 kg) were incubated in plastic pots (0.8 L) for eight weeks. In the flooded treatments, a 2-cm layer of deionized water (0.6 L) was maintained above the soil surface. Soil acidity (pH) and redox potential (Eh) were measured weekly in flooded treatments using a digital pH meter with a combined platinum and Ag/AgCl electrode directly in the pots (Figure S2).

After eight weeks, air-dried subsamples were then collected for sequential extraction of available Mn and residual Mn (pseudo-total concentration). Available Mn was extracted with Mehlich-1 solution (0.05 M HCl + 0.0125 M H_2SO_4) at a 1:10 soil: solution ratio. The samples were shaken for 5 min, filtered, and the Mn concentration was determined by inductively coupled plasma optical emission spectrometry (ICP-OES). Afterward, samples were oven-dried (65º C for 72 h) and transferred to glass digestion tubes for residual Mn extraction. Samples were digested with 10 mL of HCl (37%, v/v) and HNO_3 (65%, v/v) at a 4:1 ratio under block digestion heating (60°C for 180 min, 105°C for 60 min, and 140°C for 30 min). Extracts were filtered, volume-adjusted to 50 mL, and Mn concentration was determined by ICP-OES.

2.3 Plant cultivation experiment

Soil samples from the incubation experiment were used in two plant cultivation experiments with the same experimental design, with three replicates, growing maize (*Zea mays* L., cv. BM3051) and wheat (*Triticum aestivum* L., cv. BRS 264). The samples were air-dried, gently crushed, and sieved (2 mm). Soil

samples were placed in plastic pots (0.8 L) and received the following fertilization (mg kg^{-1}): 200 N (NH_4NO_3), 300 P (KH_2PO_4), 200 K (KCl), 450 Ca ($CaCl_2$), 90 Mg ($MgSO_4$), 4.0 Zn ($ZnSO_4$), 3.6 Mn ($MnSO_4$), 1.3 Cu ($CuSO_4$), 0.8 B (H_3BO_3), and 0.45 Mo (H_2MoO_4). Seven days after fertilization, six maize or wheat seeds were sown per pot, and seedlings were thinned to three (maize) or five (wheat). Soil moisture was maintained near field capacity by daily weighing and addition of deionized water.

Plant shoots were harvested at 20 (maize) and 40 (wheat) days after emergence, washed (tap water, 0.1 mol L^{-1} HCl solution, and deionized water), and oven-dried at 70°C for 72 h until constant weight, and shoot dry matter (SDM) was determined using a digital scale. Dried leaves were ground, and subsamples (0.5 g) were submitted to nitro perchloric digestion (HNO_3: $HClO_4$, 2:1 v/v) under block digestion heating (50°C for 60 min, 100°C for 60 min, 150°C for 60 min, and 200 ºC for 30 min). The extracts were filtered, and the Mn concentration was determined by ICP-OES.

2.4 Statistical analysis

Data were subjected to normality testing (Shapiro-Wilk test, $p > 0.05$), homoscedasticity testing (Cochran test, $p > 0.05$), and analysis of variance (ANOVA). When interactions between factors were significant ($p \leq 0.05$), the impact levels and flooding conditions for each factor were compared using the Scott-Knott test ($p \leq 0.05$). When interactions were not significant ($p > 0.05$), the factors were compared separately by the Scott-Knott test ($p \leq 0.05$) using SPEED Stat 3.4 software (Mundstock et al. 2020).

3 Results and discussion

Contamination and flooding interacted significantly in all variables in the soil incubation experiment. Contamination reduced Eh and increased pH (Figs. 1A, 1B, and S3). The air-dried contaminated treatments had lower Eh (≈ -64%) and higher pH (≈ + 22%) than the control treatment. However, the flooded high-impact treatment had higher Eh (+ 31%) and lower pH (-10%) than the flooded reference. Flooding decreased Eh and increased pH, with stronger effects in the reference, low-impact, and medium-impact treatments, where Eh was reduced by about 117 mV, while in high-impact, Eh decreased by only 24 mV.

Flooding increased pH by around 2.4 units in these treatments, while in high-impact, pH increased by only 0.4 units. Contamination increased soil Mn only in air-dried treatments (Figs. 1C and D), with high-impact promoting two (available-Mn) and three (residual-Mn) times the control. Flooding increased soil Mn only in the reference and low-impact treatments, with inputs around two (available-Mn) to three times (residual-Mn) those of air-dried treatments.

Contamination levels and flooding did not interact significantly for shoot dry matter production and Mn concentrations in maize and wheat. However, the tailings contamination affected these variables in both maize and wheat (Fig. 2). All the contamination impact levels inhibited shoot dry matter production by 58% in maize and 40% in wheat (Figs. 2A and 2B). Tailings contamination increased Mn concentrations in both maize and wheat shoots. Mn concentrations in wheat were 2.4 times higher in contaminated

treatments than in the reference treatment. However, only the high-impact level increased Mn concentrations in maize, resulting in Mn concentrations 2.4 times higher than in the reference treatment.

The soil pH and Eh results indicate that both tailings contamination and flooding shifted the soil's redox state from oxidizing to reducing. Aerobic microbial respiration rapidly consumes oxygen (O_2) in flooded soil because water restricts O_2 diffusion. Thus, the microbiome shifts the electron acceptor from O_2 (aerobic respiration) to other compounds, such as nitrate, sulfate, and iron and manganese oxides (anaerobic respiration), producing reduced compounds and lowering soil Eh (Ponting et al. 2021). This may explain both the flooding and contamination effects in Eh, since most tailings in the Fundão dam were stored as mud (Carmo et al. 2017), which likely lowered the tailings' Eh before the rupture. This may also explain the pH response, since compound reduction consumes protons (Meng et al. 2023), probably increasing pH in both flooding and contaminated treatments. Interestingly, we observed a higher resistance to Eh and pH changes by flooding in high-impact samples, which can be the result of a combination of lower organic matter – the main electron donor for compound reduction (Marschner 2021) – as indicated in Table S1, with a negative impact on biological processes, like respiration, promoted by Fundão Dam tailings contamination (Silva et al. 2021).

Tailings contamination increased available-Mn and residual-Mn compared with the reference area under air-dried conditions, due to the high Mn total content (≈ 400 to 880 mg kg^{-1}) in the original Fundão Dam tailings (Queiroz et al. 2021). However, under flooding, Mn amounts in the reference did not differ (available-Mn) or were slightly higher (residual-Mn) than in contaminated areas, indicating a high Mn reserve even in non-impacted areas. The increase in available-Mn and residual-Mn due to flooding in reference and low-impact samples indicates that reducing Mn compounds increases Mn availability in these areas, while in higher-impact areas, Mn is already available and constitutes a potentially toxic element in tailings-contaminated areas. Interestingly, flooding increased residual Mn, indicating that tailings contain highly stable Mn forms such as pyrolusite (MnO_2) (Queiroz et al. 2021), which are partially resistant to the extractors used ($HCl + HNO_3$) (Ducret and Barbeau 2024) but appear to solubilize under soil flooding.

The less available Mn fractions in Fundão Dam tailings include Mn associated with ferrihydrite, lepidocrocite, and crystalline oxides (Queiroz et al. 2018, 2021), where Mn is in III or IV oxidation states and could be reduced by anaerobic microorganism respiration, releasing MnII (Mn^{2+}), which corresponds to the more bioavailable Mn form (Canfield et al. 2005; Learman et al. 2011). This effect contributed to impaired plant growth under tailings exposure (Figs. 2A and 2B), considering the concentrations of available Mn in soil and in leaves higher than tolerated for many Mn non-accumulator species (2.7 to 35 mg kg^{-1} available-Mn in soil and 70 to 380 mg kg^{-1} Mn in dry leaves) (Oliveira et al. 2025; Silva et al. 2024; White and Brown 2010). Thus, the high Mn concentration in tailings contributes to its environmental risk, which the hydrological regime can regulate through soil redox conditions.

4 Conclusions

Both tailings contamination and flooding increased Mn availability in the studied soils. Tailings deposition increased available Mn concentrations by up to 2.1-fold and Mn uptake by up to 2.4-fold, while inhibiting plant growth by up to 60% in maize and 39% in wheat. Flooding increased Mn availability by approximately 120% in the reference soil and 51% under low-impact conditions. In contrast, in areas with higher levels of tailings deposition, Mn was already highly available in the absence of flooding. Overall, these findings indicate that tailings contamination and flooding can increase Mn bioavailability in soils, potentially enhancing the risk of Mn phytotoxicity in crops cultivated in the Gualaxo River region affected by the Fundão Dam collapse.

Declarations

Competing interests:

The authors declare no competing interests.

Author Contribution

Conceptualization: G.Z.V., A.A.S.C., M.A.C.C. Soil sampling: T.R.R., A.O.S., S.A.B., M.A.C.C. Plant cultivation and laboratory analyses: G.Z.V., A.A.S.C. Supervision: A.A.S.C., M.A.C.C. Data analysis and interpretation: A.A.S.C. Funding: L.R.G.G., S.A.B., M.A.C.C. Writing – original draft: A.A.S.C., G.Z.V. Writing – revision and editing: A.A.S.C., with contributions of all authors.

Acknowledgement

The authors thank the Brazilian National Research Council (CNPq), the Coordination for the Improvement of Higher Education Personnel (CAPES), and the Research Support Foundation of the State of Minas Gerais (FAPEMIG) for financial support.

References

1. Canfield, D. E., Erik Kristensen, & Bo Thamdrup. (2005). The Iron and Manganese Cycles. In *Advances in Marine Biology* (Vol. 48, pp. 269–312). https://doi.org/10.1016/S0065-2881(05)48008-6
2. Carmo, F. F. do, Kamino, L. H. Y., Junior, R. T., Campos, I. C. de, Carmo, F. F. do, Silvino, G., et al. (2017). Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context. *Perspectives in Ecology and Conservation*, *15*(3), 145–151. https://doi.org/10.1016/j.pecon.2017.06.002
3. Ducret, J., & Barbeau, B. (2024). A revised digestion method to characterize manganese content in solids. *MethodsX*, *12*(April), 0–6. https://doi.org/10.1016/j.mex.2024.102731
4. Kochian, L. V., Hoekenga, O. A., & Piñeros, M. A. (2004). How do crop plants tolerate acid soils? Mechanisms of aluminum tolerance and phosphorous efficiency. *Annual Review of Plant Biology*,

55(1), 459–493. https://doi.org/10.1146/annurev.arplant.55.031903.141655

5. Kütter, V. T., Martins, G. S., Brandini, N., Cordeiro, R. C., Almeida, J. P. A., & Marques, E. D. (2023). Impacts of a tailings dam failure on water quality in the Doce river: The largest environmental disaster in Brazil. *Journal of Trace Elements and Minerals*, *5*(June), 100084. https://doi.org/10.1016/j.jtemin.2023.100084
6. Learman, D. R., Wankel, S. D., Webb, S. M., Martinez, N., Madden, A. S., & Hansel, C. M. (2011). Coupled biotic-abiotic Mn(II) oxidation pathway mediates the formation and structural evolution of biogenic Mn oxides. *Geochimica et Cosmochimica Acta*, *75*(20), 6048–6063. https://doi.org/10.1016/j.gca.2011.07.026
7. Marschner, P. (2021). Processes in submerged soils – linking redox potential, soil organic matter turnover and plants to nutrient cycling. *Plant and Soil*, *464*(1–2), 1–12. https://doi.org/10.1007/s11104-021-05040-6
8. Meng, H., Hu, S., Yang, Y., Chen, G., Chi, W., Cheng, K., & Liu, T. (2023). Quantitative understanding of the impact of flooding durations on Cd variations in an acidic paddy soil during the flooding and drainage processes. *Soil Security*, *13*(June), 100114. https://doi.org/10.1016/j.soisec.2023.100114
9. Mundstock, A. X. de C., Mendes, F. Q., Mendes, F. Q., & Tavares, L. de F. (2020). SPEED Stat: a free, intuitive, and minimalist spreadsheet program for statistical analyses of experiments. *Crop Breeding and Applied Biotechnology*, *20*(3), e327420312. https://doi.org/10.1590/1984-70332020v20n3s46
10. Oliveira, F. N. de, Morsch, L., Moura-Bueno, J. M., Tassinari, A., Trentin, E., Marques, A. C. R., et al. (2025). Critical Levels of Copper, Zinc, and Manganese Toxicity in Soil and Tissues of Plants That Cohabit Vineyards in the Pampa Biome. *Horticulturae*, *11*(7), 1–12. https://doi.org/10.3390/horticulturae11070831
11. Ponting, J., Kelly, T. J., Verhoef, A., Watts, M. J., & Sizmur, T. (2021). The impact of increased flooding occurrence on the mobility of potentially toxic elements in floodplain soil – A review. *Science of the Total Environment*, *754*, 142040. https://doi.org/10.1016/j.scitotenv.2020.142040
12. Queiroz, H. M., Nóbrega, G. N., Ferreira, T. O., Almeida, L. S., Romero, T. B., Santaella, S. T., et al. (2018). The Samarco mine tailing disaster: A possible time-bomb for heavy metals contamination? *Science of the Total Environment*, *637–638*, 498–506. https://doi.org/10.1016/j.scitotenv.2018.04.370
13. Queiroz, H. M., Ying, S. C., Abernathy, M., Barcellos, D., Gabriel, F. A., Otero, X. L., et al. (2021). Manganese: The overlooked contaminant in the world largest mine tailings dam collapse. *Environment International*, *146*, 106284. https://doi.org/10.1016/J.ENVINT.2020.106284
14. Reis, T. R., Alves, P. R. L., Nunes, M. R., Bandeira, F. O., Silva, L. C. V., de Souza, A. F., et al. (2025). Resilience of soil fauna to pesticide contamination in areas impacted by mining tailings. *Science of The Total Environment*, *1001*(May), 180492. https://doi.org/10.1016/j.scitotenv.2025.180492
15. Silva, A. O., Guimarães, A. A., Lopez, B. D. O., Zanchi, C. S., Vega, C. F. P., Batista, É. R., et al. (2021). Chemical, physical, and biological attributes in soils affected by deposition of iron ore tailings from

the Fundão Dam failure. *Environmental Monitoring and Assessment*, *193*(8), 462. https://doi.org/10.1007/s10661-021-09234-4

16. Silva, A. P. V., Silva, A. O., de Lima, F. R. D., Benedet, L., Carriço, C. O., Franco, A. de J., et al. (2024). Reduction of pH on the Bioavailability of Potentially Toxic Elements for Plants Grown in Iron Mining Tailing. *Water, Air, & Soil Pollution*, *235*(7), 409. https://doi.org/10.1007/s11270-024-07205-2
17. Silva, F. C. da. (2009). *Manual de análises químicas de solos, plantas e fertilizantes*. (F. C. da Silva, Ed.) (2nd ed.). Brasília: Embrapa Informação Tecnológica.
18. Silva, E. D. B., Souza, W. C. L. De, Nardis, B. O., Alleoni, L. R. F., Grazziotti, P. H., Santos, L. L. Dos, et al. (2024). Toxicity and Availability of Manganese in the Growth of Tropical Grasses in Contaminated Soil. *Applied and Environmental Soil Science*, *2024*. https://doi.org/10.1155/2024/7444193
19. White, P. J., & Brown, P. H. (2010). Plant nutrition for sustainable development and global health. *Annals of Botany*, *105*(7), 1073–1080. https://doi.org/10.1093/aob/mcq085
20. Zhang, L., Li, Y., Wang, Y., Liu, Z., Kronzucker, H. J., Wang, Z., et al. (2025). Ion toxicity in waterlogged soils: mechanisms of root response and adaptive strategies. *Frontiers in Plant Science*, *16*(August), 1–14. https://doi.org/10.3389/fpls.2025.1653008
21. Zhang, Z., Yang, P., Wen, K., Mao, H. R., Zhao, Z., Liu, C., et al. (2025). Manganese oxidation states and availability in forest weathering profiles of contrasting climate. *Geochimica et Cosmochimica Acta*, *388*, 221–235. https://doi.org/10.1016/J.GCA.2024.10.006

Figures

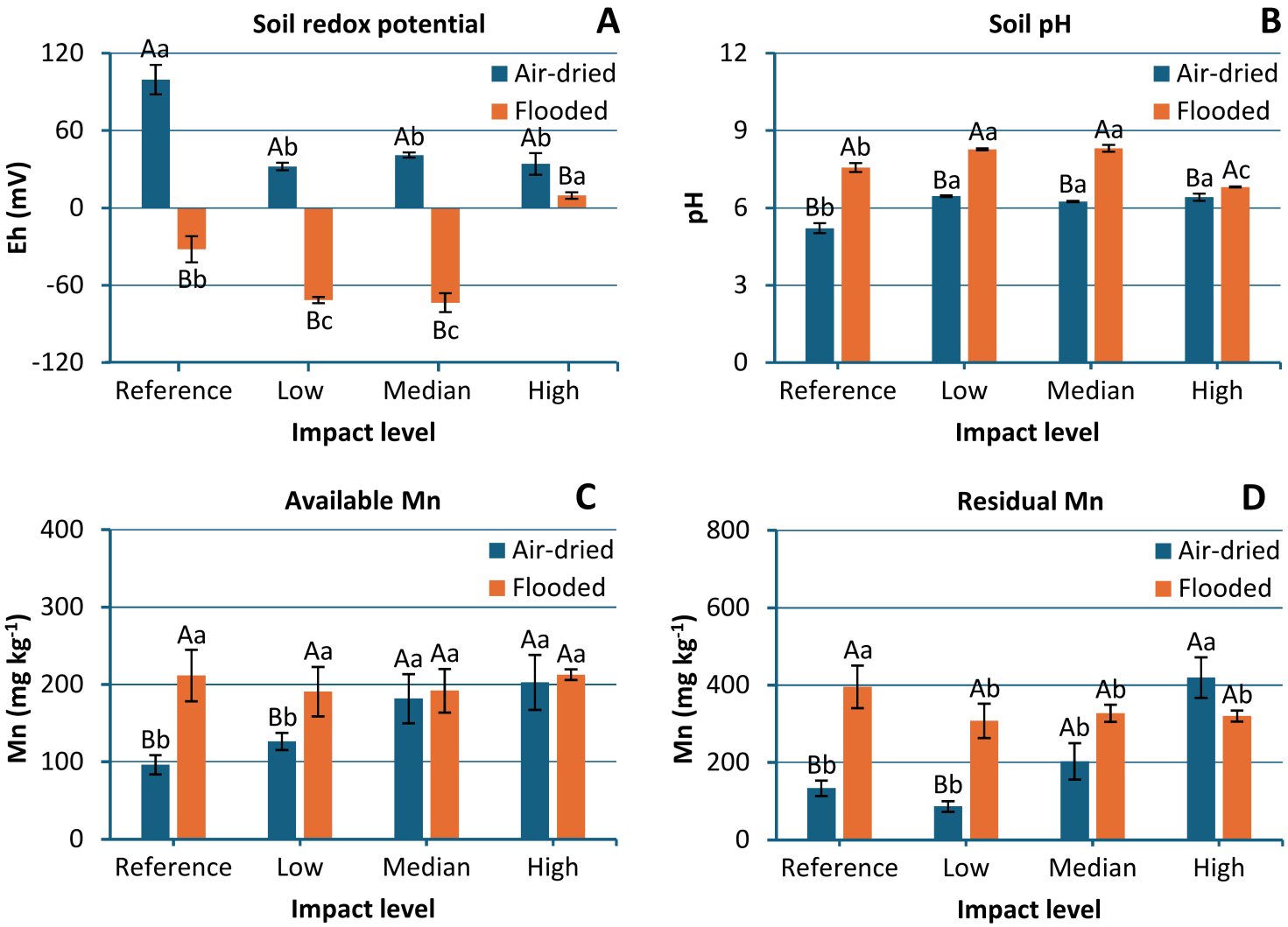

Figure 1

Redox potential (A), pH (B), available Mn (C), and residual Mn (D) concentrations in soil under different levels of contamination with iron mining tailings and after artificial flooding (eight weeks). Means ± standard errors of six replicates. Uppercase letters indicate significant differences between flooding conditions within the same contamination level, whereas lowercase letters indicate differences among contamination levels within the same flooding condition, according to the Scott-Knott test ($p \leq 0.05$).

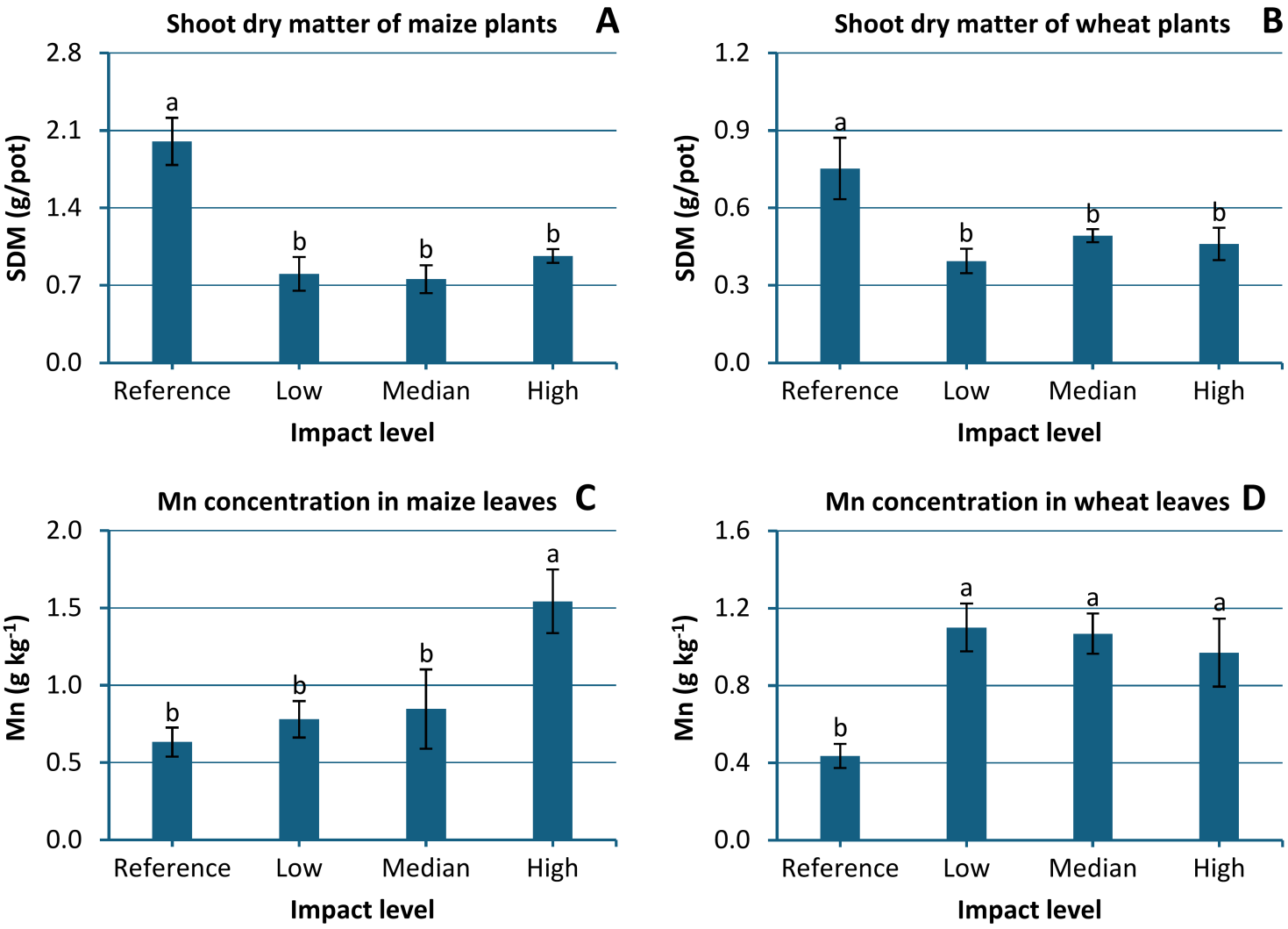

Figure 2

Shoot dry matter (A and B) and Mn concentrations (C and D) in maize and wheat plants grown in soils with different levels of contamination by iron mining tailings. Means ± standard errors of three replicates. Different letters indicate differences among contamination levels according to the Scott-Knott test ($p \leq 0.05$).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterialGiovana02102026.docx