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Using Mine Tailings as a Soil Improver to Reduce Micronutrient Deficiencies in Wheat Crops, Western Morocco

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ABSTRACT

Micronutrient deficiencies in agricultural soils significantly affect crop productivity and the nutritional quality of produce, posing potential risks to human health. Abandoned mine tailings, which are rich in micronutrients, can serve as an effective solution to enhance the nutritional value of crops while also mitigating environmental impact. In this study, the soils were sourced from the semi-arid Doukkala region in western Morocco, while the tailings were obtained from the abandoned Kettara mine in the nearby Marrakech region. This study assessed the biomass and bioconcentration of wheat (*Triticum aestivum* L.) grown in three different soils amended with treated mine tailings (TMT) at doses of 0, 0.2, 1, 2, and 4 $g \cdot kg^{-1}$. The experiment, conducted under greenhouse conditions and in pots, employed a split-plot design with three replicates, monitoring morphological parameters and plant biomass. Concentrations of Cu, Fe, Zn, and Mn in wheat grains were measured by inductively coupled plasma-atomic emission spectrometry (ICP AES) after harvest. The results indicate an increase in root length, shoot height, number of tillers, shoot biomass and grain biomass with TMT amendment doses of less than 1 $g.kg^{-1}$ soil, by 13.6, 42.1, 42.6, 49.6, and 32.9% respectively. However, these parameters decreased with doses > 2 $g \cdot kg^{-1}$. Significant linear correlations were observed between the concentrations of micronutrients in wheat grains and those present in the soil. The bioconcentration factor increased but remained below 1. This research reveals that TMT are perfectly suitable to fertilize wheat using doses < 1 $g \cdot kg^{-1}$, ensuring safe application for the environment and human health. Through this research, it was demonstrated that within certain thresholds, TMT can enhance the mineral nutrition of plants as well as positively impact agricultural productivity and product quality. These results can be replicated in other regions worldwide by adhering to the described procedure.

Keywords: wheat, soil amendment, treated mine tailings, nutritional quality of agricultural, micronutrients, bioconcentration factor.

INTRODUCTION

Under the effect of climate change, population growth and changing eating habits, global food demand will create pressure on the supply of the three main cereals: wheat, rice, and corn. Wheat is a staple food for both the rich and the poor, contributing 20% of the protein and calories consumed by a growing global population (Reynolds et al., 2012). Global food production has been increasing through several possible measures, such as increasing irrigated areas, appropriately increasing the amount of fertilizers, and improving water and crop use efficiency. However, the increase in production has not been accompanied by improvement in quality, which can have a negative impact on animal and human health. Grain quality is the main criterion for evaluating wheat on the world market. Thus, a large part of the yield quality is influenced by fertilization. In addition to nitrogen, phosphorus, potassium, magnesium, and sulfur, as well as trace elements, have decisive influences on productivity and the degree of compliance with the quality criteria. Crops typically require low quantities of micronutrients per hectare. For field crops, Fe, Cu, Mn, Zn, B, and Mo are the most frequently cited micronutrients limiting the normal development of main crops. Faced with this situation and in the concept of circular economy, mining waste offers a promising means as a source of micronutrients for plants.

Over the past centuries, humanity has exploited and used mineral resources essential to its survival and well-being (Lynch, 2002; Yu and Zahidi, 2023). However, mineral extraction and processing have led to significant environmental deterioration due to contamination by trace metal elements and the creation of acid mine drainage (El Gharmali et al., 2004; Adnani, 2008; Yu and Zahidi, 2023). According to Salomons and Forstner (1988) there are four types of waste: waste rock (worthless rock), mining tailings (residuals after ore processing), dumps or leach piles (used to chemically extract metals), and sludge resulting from mine water treatment. However, solving the mine tailings problem is a complex challenge that requires an integrated approach and collaboration between the mining industry, governments, local communities, and environmental experts. When not managed, these tailings can become an environmental hazard (Tang et al., 2021), causing problems, such as acid mine drainage, flow of acid water from mining waste (Stanislaw et al., 2007; Srirattana et al., 2021; Yuan et al., 2022). At the same time, this waste constitutes a new stock of metals and minerals needed to transition to a green circular society (Malyukova et al., 2023). Although the literature on mine tailings reuses and resource valorization is relatively abundant, this domain remains insufficiently explored and requires continuous attention (Araujo et al., 2022). The application of the circular economy concept to mining waste offers a promising way to reduce environmental responsibility and increase the economic value of mining waste from mining operations (Chryss et al., 2012; Adiansyah et al., 2015; Liu et al., 2017; Tayebi-Khorami et al., 2019).

Numerous studies have focused on valorizing mine tailings by exploring their applications in industry and civil engineering (Delaide 2017; Araujo et al., 2022). However, the valorization of mine tailings as agricultural soil amendments has been overlooked (Edkari et al., 2014). It represents an innovative alternative aimed at addressing both the environmental issues associated with this waste and enhancing soil fertility for sustainable agriculture. By reusing mine tailings as soil amendments, not only is their potential environmental impact mitigated, but also it contributes to addressing nutritional quality issues in agricultural products by supplying essential nutrients, particularly micronutrients, and improving the edaphic environment of crops and soil properties. Crops typically require low quantities of micronutrients per hectare. For field crops, Fe, Cu, Mn, Zn, B, and Mo are the most frequently cited micronutrients limiting the normal development of main crops (Welch and Shuman, 1995; Tavakoli et al., 2014; Rout and Sahoo, 2015). Although these elements may be present in the soil, their effective availability to plants depends on factors such as the reserve in the parent rock, the level of organic matter, soil pH, and precipitation conditions (Tripathi et al., 2015). Additionally, their effective uptake is influenced by interactions with other major nutrients, such as nitrogen, sulfur, calcium, or phosphorus, and the presence of other micronutrients. Deficiency levels can sometimes approach toxicity levels (Graham, 2008), and the type of tillage can also impact micronutrient availability (Amami et al., 2021). The recent research, including that conducted by Sharafi et al. (2021), demonstrated the significant impact of micronutrients on grain yield, dry matter, as well as concentrations of iron, zinc, and copper. Furthermore, the link between micronutrient deficiency in soil and humans is well-established. Plants grown in the soils depleted of micronutrients will have reduced levels of these elements, potentially leading to micronutrient deficiency in humans consuming these plants (Graham, 2008).

Research conducted across various countries in Asia, Africa, and Latin America has established a link between micronutrient deficiencies in soil and similar deficiencies in humans (Shukla et al., 2018). To address micronutrient deficiencies in agricultural soils, various global initiatives have introduced new green technologies for sustainable development. These include precise fertilization techniques, low solubility fertilizers, coated fertilizers, bio-based fertilizers, nano-fertilizers, and even the transformation of abandoned tailings ponds into fertile agricultural soils through appropriate rehabilitation efforts (Mikula et al., 2020; Xu, 2022; Guardiola-Márquez et al., 2023; Yu and Zahidi, 2023). Nanotechnology, considered an emerging technology, is viewed as a promising avenue for sustainability in the agricultural sector (Khan et al., 2021; Zafar et al., 2021).

The challenge lies in improving the transfer of micronutrients from agricultural soils to plant parts, particularly in wheat (*Triticum aestivum* L.) (Augustine and Kalyanasundaram, 2020). Wheat provides over 20% of the calories consumed globally but is inherently low in zinc (Zn) and iron (Fe). Biofortification, involving agronomic interventions, genetic engineering, and conventional plant breeding, has emerged as a promising strategy to combat Fe and Zn deficiencies in food crops (Bouis and Welch, 2010; Stangoulis and Knez, 2022). Mineral deficiencies in soils and crops negatively impact productivity, nutritional quality, and human health (Assunção et al., 2022; Dhaliwal et al., 2022; Murgia and Morandini, 2023).

In Morocco, the mining industry is strategically important, generating a large amount of waste rock and mine tailings (Khalil et al., 2013; Midhat et al., 2019; Zine et al., 2020b). Proper management of these residues can create economic opportunities and jobs. However, scientific studies on the exploitation of abandoned mine tailings in Morocco as a source of micronutrients for plants are crucial for sustainable agricultural development. Micronutrients can enhance soil fertility and crop quality, addressing food demand in a fragile ecosystem affected by unfavorable climatic conditions. Morocco's agricultural sector plays a vital economic and social role, contributing approximately 14% to Gross domestic product (GDP). Cereal crops, particularly wheat, are essential, covering over 5 million hectares and generating 20% of total agricultural sales. Wheat is grown on approximately 2 million hectares; durum wheat and barley are also grown over significant areas. Micronutrient deficiency is a public health concern, especially affecting women and children. The Moroccan Ministry of Health launched a national fortification program to address deficiencies, with Fe deficiency alone costing the state significant resources annually (Zahour, 2021). This study focuses on the Casablanca-Settat region in western Morocco, with great potential for cereal production. Poor fertilization practices and intensive irrigation have led to humic stock loss, carbonate leaching, and soil structure deterioration. Excessive mineral fertilization has accumulated phosphorus, reducing micronutrients absorption by plants (El Bourhrami et al., 2022; Rerhou et al., 2022, Bel-Lahbib et al., 2023). This study offers an efficient and sustainable solution by reusing mine tailings, specifically from the Kettara mine, as a mineral fertilizer source rich in micronutrients and the approach applied is anticipated to be less risky and costly than current tailings facilities.

For this purpose, this study aimed to address plant micronutrient needs through the valorization of mining waste, tackling various environmental problems. The objective was to contribute to improving soil fertility in micronutrients in the semi-arid agricultural area of Morocco. The strategic goals included (1) Evaluating the amendment of agricultural soils with mine tailings rich in micronutrients at studied doses, (2) Determining the transfer of mineral micronutrients in wheat grains, and (3) Finding appropriate doses without soil and plant contamination.

MATERIALS AND METHODS

Study area description

The Casablanca-Settat region, covering an area of 19 448 km², is delimited to the North-East by the Rabat-Salé-Kénitra region, to the East by the Beni Mellal-Khénifra region, to the South by the Marrakech-Safi region, and to the North and West by the Atlantic Ocean. The used agricultural area of this region represents 58.1% of its total area, or 1 335 639 hectares. Irrigated land covers approximately 146 000 hectares, or nearly 11% of the regional used agricultural area. The semi-arid climate of the region, under the influence of the Atlantic Ocean, is characterized by apparent variability, with minimum temperatures of 7 °C and maximum of 27 °C. Although heat peaks, reaching 38 °C to 40 °C, can be recorded a few days a year, their frequency remains exceptional. Rainfall varies from year to year, oscillating between 220 and 760 mm with a mean of 310 mm (Figure 1). Agriculture and livestock are the main sources of income for the active rural population of the region. Agricultural practices are essentially based on tillage and include the cultivation of cereals, legumes, sugar beets, fodder, market gardening, olive trees, vines, and arboriculture. The success of these activities depends on the quality of soils and surface and groundwater resources available in the region. At the same time, the majority of farmers practice intensive breeding of sheep and cattle, as well as poultry farming and beekeeping. The study area presents a diversity of underground resources and a topography conducive to intensive agriculture. The deep soils located in the interior of the region, characterized by their fertility, are used for large crops and high-value crops. On the other hand, the coastal zone is made up of alternating depressions and consolidated dunes, forming part of the semi-arid domain and characterized by generally poor soils.

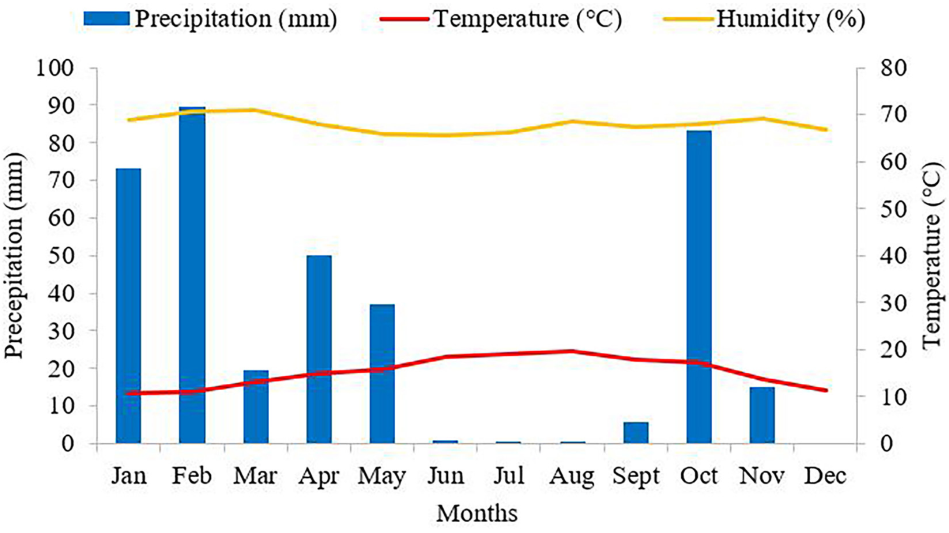

Figure 1. Climatic conditions in the experiment site in 2023

Experimental design

The experiment was conducted using a split-plot design, with soil as the main factor, comprising three levels, and the dose of mine tailings as the secondary factor, with five levels, divided into three blocks. Initially, the three soil with different texture were divided into three blocks. Then, the five mine tailings dose conditions were randomly and independently distributed within these 15 pots, making a total of 45 pots. The main objective was to evaluate the effect of soil, treatment dose and the interaction between soil and treatment. Figure 2 demonstrates the flowchart of the methodology employed.

Treated mine tailings (TMT)

The treated mine tailings (TMT) utilized in this study were collected from the abandoned Kettara mine, situated approximately 35 km northwest of Marrakech. They are characterized by: acidic pH approximately at 2.34; abundance in available micronutrients: Fe, Cu, Mn, Zn; elevated presence of secondary elements: S, Mg, and Ca; and low levels of toxic heavy metals: Cd, Pb (Table 1). These findings align with those reported by other researchers (Hakkou et al., 2008a, b; Midhat et al., 2019; Zine et al., 2020a).

Plant material

Wheat seeds (*Triticum aestivum* L.) were procured from the regional center of the national seed commercialization society (SONACOS). The Achtar variety, chosen for its potential yield of 45 quintals. ha^{-1} and a relatively short life cycle, holds significant popularity within the wheat production system in Morocco.

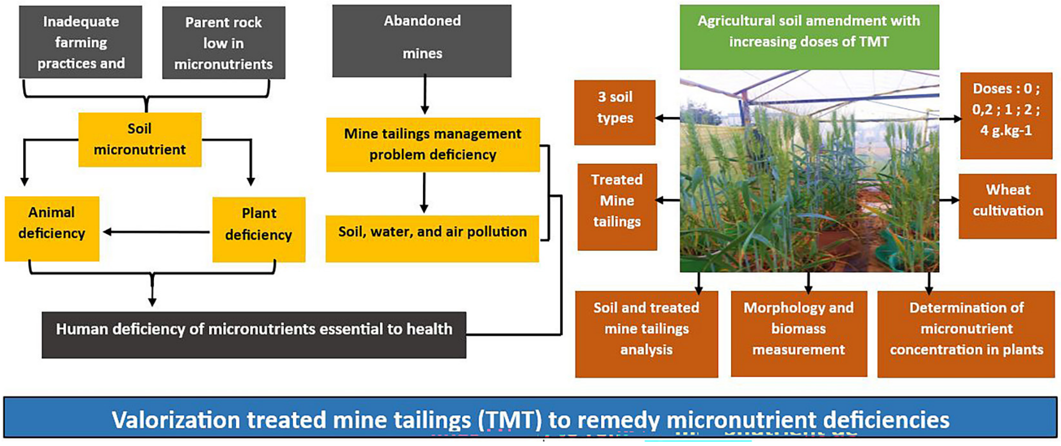

Figure 2. Flowchart of the methodology employed

Sowing

The experimentation transpired within the controlled environment of the greenhouse situated at the Faculty of Sciences, Chouaib Doukkali University in El Jadida, Morocco. This ensured a meticulously regulated and cohesive context for this research. For this study, Treated Mine Tailings (TMT) were blended with agricultural soils at varying doses: 0, 0.2, 1, 2, and 4 g·kg^{-1}. Plastic pots with a volume of 5 L were employed, each containing 3 kg of soil per pot, designed with careful consideration for drainage perforations. Liquid quantities infiltrated were reintroduced to maintain nutrient supply throughout the experiment. In each pot, a total of 20 *Triticum aestivum* L. seeds were sown. The plants were cultivated in the greenhouse for 92 days, commencing on January 28th, 2023. Throughout this period, they adhered to a natural day/night cycle, receiving irrigation and NPK fertilizers in accordance with their growth stages. Manual weeding was undertaken to uphold experimental conditions. After ten days, a plant count was conducted, followed by a thinning process to maintain a consistent population of 10 plants per pot, ensuring precise and significant observations during the study.

Plant growth parameters and biomass assessment

Plant growth parameters and biomass assessment were integral components of the study. Measurements encompassed shoot height, root length, and tillers per plant. Germination success was quantified as a percentage, obtained by dividing the number of successfully germinated seeds by the initially planted total. A meticulous protocol was employed to prepare plant material for subsequent analysis. Plant components (roots, spikes, and shoots) were carefully cleaned, then dried at a constant 65 °C for 72 hours before fine milling. Two pivotal parameters, above-ground biomass (cumulative mass of spikes and shoots) and total biomass (total shoots and roots biomass), were utilized to evaluate plant growth.

Soils analysis

For physicochemical analyses, samples of agricultural soil and mine tailings were taken. Before mixing, soils underwent drying and particle size analysis. The collected soil samples were air-dried, crushed, and passed through a 2 mm sieve to obtain a homogeneous sample for analysis. The soil tested and the TMT were processed for various physicochemical analyses including particle size analysis (Robinson et al., 1997), pH (1:2.5), soil organic matter (SOM) (Walkley and Black, 1934), carbonate content ($CaCO_3$) (Bernard calcimeter), electrical conductivity (EC) (1:5), assimilable phosphorus (P_2O_5) (Olsen, 1954), magnesium oxide (MgO), sodium oxide (Na_2O), potassium oxide (K_2O), and calcium oxide (CaO) (Ammonium acetate extraction solution), cation exchange capacity (CEC) (Metson, 1957), total nitrogen (Kjeldahl method) (Bremner and Mulvaney, 1982), nitrate nitrogen (NO_3-N) (Sims and Jackson 1971), ammoniac nitrogen (NH_4-N) (Dorich and Nelson, 1983), micronutrients zinc (Zn), manganese (Mn), iron (Fe) and copper (Cu) (Lindsay and Norvell 1978).

Table 1. Physico-chemical characterization of the mine tailings used (means ± standard)

Parameters	Average	Standard deviation
Clay %	11.5	4.51
Silt %	5.5	5.91
Sand %	83	8.54
SOM	1.32	0.15
pH	2.34	0.03
EC uS.cm^{-1}	7.57	0.02
CEC meq.100g^{-1}	6.92	1.88
P_2O_5 mg.kg^{-1}	3.14	0.02
CaO mg.kg^{-1}	2167	849
K_2O mg.kg^{-1}	79.33	25.03
MgO mg.kg^{-1}	3169.67	235.06
Na_2O mg.kg^{-1}	416	229.27
Cu mg.kg^{-1}	1343.47	48.63
Fe mg.kg^{-1}	13123.73	828.68
Mn mg.kg^{-1}	26.4	1.05
Zn mg.kg^{-1}	152.64	12.3
Cl^- mg.kg^{-1}	3996	2.00

Analysis of micronutrient concentrations in wheat grain after harvest

In this study, the essential micronutrients Cu, Fe, Mn, and Zn were analyzed due to their crucial role in the physiological processes of living organisms and their interactions with soil, plants, and food. A total of 45 wheat grain samples were prepared. The entire plants, including aerial parts and roots, were harvested 92 days after sowing, followed by washing and rinsing with deionized water. Subsequently, the specimens were dried in an oven at 65 °C for 72 hours and then weighed. The quantification of micronutrients content in plant grains followed a detailed protocol: dried grains were ground in a porcelain mortar, calcined in a muffle furnace at 450 °C for 4 hours, and the ashes obtained were mineralized with aqua regia (HNO_3 at 25% and HCl at 75%). The resulting solution was reduced to dryness on a sand bath until complete decolorization occurred. The residue obtained underwent redissolution in 10 ml of hydrochloric acid (5% HCl), filtration at 0.45 microns, and dilution with hydrochloric acid (5% HCl) to a final volume of 20 ml, adhering to the methodology outlined by (Tauzin and Juste, 1986). The concentrations of Fe, Cu, Zn, and Mn in the grains were quantified using inductively coupled plasma-atomic emission spectrometry (ICP AES).

Determination of bioconcentration factor

Bioconcentration factor (BCF) determination aims to measure micronutrients in the edible parts of cereal crops, especially in grains, based on the concentration of metals in the soil (Cui et al., 2004). If the BCF was greater than 1, it indicates that micronutrients were present in high quantities inside the cultivated parts compared to the soil (Kisku et al., 2000). The bioconcentration factor was calculated according to the following (Equation 1):

$$BCF = \frac{MCWG}{MCS} \tag{1}$$

where: *BCF* – the bioconcentration factor, *MCWG* – micronutrients concentration in wheat grains (mg.kg-1), *MCS* – micronutrient concentration in soil (mg.kg-1).

Data analysis

An analysis of variance (Two-way ANOVA) was conducted using SPSS software, version 20, to evaluate the significant impact of TMT amendment doses on biomass, plant morphological parameters, and micronutrient concentrations (Fe, Cu, Mn, and Zn) in wheat (*Triticum aestivum* L.) plant tissues, with a confidence level of 5%. The Least Significant Difference test (LSD) at a probability level (*p*) less than 0.05 was employed to discern significant differences between the means of all treatments. Additionally, regression analysis was performed to assess the relationship between biomass and morphological parameters of wheat plants cultivated in soils amended with various doses of mine tailings. Regression procedures were also applied to explore statistical relationships between micronutrient concentrations in wheat tissues (expressed in $mg \cdot kg^{-1}$) and amendment doses (expressed in $g \cdot kg^{-1}$).

RESULTS AND DISCUSSION

Results of physicochemical analyses of the initial soil

The data presented in Table 2 delineate the outcomes of physicochemical analyses conducted on the three initial soils tested. Employing a texture triangle, soil 1 characterized by a clay texture, soil 2 silt texture, and soil 3 sandy loam texture (Figure 3). Concurrently, these soils exhibit alkaline pH values of 8.26, 8.46, and 8.03, respectively. This alkaline propensity raises concerns regarding the availability of specific micronutrients, such as iron, manganese, copper, and zinc. It also predisposes these soils to deficiency issues, such as iron chlorosis, which can inflict damage on plants, particularly fruit trees.

In addition, the results indicate that soil 1 and soil 3 are deficient in organic matter and micronutrients (Fe, Cu, and Zn). Exceptionally, soil 2 is relatively enriched in micronutrients, with rich levels of phosphorus and potassium.

Physicochemical analyses of the soil after the addition of mine tailings

Following the application of Treated Mine Tailings (TMT), there was a notable and significant elevation in the overall concentrations of Cu and Fe in the soil, as illustrated in Figure 4. These concentrations surpassed those observed in the initial soil (T0), indicating a substantial impact resulting from the addition of mine tailings.

Effects of the mine tailings addition on the germination rate

Throughout this experiment, it was observed that the germination of *Triticum aestivum* L. seeds remained unaffected significantly by the varied doses of mine tailings applied. As shown in Figure 5, the impact on germination percentage does not appear to be directly correlated with the concentration of micronutrients present in the

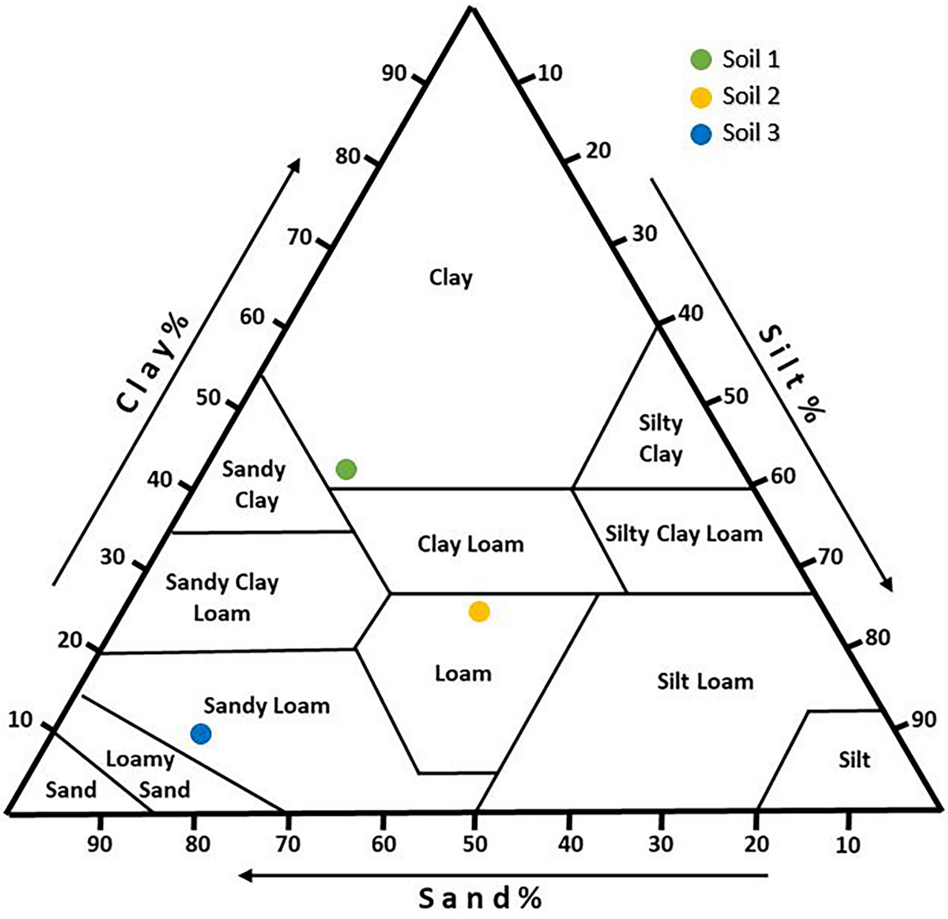

Figure 3. Triangle textural of soil tested

Table 2. Physico-chemical characteristics of the initial soils studied

Soil properties	Soil 1	Soil 2	Soil 3
Clay %	41	26.4	9.9
Silt %	16	36.8	17.9
Sand %	42	36.9	72.2
SOM %	1.83	1.92	1.10
pH	8.26	8.46	8.03
EC uS.cm^{-1}	240	459	346
$CaCO_3$ %	2.29	0.13	0.27
P_2O_5 mg·kg^{-1}	79	219	89
CaO mg·kg^{-1}	7252	4290	4150
K_2O mg·kg^{-1}	135	399	99
MgO mg·kg^{-1}	1337	1292	504.6
Na_2O mg·kg^{-1}	464	755.3	340
Cu mg·kg^{-1}	0.33	3.35	0.52
Fe mg·kg^{-1}	12	4.68	3.99
Mn mg·kg^{-1}	19.92	68.11	44.05
Zn mg·kg^{-1}	0.42	1.35	1.87
CEC meq·100g^{-1}	14.01	6.46	1.84
N-NO_3 mg·kg^{-1}	15.36	16.24	10.13
N- NH_4 mg·kg^{-1}	3.99	2.95	4.77

mine tailings. On average, the impact is similar to the control even though various scientists already established that micronutrient priming improved the germination, vegetative growth and yield of various crops (Mondal and Bose, 2019).

Effect on plant height, number of tillers and root length

Highest plant height (63 cm) at harvest, was recorded with dose 1 g·kg^{-1} in comparison to other mine tailings-fortified treatments (Figure 6) while, the statistically lowest plant height of (42 cm) was recorded under the treatment 4 g·kg^{-1}.

The increase in plant height is attributable to the essential roles and high availability of micronutrients provided by treated mine tailings, rich in micronutrients such as Cu, Fe, Mn, and Zn. These elements contribute to the formation of several enzymes, cell walls and plant growth. Cu accelerates an enzyme activator and the synthesis of proteins and chlorophyll. It is also involved in the process of biological nitrogen fixation and in the regulation of Mn absorption (Nazir et al., 2019).

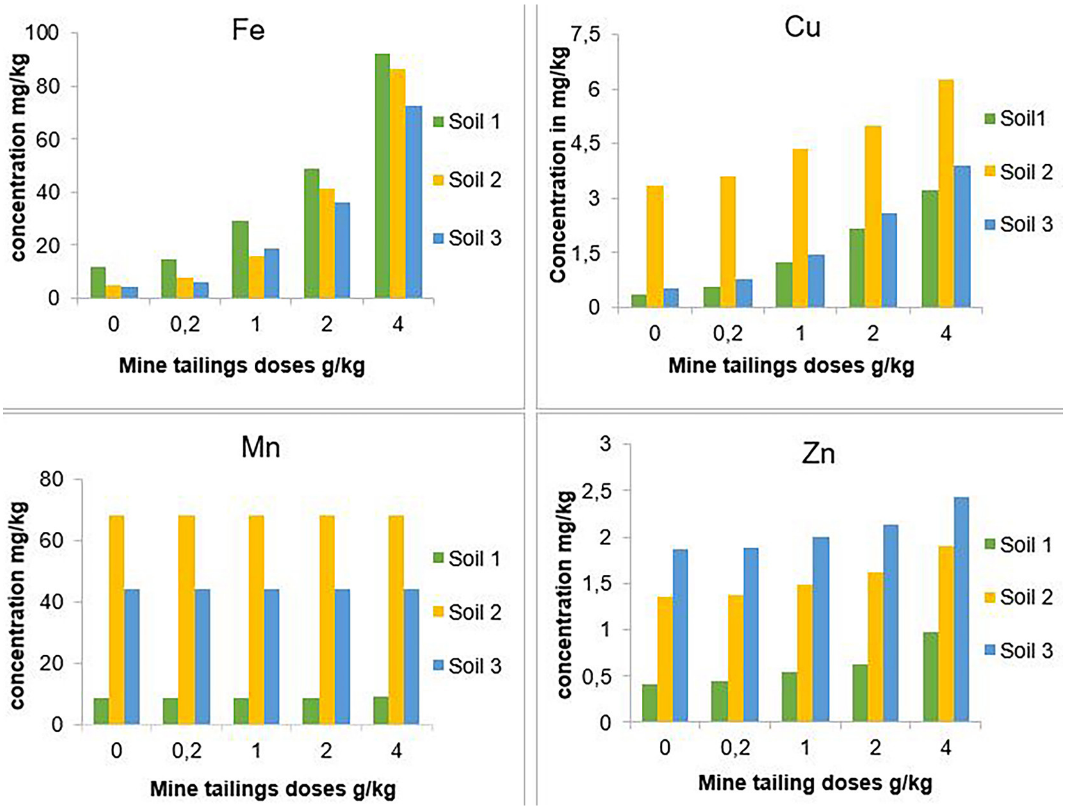

Figure 4. Average concentrations of micronutrients in the soil as a function of application doses after the wheat harvest (92 days after sowing)

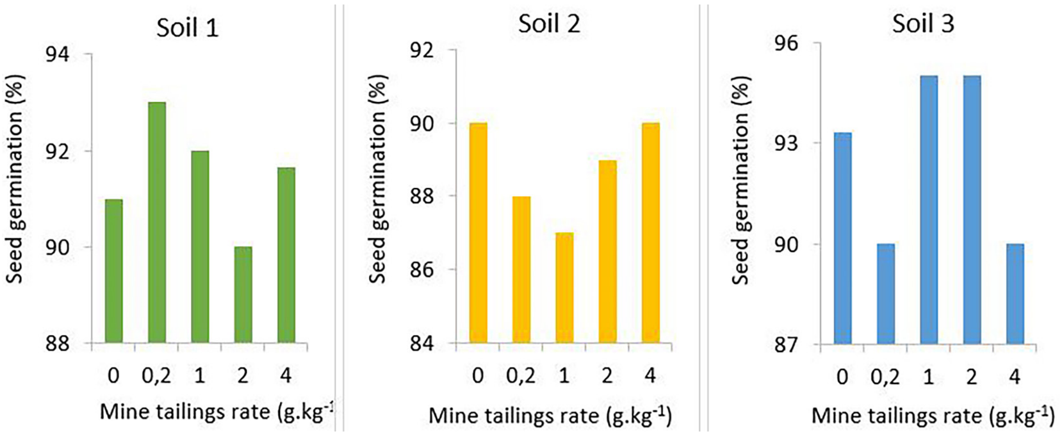

Figure 5. Effects of different treatments on the germination rate (%) of the wheat crop (*Tritium aestivum* L.)

Manganese is directly involved in photosynthesis and the production of chlorophyll, by activating the enzymes necessary for the distribution of growth regulators within the plant. Zinc is of particular importance during the early stages of growth and seed formation, while contributing to the production of chlorophyll and carbohydrates. Iron, for its part, is essential for the formation of chlorophyll, plant respiration (in particular the transport of oxygen) and the synthesis of certain proteins. It is also a major component of several enzymes, including catalase, peroxidase, and cytochrome oxidase. The trend of decreasing plant height is due to the high dose and antagonism of micronutrients, which reduces plant growth. this phenomenon is explained by Rietra et al. (2017).

The number of tillers per plant as affected by the addition of different mine tailings is shown in Figure 6. Analysis of the results of different treatments applied reveals significantly different

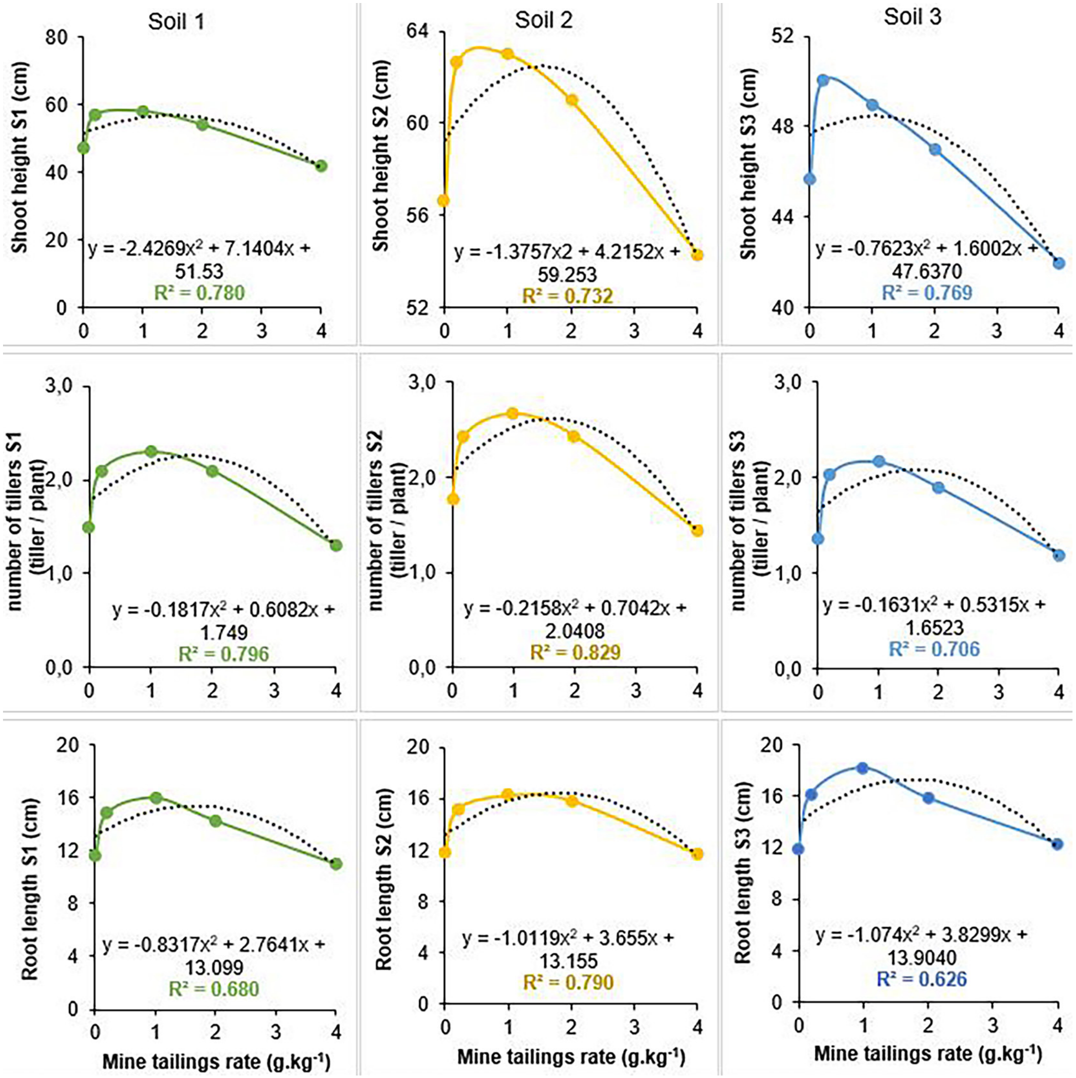

Figure 6. Effects of different treatments on the number of tillers, the root length and the stem length in the wheat crop (*Triticum aestivum* L.)

responses. The number of tillers per plant was recorded significantly maximum (2.67) for silt soil under the 1 g·kg^{-1} treatment compared to other TMT treatments and statistically at par with the 0.2 g·kg^{-1} and 2 g·kg^{-1} treatments. The application of mine tailings reduces stem weakness and leads to the formation of more fertile tillers (Zafar et al., 2016; Saquee et al., 2023).

The architecture of the root system plays a fundamental role in the absorption of nutrients, including Cu, Fe, Mn, and Zn. These elements, being essential nutrients for plants, are absorbed by the roots improving both their growth and their yield and the nutritional quality of the wheat. These micronutrients, by promoting phytosynthesis, also allow root development (Saquee et al., 2023). The results revealed that the plants underwent treatments of 0.2 g·kg^{-1} and 1 g·kg^{-1} had longer and more vigorous roots, especially for soil 3 (Soil with a Sandy texture). These developed root systems lead to a higher biomass yield.

However, mine tailings inputs had an impact on the morphology of the wheat crop (*Triticum aestivum* L.). Indeed, the different morphological parameters revealed significant trends. The length of the roots, the length of the shoots and the number of tillers per plant are gradually increased with the mining tailings amendment doses of 0.2 and 1 g·kg^{-1}, followed by a decrease observed for doses higher than 2 g·kg^{-1}.

Effect on the biomass of the aerial and root part of the crop

A consistent pattern was evident in the measurements of root, shoot, and wheat grain biomass,

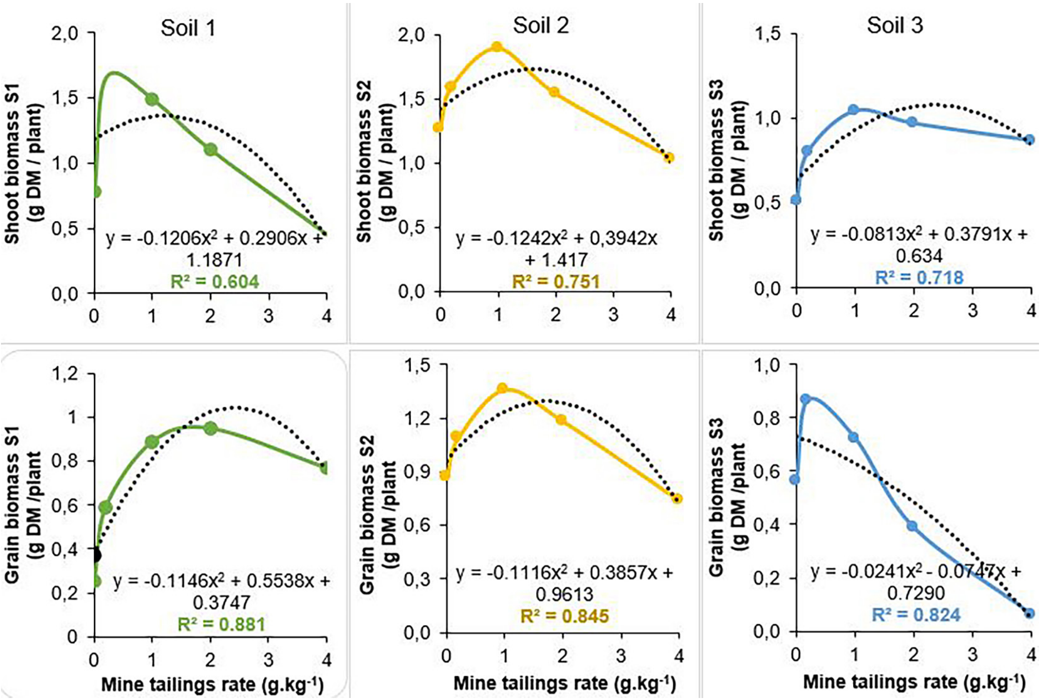

Figure 7. Effects of different doses of mining tailings amendment on the root biomass and the aboveground biomass of the wheat crop (*Triticum aestivum* L.)

as depicted in Figure 7. The observed phenomenon of enhanced growth and yield of *Triticum aestivum* L. at lower levels of mine tailings, amendments can be ascribed to the sufficient provision of micronutrients meeting the plant's nutritional demands. The improved growth of wheat with the addition of mine tailings at these lower concentrations aligns with similar trends observed in other monocotyledonous plants, such as triticale and corn.

Conversely, the decline in wheat growth observed at higher doses of mine tailings amendments can be attributed to potential micronutrients toxicity effects and antagonistic interactions with other mineral elements, including calcium, nitrogen, phosphorus, and potassium, as well as micronutrients (Rietra et al., 2017). The intricate interplay between micronutrients and plant absorption has been extensively investigated. Research indicates that certain micronutrients, such as Zn, can inhibit the absorption and accumulation of essential elements, like K, Ca, and Fe. Due to their structural resemblance to essential cations, micronutrients may compete for uptake by root cells, hindering nutrient absorption (Hunter and Vergnano, 1953; Siedlecka, 1995; Kabata-Pendias, 2011; Gupta et al., 2019). At elevated doses of mine tailings inputs, micronutrients have the potential to enter plant root cells, exerting their effects through direct interactions with the sulfhydryl groups of proteins, which may lead to reduced plant growth (Li et al., 2020; Narayan et al., 2023). Additionally, the generation of reactive oxygen species in plant cells in response to micronutrients can damage essential macromolecules, including proteins and lipids, ultimately resulting in decreased plant growth (Sharma et al., 2012; Tripathy and Oelmüller, 2012; Rodrigues De Queiroz et al., 2023).

In this work, treated mine tailings can undergo further treatments to improve the availability of micronutrients and avoid complexation with organic matter. In this regard, nanochelated iron fertilizers hold considerable potential to create valuable results in agriculture (Fakharzadeh et al., 2020). Synthesis of zinc oxide nanoparticles and encapsulation of nanoparticles can be carried out in fertilizers (Beig et al., 2022). The study conducted by Ghazouani et al. (2023) highlighted the effect of biochar on the mitigation of water stress in rainfed durum wheat under the specific conditions of the semi-arid environment of North-West Tunisia. This technique could be effective in this work in the case of enriching this biochar with micronutrient. Other approaches developed by Jubeen et al. (2020) and Fareed et al. (2022) were of interest in this work to further improve the availability of micronutrients. The impact of the long-term TMT supply was taken into consideration to avoid impacts on soil quality (Ibrahimi et al., 2022).

Relationships between extractable micronutrient in soil and its content in wheat grains

The relationships between extractable micronutrients in the soil and their corresponding content in wheat grains were investigated. Table 3 shows the analyses of variance that demonstrated the significant effects of tested soils, treatment and the interaction between soils and treatment on micronutrients concentrations in the grains. The results from the analyses of common wheat grains (*Triticum aestivum* L.) using ICP-AES revealed average concentrations of Fe (118.95 ± 30.78 mg·kg^{-1}), Cu (10.72 ± 3.24 mg·kg^{-1}), Mn (36.14 ± 8.30 mg·kg^{-1}), and Zn (21.57 ± 8.43 mg·kg^{-1}). Notably, these average values exceeded those reported in other comparable studies (Fageria 2001a, 2001b, 2002a, 2002b). Table 4 provides an overview of the micronutrient concentrations measured in wheat grains cultivated over a 92 – day period in soils subjected to varying doses of mine tailings. These concentrations exhibited an overall increase for all studied micronutrients following the different treatments applied. Specifically, the concentrations of Fe and Zn experienced significant increases with amendment doses of 0.2, 1, and 2 g·kg^{-1}. Meanwhile,

Table 3. Effects of different doses of mining tailings amendment on micronutrients concentrations in Wheat (*Triticum aestivum* L.) grains harvested after 92 days (means ± standard error, n = 45)

Source	DL	Copper	Iron	Manganese	Zinc
Soil type (ST)	2	517.57**	8.17**	1703.19**	2584.30**
Block (B)	2	486.28	7.65	141.40	46.63
ST x B	4	1.62	2.46	3.86	0.52
Treatment (T)	4	93.35*	262.07**	36.97*	360.87*
ST x T	8	42.49	20.56**	195.69**	118.94**
*: p < 0.05, **: p < 0.01.					

Table 4. The average concentrations of micronutrients in the grains of Triticum aestivum L. harvested after 92 days according to the different doses of mine tailings amendment (means ± standard error)

Micronutrient		Cu			Fe		
		Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3
Mine tailing dose (g·kg^{-1})	T0	13.38 ± 2.97^{a}	11.80 ± 2.45^{b}	11.54 ± 2.35^{b}	93.44 ± 10.02^{a}	82.78 ± 5.05^{e}	99.12±4.47^{f}
	T1	14.05 ± 2.83^{a}	8.49 ± 2.26^{ab}	9.18 ± 2.23^{ab}	157.37 ± 4.75^{b}	128.41 ± 14.56^{c}	169.13±7.63^{d}
	T2	14.78 ± 2.64^{a}	9.32 ± 2.26^{ab}	9.64 ± 1.70^{ab}	133.83 ± 7.63^{c}	157.60 ± 3.36^{b}	166.61±3.30^{d}
	T3	11.35 ± 2.02^{b}	6.40 ± 2.37^{c}	8.16 ± 2.37^{ab}	114.22 ± 2.53^{d}	113.34±9.51^{d}	90.03 ± 5.00^{a}
	T4	13.03 ± 2.24^{a}	6.80 ± 2.41^{c}	12.89 ± 2.21^{a}	92.93 ± 6.56^{a}	93.21±7.6^{a}	92.29 ± 7.63^{a}
Safe limit^{1}		20			450		
Phytotoxic range^{2}		20–100			> 1000		
		Mn			Zn		
		Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3
Mine tailing dose (g·kg^{-1})	T0	30.85 ± 3.16^{a}	44.34 ± 2.47^{c}	39.34 ± 2.75^{c}	12.08 ± 0.45^{a}	17.48 ± 1.31^{b}	31.34 ± 2.00^{d}
	T1	36.02 ± 2.96^{b}	45.41 ± 2.27^{c}	27.07 ± 2.24^{e}	12.04 ± 1.91^{a}	20.09 ± 1.61^{b}	39.27 ± 1.06^{e}
	T2	32.56 ± 2.23^{a}	50.06 ± 2.77^{d}	26.14 ± 2.11^{e}	12.39 ± 2.02^{a}	16.44 ± 0.67^{b}	32.40 ± 0.79^{d}
	T3	44.19 ± 2.01^{c}	39.44 ± 3.10^{c}	25.04 ± 2.65^{e}	19.01 ± 1.80^{b}	14.22 ± 1.37^{c}	31.21 ± 1.22^{d}
	T4	34.20 ± 1.08^{b}	42.65 ± 2.42^{c}	24.86 ± 1.61^{e}	20.91 ± 1.17^{b}	18.34 ± 1.50^{b}	26.36 ± 0.77^{d}
Safe limit^{1}		-			60		
Phytotoxic range^{2}		> 400			100–150		
Means in the same row, denoted by different letters, exhibit significant differences at P < 0.05, as determined by the LSD test. ^{1}: (Joint 2011); 2: (Kabata-Pendias 2011).							

Table 5. The average bioconcentration values in the grains of Triticum aestivum L. harvested after 92 days according to the different doses of mine tailings amendment (means ± standard error, n = 3)

Micronutrient		Cu			Fe		
		Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3
Mine tailing dose (g·kg^{-1})	T0	0.431 ± 0.0959^{a}	0.347 ± 0.0720^{c}	0.427 ± 0.0868^{a}	0.001 ± 0.0001^{a}	0.001 ± 0.0001^{a}	0.0012 ± 0.0000^{a}
	T1	0.449 ± 0.0903^{a}	0.248 ± 0.0660^{b}	0.337 ± 0.0819^{b}	0.002 ± 0.0000^{b}	0.002 ± 0.0002^{b}	0.0019 ± 0.0001^{b}
	T2	0.457 ± 0.0815^{a}	0.264 ± 0.0641^{b}	0.340 ± 0.0599^{b}	0.002 ± 0.0000^{c}	0.002 ± 0.0001^{c}	0.0019 ± 0.0000^{b}
	T3	0.337 ± 0.0598^{b}	0.174 ± 0.0646^{a}	0.275 ± 0.0797^{c}	0.002 ± 0.0000^{c}	0.002 ± 0.0001^{d}	0.0010 ± 0.0000^{a}
	T4	0.358 ± 0.0615^{b}	0.173 ± 0.0611^{a}	0.398 ± 0.0681^{a}	0.001 ± 0.0000^{a}	0.001 ± 0.0001^{a}	0.0010 ± 0.0001^{a}
Micronutrient		Mn			Zn		
		Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3
Mine tailing dose (g·kg^{-1})	T0	0.038 ± 0.0086^{a}	0.032 ± 0.0011^{a}	0.031 ± 0.0032^{a}	0.142 ± 0.0121^{a}	0.120 ± 0.0126^{a}	0.3457 ± 0.0153^{a}
	T1	0.046 ± 0.0116^{b}	0.034 ± 0.0018^{a}	0.021 ± 0.0022^{b}	0.157 ± 0.0321^{a}	0.140 ± 0.0149^{b}	0.4109 ± 0.0344^{b}
	T2	0.045 ± 0.0028^{b}	0.037 ± 0.0015^{b}	0.021 ± 0.0025^{b}	0.146 ± 0.0262^{a}	0.113 ± 0.0097^{a}	0.3704 ± 0.0371^{a}
	T3	0.061 ± 0.0046^{c}	0.028 ± 0.0026^{a}	0.020 ± 0.0027^{b}	0.238 ± 0.0224^{b}	0.094 ± 0.0125^{a}	0.3489 ± 0.0529^{a}
	T4	0.043 ± 0.0088^{b}	0.030 ± 0.0024^{a}	0.019 ± 0.0018^{b}	0.253 ± 0.0018^{b}	0.111 ± 0.0021^{a}	0.2858 ± 0.0387^{c}

the concentrations of Cu showed a significant increase only with the amendment dose of 4 g·kg^{-1}. Pollard et al. (2002) and Martinka et al. (2014) have also demonstrated the accumulation of micronutrients in different parts of plants.

Previous studies on the concentrations of Fe, Mn, and Cu in wheat grains are relatively limited. Wheat breeding programs often prioritize enhancements in productivity, disease resistance, and adaptability to climate change, sometimes overshadowing the investigation of micronutrients concentrations. Nevertheless, considering the nutritional significance of these elements for human health, the utilization of mine tailings as an amendment and source of essential micronutrients could present an effective solution for enriching wheat grains with Fe, Cu, Mn, and Zn.

Bio-concentration factor of micronutrients in wheat plants

Table 5 shows the average bioconcentration values in wheat grains as a function of the different doses of tailings amendment. The bioaccumulation factor (BCF) was computed for wheat grains, given their pivotal role as a vital component in human nutrition according to Yilmaz and Temizgül (2014) and Cui et al. (2004). The transfer and accumulation of micronutrients from soil to plants constitute a highly intricate process influenced by multiple factors. These factors encompass the chemical forms of micronutrients, soil pH, soil organic matter content, plant species, climatic conditions, and irrigation with polluted water (Yang et al., 2022). The findings of this research indicate that the accumulation of Fe in wheat grains was notably significant only at mine tailing amendment doses of 0.2 and 2 g·kg^{-1}. Conversely, no significant accumulation of Cu, Zn, and Mn was observed, irrespective of the treatment level applied. These outcomes suggest that the efficacy of mining tailings amendment varies based on the specific element and dose applied, underscoring the intricate nature of interactions between plants and micronutrients present in soils.

CONCLUSIONS

Abandoned mines and soil micronutrient deficiencies present significant environmental and nutritional challenges for humans. This study investigated the potential use of treated mining residues as soil amendments in the studied region. The primary objective was to determine the optimal dose that supports wheat growth – an essential crop providing over 20% of the global caloric intake but naturally low in micronutrients (Fe, Cu, Mn, and Zn) – without surpassing health and environmental safety standards.

Three different soil types and five doses of TMT were evaluated for their impact on wheat growth. The results reveal that the region soils are deficient in Fe, Cu, Mn, and Zn, whereas mine tailings from nearby mines contain these elements in abundance. The doses of 0.2 and 1 g/kg of TMT were identified as most suitable for optimal wheat growth. Additionally, grain analyses showed that these doses enhanced the nutritional quality of wheat without exceeding safety standards. In semi-arid environments, where soils often lack essential micronutrients, this study demonstrates the feasibility of using abundant and underutilized mine tailings as a cost-effective alternative to commercial fertilizers for small-scale farmers.

The bioconcentration factor, which measures the transfer of micronutrients to wheat grains, remained below 1, indicating that TMT can be safely used to fertilize wheat at doses below 1 g·kg^{-1} without posing environmental or health risks. This study highlighted the potential of treated mine tailings to enhance plant mineral nutrition, thereby improving agricultural productivity and the quality of agricultural products. The experimental approach could be applied to other plant species and semi-arid regions with micronutrient deficiencies. However, the implementation of these "mineral biofortification" strategies requires further multidisciplinary studies that incorporate molecular plant physiology, soil science, as well as animal and human nutrition.

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