Nature-Based Solutions 8 (2025) 100266

Contents lists available at ScienceDirect

Nature-Based Solutions

journal homepage: www.elsevier.com/locate/nbsj

The effect of compost and moringa leaf extract biostimulant on the phytoremediation of gold mine tailing in South Africa using *Chrysopogon Zizanioides* (l.) roberty

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ARTICLE INFO

Keywords:
Organic amendments
Plant growth promotors
Heavy metal tolerance
Sustainable rehabilitation
Mine waste management
Ecological restoration

ABSTRACT

This study investigated the efficacy of compost and Moringa oleifera leaf extract (MLE) in enhancing the phytoremediation potential of vetiver grass on the gold mine tailings storage facilities (TSF) in the Witwatersrand goldfields region in South Africa. We hypothesized that: (1) Concentrations of heavy metals are high on the tailings material, (2) The growth and phytoremediation potential of vetiver grass will be enhanced in compost-amended tailings with MLE application, with the greatest improvement observed at the highest compost amendment rate (30 % > 15 % > 0 %). The TSF indeed exhibited elevated levels of heavy metals, with arsenic (As) and chromium (Cr) concentrations surpassing both Soil Screening Values (SSV) 1 and 2, while copper (Cu), lead (Pb), and nickel (Ni) levels exceeded SSV1, indicating potential environmental and health risks. A factorial split-plot design was employed, with three levels of compost treatment (0 %, 15 %, and 30 %) and either 0 % or 3 % MLE application sprayed on vetiver grass weekly for 16 weeks. The results showed that vetiver grass died in unamended tailings regardless of MLE application. However, there was no significant difference in growth parameters between vetiver planted on 15 % and 30 % compost amendment. The concentrations of As, Cr, Ni, and Cu were higher in the roots than in the leaves across all treatments. Application of MLE significantly reduced metal uptake (As, Cu, Cr, Ni) in vetiver roots in both the 15 % and 30 % compost amendments. But MLE did not affect the metal accumulation in the leaves of the vetiver grass except for a significant decrease in the uptake of As in 30 % compost amendment as well as a significant decrease in Ni in 15 % amendment. Pb was undetected in both leaves and roots. Notably, the application of MLE biostimulant significantly enhanced vetiver biomass in both 15 % and 30 % compost amendment treatments. This study highlights the synergistic benefits of combining compost and MLE, which enhanced phytostabilization by reducing metal uptake into roots while promoting vetiver grass growth. The findings have significant implications for tailings management, pollutant mitigation, bioenergy production, and carbon sequestration, offering a game-changing approach for sustainable and circular economy practices in mine tailings management.

Introduction

The mining industry, a crucial sector of the global economy, has a legacy of environmental degradation and health risks [1]. In the Witwatersrand region, approximately 400 km^2 of land is occupied by tailings storage facilities (TSF), which continue to release toxic metals decades after mining operations have ceased [2]. The persistent discharge of contaminants poses significant health risks to ecosystems and people residing near or on mine residue areas [3–6]. To address the environmental concerns resulting from mining, phytoremediation strategies are largely employed as a cost-effective and sustainable approach for removing or containing contaminants [7–9]. The two distinct mechanisms primarily used in phytoremediation are phytoextraction and phytostabilization. Phytoextraction uses hyperaccumulator plants for the uptake and removal of contaminants from the soil whereas phytostabilization involves excluder plant species restricting the uptake of contaminants through adsorbing onto the root, or precipitation at the rhizosphere, preventing leaching, erosion and further contamination

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https://doi.org/10.1016/j.nbsj.2025.100266
Received 6 April 2025; Received in revised form 14 August 2025; Accepted 15 August 2025
Available online 19 August 2025

[10,11].

The South African mining industry has developed the Guidelines for the rehabilitation of mined land [12] which recommends the use of indigenous grasses such as *Cynodon dactylon* (couch grass/ Bermuda), *Eragrostis teff* (Teff grass), *Chloris gayana* (Rhodes grass), *Eragrostis curvula* (Wheeping Love Grass); *Digitaria eriantha* (Smuts Finger Grass); *Medicago sativa; Paspalum notatum;* and *Cenchrus clandestinus* (Kikuyu grass) for phytoremediation. Recent findings by James [13] confirm that these guidelines remain influential in the industry's remediation practices to date. However, as the understanding of the mining impacts continues to evolve, there is a growing recognition that traditional approaches may not be sufficient to address the complex challenges posed by mining. A paradigm shift towards holistic and systems-thinking approaches that considers the complex interconnections within entire systems and emphasizes sustainability, climate resilience, and circular economy strategies are vital [14–17].

Utilizing plant species like *Chrysopogon zizanioides* (Vetiver grass) could enhance the economic and environmental viability of phytoremediation efforts [18].

Although vetiver grass is an alien species in South Africa, it is not invasive. Vetiver grass exhibits remarkable tolerance to harsh climatic and substrate conditions [19–21]. Its phytoremediation potential, combined with its potential for value-added products and services, such as high carbon sequestration and bioenergy production from its biomass, make it a valuable resource [18,22].

Vetiver grass has demonstrated significant phytoremediation potential in various applications, including the treatment of chromium (Cr)-polluted wastewater [23] and remediation of heavy metal-contaminated water [24]. Notably, vetiver grass has been shown to reduce concentrations of various heavy metals in acid mine drainage, including nickel (Ni) (38 %), zinc (Zn) (35 %), sulphate (SO_4) (28 %), manganese (Mn) (27 %), Cr (21 %), aluminium (Al) (11 %), and copper (Cu) (8 %) within a year [25]. Additionally, it can accumulate Zn, Cu, lead (Pb), cadmium (Cd), Mn, Al, and Ni [24,26–28]. However, its susceptibility to heavy metal toxicity in certain instances highlights the need to enhance its phytoremediation capacity [24].

A promising yet underexplored approach to a holistic and environmentally friendly approach to phytoremediation involves utilizing vetiver grass enhanced with compost and biostimulants to mitigate nutrient deficiencies [29,30]. Biostimulants are plant or animal derived substances that promote plant growth and resilience by improving nutrient uptake and utilization rather than providing additional nutrients [31,32]. Biostimulants can significantly induce plant resilience to a range of environmental stresses, leading to improved growth and performance [33]. *Moringa oleifera* leaf extract (MLE) is a rich source of metabolites with biostimulant potential in agriculture. MLE has been utilized to enhance plant growth, improve food production, and increase tolerance to both abiotic and biotic stresses [34,35].

This study investigated the combined effects of MLE and compost amendments on vetiver grass' phytoremediation capacity. We hypothesize that the synergy of these amendments enhances vetiver grass growth, metal uptake, and biomass production.

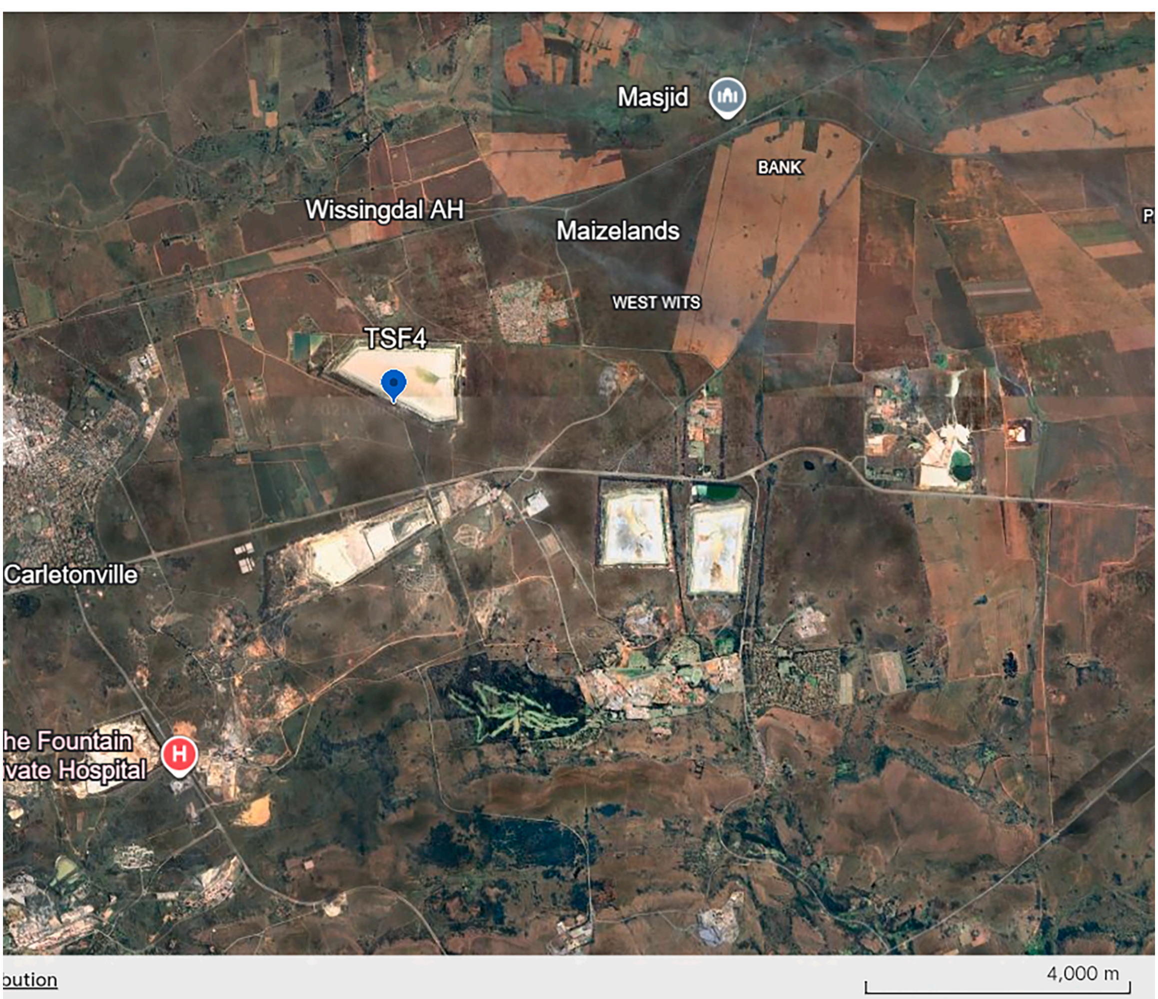

Fig. 1. Google Earth imagery of the tailings (TSF 4), the study site.

Materials and methods

Study site

Driefontein TSF 4 is located approximately 6 kilometers east of Carletonville, Gauteng Province (26°21′9.90"S 27°27′29.01"E). The TSF 4 was first used in the 1990s, and it is still operational. Tailings deposition is performed via the cyclone method. As of 2019, the maximum height and volume were 40 m and 55 million cubic meters, respectively [36]. TSF 4 is surrounded by farmland and human settlements, its location is shown on Google Maps below (Fig. 1).

The mean annual precipitation (MAP) at the study site is estimated to be 661.3 mm per annum [37]. The minimum temperatures occur in the month of July, with average temperatures ranging between minimum 5.3°C and maximum 17.6°C. Maximum temperatures are experienced in the month of January (average minimum 16.7°C and average maximum 27.5°C) [38].

Design and preparation of small-scale field trials

The trials were conducted at TSF 4 from November 2021 to March 2022. A split-plot design was employed in the study. The experiment had a 3×2 factorial design, consisting of three levels of compost treatment (0 %, 15 %, and 30 %) and two levels of MLE treatment (0 % MLE and 3 % MLE), using *Chrysopogon zizanioides* as the vetiver cultivar. Treatment details and descriptions are presented in Table 1 below.

Three blocks, each measuring 1 m × 2 m, were prepared by loosening the compacted soil to a depth of approximately 25 cm using a wood-handled pick. Within each block, 20 holes were dug and filled with soil amended with compost. For blocks 1, 2 and 3, 0 %, 15 % and 30 % compost amendments were employed, respectively.

One-month-old vetiver tillers donated by Hydromulch (Bapsfontein, Gauteng Province, South Africa) were removed from the soil that they came in and pruned to a height of 20 cm to establish the baseline height. A single vetiver grass slip was picked from the batch and planted in each hole. Vetiver grass was watered every day during the first week, after which the plants were not watered unless it rained. Each block was then divided into two sections, with 10 holes in each section. The MLE was purchased from a local commercial supplier in Pretoria (South Africa) and diluted with tap water to form a 3 % MLE (v/v) as per the supplier's recommendations for dilution, and methods by Hoque et al [39]; Mazrou [40]; Abd El Mageed et al [41]. The resultant solution was then sprayed once a week on vetiver grass using a 5 L Garden Pressure Sprayer, with a calibrated dispensing volume of 25 mL per application. The chemical properties of MLE and compost used are provided in Table 2. The other section was sprayed with tap water only until week 16.

The data is presented in round figures

Chemicals and reagents

The chemicals, reagents and solvents used were of analytical grade. Hydrochloric acid (HCl), nitric acid (HNO_3), hydrofluoric acid (HF) and hydrogen peroxide (H_2O_2) were purchased from Fisher Scientific (London, UK). The ultrapure water used throughout the experiment was prepared using a direct-Q 3 UV Millipore system (Massachusetts, USA). The stock solutions and a range of working standard solutions were diluted with ultrapure water.

Table 1
Description of compost and MLE treatments used at the TSF.

Treatment	Description
0 %C 0 %B	no amendment, no MLE biostimulant
0 %C 3 %B	no amendment, 3 % MLE biostimulant
15 %C 0 %B	15 % compost amendment, no MLE biostimulant
15 %C 3 %B	15 % compost amendment, 3 % MLE biostimulant
30 %C 0 %B	30 % compost amendment, no MLE biostimulant
30 %C 3 %B	30 % compost amendment, 3 % MLE biostimulant

Table 2
Calculated concentrations of some elements from the measured stock solutions of MLE and measured element concentrations in compost [42].

Element	MLE elemental concentrations (μg/l) (mean ± std)	Compost Elemental Concentrations (mg/kg) (mean)
Al	3,2 ± 0,4	17685
Ca	469,10 ± 4,9	11583
Co	0,50 ± 0,00	51
Cu	2,5 ± 0.2	127
Fe	5,90 ± 0,10	40851
K	682,0 ± 23,80	6714
Mg	149,80 ± 2,2	2759
Mn	12,20 ± 0,20	432
P	642,2 ± 2,50	14717
Zn	2,60 ± 0,30	198
S	57,80 ± 1,2	3887

Instrumentation

The mass of the samples was measured using an analytical balance (Precisa 180A, Switzerland). The soil and plant samples were digested using a Multiwave 3000 microwave digester (Anton Paar, Switzerland). Element analysis was performed using inductively coupled plasma optical emission spectroscopy (ICP−OES) (Spectro, Kleve, German), and the pH and electrical conductivity (EC) were measured using a Bante 900P multiparameter water quality meter (Bante Instruments).

Vetiver grass preparation for analysis

At 16 weeks, three randomly selected plants from each section were carefully uprooted. This sampling time was informed by previous studies which suggest that critical responses to environmental factors can be observed from 12 weeks onwards [19,27,43]. The plants' morphological characteristics, including the number of tillers and leaves and leaf length, were measured, averaged, and recorded. The leaves and roots were then separated and subjected to a thorough washing protocol: initially under running tap water, followed by rinsing in 0.05 % HNO_3 to remove surface metals, and finally a rinse with distilled water. After separation, the roots and shoots were air-dried in the laboratory at room temperature to a constant weight, following established methods [27, 42,43].

Vetiver preparation for microwave extraction

Portions of vetiver leaves and roots from different samples were ground to powder using a Mellerware blender. A mass of approximately 0,1000 g of ground material was placed in a microwave digestion vessel. To this mixture, 8 mL of HNO_3 and 2 mL of H_2O_2 were added. Digestion was carried out for 30 minutes in a microwave digester. The digested samples were then transferred to 50 mL centrifuge tubes, which were filled with deionized water. All the samples were filtered through 22 μm pore syringe filters prior to analysis. This microwave digestion procedure was based on the methods outlined by Florian and Knapp [44].

Preparation of tailings for pH and EC measurements

The tailings were sieved, and a mass of 2,000 g of < 125 μm substrate material was weighed into a 50 mL plastic centrifuge tube. A volume of 40 mL of deionized water was added, and the mixture was subsequently placed on an end-to-end rotator for 10 minutes prior to measuring the pH and EC [42].

Soil preparation for microwave digestion and analysis

Tailings were dried in the laboratory at room temperature for 10 days, then homogenized and sieved to < 25 μm particles. For total element concentration analysis, approximately 0.250 g of the sieved tailings were weighed into acid-washed PTFE-TFM liners. A digestion mixture of 9 mL HCl, 3 mL HNO_3, 1 mL HF, and 6 drops of H_2O_2 were added, and the samples were microwave-digested for 60 minutes in the microwave digester. The resulting solution was then transferred to 50 mL centrifuge tubes, diluted with deionized water, and filtered through 0.22 μm Millex PVDF membrane syringe filters prior to ICP-OES analysis [42,44].

Chemical analysis

ICP−OES was used to determine the concentrations of the elements. A total of 15 elements, consisting of toxic metals and macro- and microelements, were quantified in the tailings material to determine the baseline element content prior to planting. After the experiment, the elements of interest (those with concentrations exceeded the South African soil screening values (SSV)): (arsenic (As), Cr, Cu, Mn, Ni and Pb) were quantified in the roots and leaves of vetiver grass. The method for determining the concentrations of the metals in the plant parts and soils was validated using standards. The correlation coefficients of the standards for tailings/soil and plant material were 0,9993 and 0,9997, respectively.

Statistical analysis

The SAS Enterprise Guide 7.1 was used to compute the two-way ANOVA test and Fisher's least significant difference test to test for significant differences in values with changes in treatments.

Results and discussion

Baseline element concentrations of the study site and SSV

The baseline concentrations of the selected elements and the corresponding SSV, as listed in the norms and standards for the remediation of contaminated land and soil quality, are presented in Table 3 below. SSV1 represents soil quality values protective of both human health and eco-toxicological risk, including contaminant migration to water resources. This value is conservative and has the lowest concentration among potential source-pathway-receptor models. SSV2 (Informal Residence) represents soil quality values protective of risk to human health, excluding water resource contamination. The SSV1 and SSV2 (Informal Residence) values were used as remediation target values for this study.

Table 3
Concentrations of elements in the tailings (TSF 4) and South African SSV (mg/kg) (Department of Environmental Affairs [45], 2010).

	Soil screening values (SSV) for metals Measured concentrations in tailings	SSV 1 All land uses Protective of the water resources	SSV 2 Informal Residence
Al	16806,12	—-	—-
As	151,93	5,80	23,00
Ca	5093,07	—-	—-
Cd	BD	7,50	15,00
Co	61,92	300,00	300,00
Cr	112,22	6,50	6,50
Cu	99,31	16,00	1100,00
Fe	37065,63	—-	—-
Mg	3711,60	—-	—-
Mn	607,32	740,00	740,00
Ni	141,52	91,00	620,00
Pb	28,11	20,00	110,00
Na	1288,77	—-	—-
P	976,52	—-	—-
Zn	142,02	240,00	9200,00

——No values provided
exceeds SSV1 and SSV2,
exceeds SSV1 only

The concentrations of As, Cr, Cu, Ni, and Pb exceeded SSV1, with As showing the most significant exceedance (26 times), followed by Cr (17 times), Cu (6 times), Ni (2 times), and Pb (1 time). Further, concentrations of As and Cr exceeded the SS2 values (informal residence). These heavy metals pose significant global concerns due to their toxicity to plants and humans, contaminating soil, retarding plant growth, and impairing photosynthesis, ultimately affecting human health [46]. The accumulation of heavy metals can pose ecological risks, impose stress on living organisms, and contribute to increased mortality rates [47–50].

As exposure poses significant health risks, including skin disorders, cognitive impairment, and various cancers, affecting approximately 200 million people globally [51]. Pb exposure can cause irreversible neurological damage, particularly in children [52,53]. Ni contamination poses significant risks to terrestrial ecosystems, food production, and public health, with chronic exposure having long-term implications for the food supply chain and human health [54]. It is a highly toxic heavy metal that can cause various adverse health outcomes, including chronic fatigue, constipation, loss of appetite, mental retardation, impaired cognitive function, insomnia, and neuromuscular effects [55].

Cr's toxicity varies, with hexavalent Cr being particularly hazardous due to its bio-leachability and water solubility, posing risks to human health and the environment [56,57]. Cu, while essential, can cause acute health issues when consumed in excess, including gastrointestinal disturbances and liver damage [58,59]. Given the severity of these health risks and environmental impacts, these findings highlight the need for concern and mitigation efforts.

Physical and chemical assessment of the study sites

The physicochemical properties (pH and conductivity) of the tailings before and after the experiment were measured, and the results are presented in Table 4.

The alkaline pH of the tailings, further increased by compost application, is crucial when considering phytoremediation of As, Cr, Cu, Ni, and Pb. According to Li et al [60], soil pH affects the bioavailability, solubility, and translocation of metals in plants. The metals can be transformed from one form to the other by pH changes. At high pH, metals tend to form less soluble phosphates and carbonates [61,62], reducing their availability for uptake by plants. Only biologically available forms of metals in the soil can significantly affect plants, while the remaining fraction is bound by the soil matrix irreversibly [63–66]. The pH-dependent bioavailability is crucial in understanding the potential risks and impacts of these metals on the environment and human health, as well as the implications for phytoremediation strategies, which rely on plant uptake of bioavailable metal fractions.

Chemical properties of compost and MLE

Organic amendments such as compost significantly enhance soil fertility in gold mine tailings by increasing nutrient availability and organic matter content [67]. Additionally, compost reduces the translocation of heavy metals from roots to shoots, thereby minimizing the

Table 4
pH and conductivity results of the TSF 4 material.

Site	pH	Conductivity/μS/cm
Before	9,33± 1,22	557 ± 59,2
After	10,79 ± 1,67	632,2 ± 23,5

risk of metal uptake by plants. In a study with *Chrysopogon zizanioides,* 30 % and 60 % compost application limited roots and shoots metal uptake and led to improved biomass [42]. As a result, in this study, the compost application was adjusted to 15 % and 30 % compost amendment. Compost effectiveness is rate-dependent, with optimal application rates varying by context. For example, pelleted manure compost at 180 Mg/ha boosted switchgrass and wheatgrass biomass by over 2.5-fold and above 4-fold, respectively, outperforming lower rates [68]. Therefore, optimizing compost application rates is critical for balancing nutrient enrichment and metal immobilization. Further, compost fosters microbial activities, which plays a key role in improving soil health and plant growth [69]. These microbes enhance nutrient cycling, metal mobilization, and plant-microbe interactions, creating a more favorable environment for grass growth. The effectiveness of compost is, however, dependent on tailings' geochemical properties such as pH and metal concentrations. According to Creamer et al [69], alkaline tailings may require additional amendments like dolomite to optimize compost performance.

MLE owes its efficacy to its rich composition of essential nutrients, including minerals, proteins, vitamins, carbohydrates, fiber, phenolics, and free proline [35]. Additionally, MLE contains significant levels of phytohormones, such as auxins, cytokinins, and gibberellins, which play a crucial role in plant development [70]. As a result, MLE promotes enhanced seed germination, vigorous plant growth, deeper root development, delayed fruit senescence, and increased crop yields and quality, making it a valuable asset in agriculture, particularly for crops grown under both normal and stressful conditions [34,35,71].

Metal accumulation in the leaves and roots of vetiver grass grown on the tailings

Fig. 2 illustrates the metal accumulation patterns in vetiver grass leaves grown on tailings amended with 15 % and 30 % compost, with or without 3 % MLE foliar spray. Notably, MLE application significantly increased As uptake in leaves from the 30 % compost treatment and Ni uptake from the 15 % compost treatment, while other treatments showed no significant difference. Additionally, Cr levels were higher in leaves from the 30 % compost treatment compared to the 15 % compost treatment, whereas As, Cu, and Ni levels remained unaffected by compost rate.

The effect of MLE and different compost amendment on metal uptake are presented in Fig. 3 below. The application of MLE resulted in a significant reduction in As, Cr, Cu, and Ni accumulation in vetiver grass roots across both 15 % and 30 % compost amendments. In contrast,

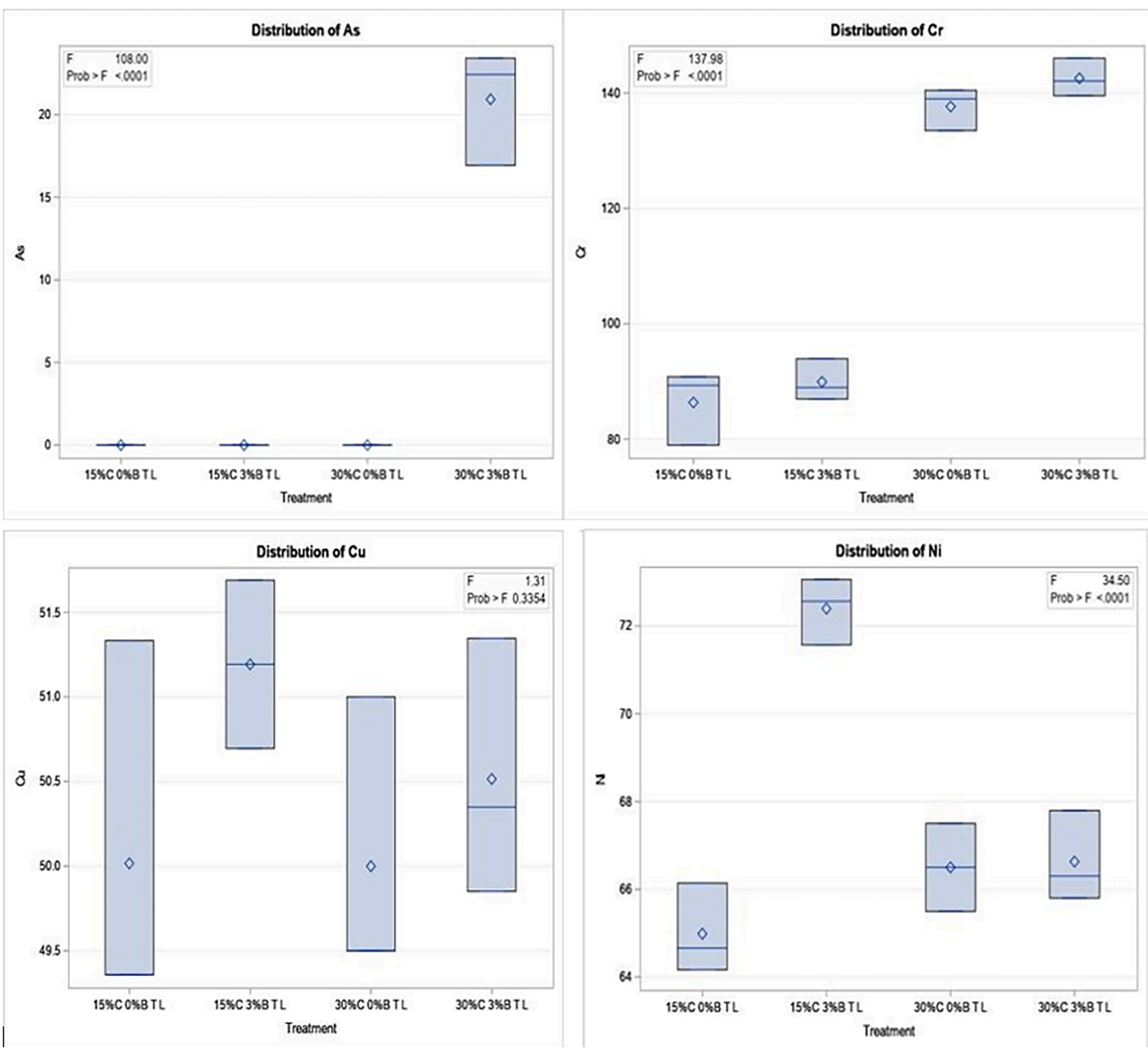

Fig. 2. Concentration of As, Cr, Cu and Ni in the leaves of vetiver grass grown in different compost and biostimulant amendment at Sibanye Stillwater tailings in the Witwatersrand Goldfields, South Africa.

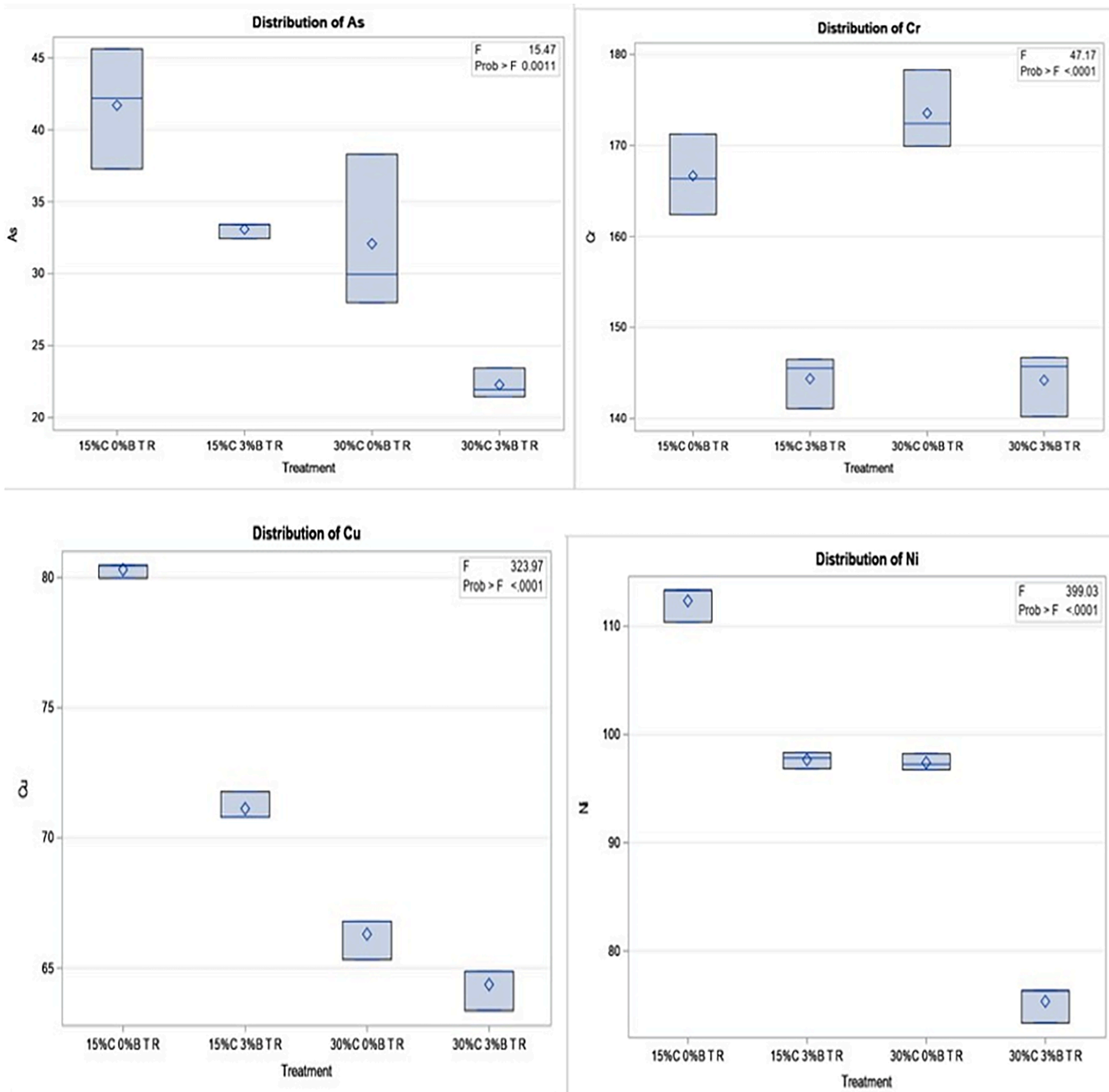

Fig. 3. Concentration of metals in vetiver roots grown in compost and biostimulant amendments at Sibanye Stillwater tailings in the Witwatersrand Goldfields in South Africa.

increasing the compost rate significantly decreased Cu and Ni concentrations.

The effect of compost and MLE on the uptake of metals have been summarized on Table 5 below. The findings align with Desoky et al [72], who reported that MLE application increased plant growth and yield, enhanced leaf photosynthetic pigments and reduced contaminants (sodium (Na), Cd, Cu, Pb, and Ni) in *Capsicum annuum* leaves and fruits. This reduction in metal uptake can be attributed to the biostimulant's ability to counteract the heavy metals derelict effects, enhance plant defense mechanisms, alleviate heavy metals toxicity, improving nutrient uptake and utilization efficiency [73,74]. Notably, the decrease in metal accumulation was offset by a significant increase in number of leaves, number of tillers and root biomass (see Table 6), which is crucial for phytostabilization. This process involves stabilizing the soil, controlling erosion, and regulating soil temperature, ultimately reducing the risk of metal dispersion and environmental harm [75]. Further, improved biomass contributes to enhanced carbon sequestration and be utilized for bioenergy production, thereby improving the environmental and economic feasibility of the phytoremediation process [76–80].

The vetiver planted on unamended tailings died within the first four weeks of planting, regardless of the biostimulant treatment. Unamended tailings often present a unique set of abiotic stresses for plants which disrupt various metabolic processes, posing a significant threat to plants growth and yield parameters [81]. Nutrient deficiency and high metal levels exceeding a critical threshold disrupts metabolism and physiology [82]. Exposure to heavy metals triggers overproduction of reactive oxygen species (ROS) leading to cellular damage, harming plants through chlorophyll degradation, protein oxidation, DNA damage and lipid peroxidation [83–85]. Heavy metal stress triggers a signaling cascade that activates transcription factors, leading to the expression of antioxidant enzymes. These enzymes scavenge ROS, thereby conferring stress tolerance in plants. Additionally, non-enzymatic antioxidants, including ascorbate and metal-binding peptides like metallothionein and phytochelatin, play a crucial role in mitigating metal toxicity by neutralizing ROS and sequestering heavy metals [86]. Despite the activation of antioxidant defense mechanisms, vetiver grass grown in unamended tailings was unable to withstand the extreme heavy metal stress and ultimately succumbed, highlighting the critical role of compost

Table 5
Summary of the effect of MLE biostimulant on the metals in the leaves and roots of vetiver grass grown on amended tailings.

Treatments		15 %C0 %B	15 %C3 %B	30 %C0 %B	30 %C3 %B
VETIVER GRASS LEAVES					
As	t groupings	A	A	A	B
	Effect of MLE	No Significant Decrease		Significant difference	
	Effect of compost at 0 % MLE	No significant difference			
Cr	t groupings	A	A	B	B
	Effect of MLE	No significant difference		No significant difference	
	Effect of compost at 0 % MLE	Significant difference			
Cu	t groupings	A	A	A	A
	Effect of MLE	No significant difference		No significant difference	
	Effect of compost at 0 % MLE	No significant difference			
Ni	t groupings	A	B	A	A
	Effect of MLE	Significant difference		No significant Decrease	
	Effect of compost at 0 % MLE	No significant difference			
VETIVER GRASS ROOTS					
As	t groupings	A	B	AB	C
	Effect of MLE	Significant Decrease		Significant Decrease	
	Effect of compost at 0 % MLE	No significant difference			
Cr	t groupings	A	B	A	B
	Effect of MLE	Significant Decrease		Significant Decrease	
	Effect of compost at 0 % MLE	No significant difference			
Cu	t groupings	A	B	C	D
	Effect of MLE	Significant Decrease		Significant Decrease	
	Effect of compost at 0 % MLE	Significant difference			
Ni	t groupings	A	B	B	A
	Effect of MLE	Significant Decrease		Significant Decrease	
	Effect of compost at 0 % MLE	Significant difference			

Table 6
Physiological parameters of vetiver grass grown on the tailings (N=3; mean ± standard deviation).

	No. leaves	No. tillers	Length (cm)	Leaf mass (g)	root biomass (g)
30 %C0 %B	$32,33 \pm 2,16^a$	4 ± 0^a	$54,33 \pm 3,13^a$	$72,29 \pm 1,89^a$	$69,36 \pm 0,31^b$
30 %C3 %B	38 ± 3^b	$6,33 \pm 0,58^b$	$69 \pm 2,08^b$	$78,98 \pm 2,12^b$	$77,88 \pm 3,25^a$
15 %C0 %B	$29,67 \pm 3,51^a$	$3,67 \pm 0,45^a$	$52 \pm 3,17^a$	$71,62 \pm 2,48^a$	$68,79 \pm 1,20^b$
15 %C3 %B	$40,33 \pm 7,68^b$	$5,67 \pm$ 1,15a[b]	$64,67 \pm 2,04^c$	$80,5 \pm 1,93^b$	$76,51 \pm 2,52^a$
P-values	0,033	<0,001	<0,001	0,007	0,001

Similar superscripts denote no significant difference and different letters denote a significant difference

amendments in enhancing its tolerance and survival.

Vetiver grass survived in both the 15 % and 30 % compost amendments. The results showed that compost amendments reduced the availability of As, Cu, Cr, and Ni, limited their translocation from roots to shoots, and mitigated oxidative stress. This finding is consistent with Cheng et al [87] and Irfan et al [88], who reported that compost application decreases heavy metal availability in soil, thereby reducing plant uptake and mitigating metal toxicity. Reducing metal bioavailability is a crucial initial step in mitigating metal pollution [89]. Organic amendments are valuable for rehabilitating severely degraded soils [90]. Compost possesses beneficial characteristics that enhance soil quality and improve crop performance and resilience under stress [91, 92]. It supplements limited nutrients in tailings and improves soil health by enhancing structure, organic carbon, cation exchange capacity (CEC), and water retention [93].

Studies have demonstrated that supplementing plants with essential mineral nutrients like P, N, Ca, and silica enhances their capacity to tolerate metal stress and counteracts toxicity [94–96]. Mlalazi et al [42] reported an increase in these nutrients due to compost amendment, alleviating metal toxicity and growth deficiency. Our findings align with those of Medyńska-Juraszek et al [97], who observed reduced heavy metal uptake in leafy vegetables amended with biochar and compost. Similarly, our results corroborate the study by Sarathchandra et al [98], which reported increased dry shoot biomass and decreased heavy metal/metalloid concentrations in shoots with increasing compost-to-tailings ratios. According to Liu et al [99], the combined application of organic amendments and ramie planting significantly increased soil pH, total carbon (C), nitrogen (N), and other essential nutrients (such as phosphorus (P) and calcium (Ca)). Concurrently, this treatment led to substantial reductions in soil extractable rare earth elements (REEs) by 80-90 % and Al concentrations by 60-90 %. Key factors influencing the availability of soil REEs, as well as root characteristics like fine root length, included soil pH, total C, N, and P concentrations. Enhanced nutrient availability competes with metal ions for transporters, hence decreasing metal uptake.

Organic matter content enhances metal adsorption by soil components, as evidenced by previous studies [100–102]. Organic compounds complex with toxic elements, render them less available for plant uptake. This is achieved through the formation of insoluble carbonates or metal oxides, which immobilize toxic metals [61,62]. Organic fertilizers have been employed to immobilize toxic elements in polluted lands, leveraging their high cation exchange capacity and complexing ability [103,104]. This effectively reduces metal bioavailability in contaminated soils (Malic et al., 2021). The organometal complexes formed through this process offer a promising solution for decreasing environmental risks posed by heavy metals [105].

Pb was not detected in the roots and leaves of vetiver grass grown in 15 % and 30 % compost amendment. The finding is consistent with Ono et al [106]'s observation that amendments application significantly reduces Pb and Cd bioavailability in mining soil. Furthermore, Pb and Cd uptake by plants is influenced by various soil properties, including pH and organic matter content [107]. Compost induces increases in pH and soil fertility thus contributing to reduced metal accumulation [42].

Physiological parameters of vetiver grass in relation to different amendments

The physiological parameters of vetiver grass grown on the tailings are provided in Table 6 below. Our study found that vetiver growth was slightly higher in the 30 % compost-amended tailings compared to the 15 % treatment, the difference was not statistically significant, indicating that both amendment rates had a similar effect on plant growth. Although these findings support previous studies, such as Sarathchandra et al [98], who reported a positive correlation between compost-to-tailings ratio and dry shoot biomass, and Domínguez et al [108], who observed enhanced growth of Silybum species with increased total organic carbon (TOC) from compost addition, our results show no significant difference. These discrepancies highlight the complexity of compost-plant interactions possibly due to different substrate conditions, abiotic and biotic factors and therefore need for further research.

Compost, as an organic soil amendment, offers distinct benefits and enhances soil health and fertility by improving structure, increasing nutrient retention, mobilizing nutrients, and boosting their bioavailability [109]. Nutrients play a crucial role in stabilizing protein structures and mitigating oxidative stress by suppressing the production of ROS. The absorption and accumulation of micronutrients in plants involve complex mechanisms, including conversion into more soluble ionic forms, followed by transportation via specific or non-specific transporters. Notably, the application of micronutrients has demonstrated significant potential in enhancing yield and quality traits of various crops under severe environmental conditions [81]. According to Alvarez-Lopez et al [93], compost amendment had a pronounced growth-promoting effect, supplying essential nutrients that are typically limiting in mine tailings, while also enhancing soil properties such as structure, CEC, TOC, and water-holding capacity. Compost application increases photosynthetic active leaves and area, retaining green color longer and maintaining higher chlorophyll content. Compost nutrients inhibit premature leaf senescence and sustain larger leaf areas, enhancing photosynthetic efficiency [72].

The application of MLE as a biostimulant significantly enhanced growth parameters of vetiver grass grown on tailings, increasing biomass in both 15 % and 30 % compost amendments. Notably, MLE also reduced metal accumulation in vetiver roots. The addition of MLE was beneficial likely because the vetiver grass's endogenous antioxidant defenses were insufficient to cope with the stress, requiring exogenous support to enhance stress tolerance [70,72,110–112]. MLE's antioxidants stimulated the plant's inherent antioxidant systems, mitigating ROS-generated stress and leading to improved vetiver growth [70]. These findings are consistent with previous studies that demonstrated the efficacy of MLE in promoting plant growth and mitigating abiotic stresses. For instance, Rashid et al. (2021) observed significant improvements in quinoa's growth attributes with 3 % MLE application, while Hafeez et al [113] found that MLE improved plant growth, chlorophyll content, and photosynthetic efficiency.

The rich composition of essential nutrients and phytochemicals in Moringa enables it to promote plant growth, enhance photosynthesis, and mitigate stresses. According to Arif et al [114], Moringa's benefits include improved water use efficiency, mineral content, and yield attributes, particularly under stressful conditions. The presence of zeatin, a cytokinin hormone, in MLE likely played a key role in stimulating plant growth and productivity by promoting cell division, differentiation, and nutrient mobilization.

MLE's antioxidants stimulate the plant's inherent antioxidant systems, mitigating ROS-generated stress. Specific sugars in MLE, such as glucose, sucrose, fructose, and trehalose, offer additional benefits, including ROS scavenging and stress mitigation. Our findings align with previous studies, including Shalaby [71] who demonstrated that MLE application mitigates salt stress effects and enhances lettuce growth, yield, and quality. Similarly, Sadak et al [115] found that MLE improved growth parameters and yield attributes, increased endogenous phytohormones, and enhanced photosynthetic pigments in wheat plants under normal and salt-stressed conditions.

The decrease in metal accumulation in vetiver grass roots can be attributed to the effect of MLE through nutrient-mediated heavy metal antagonism. This mechanism, supported by Anayat et al [94], Srivastava et al [95], and Kováčik and Dresler [116], suggests that MLE's nutrient composition can interact with heavy metals, reducing their uptake and accumulation in plants. By boosting antioxidant defenses and promoting nutrient-mediated heavy metal antagonism, MLE played a role in decreasing metal accumulation in vetiver grass roots. Overall, the application of MLE has shown promising results in promoting plant growth, enhancing stress tolerance, and improving crop productivity, making it a valuable tool for enhancing plant resilience in challenging environments.

Conclusion

This study highlights the potential of vetiver grass for phytostabilization of metal-contaminated tailings, when amended with compost and MLE. The synergistic combination of either 15 % or 30 % compost and 3 % MLE enhanced biomass production, reduced metal accumulation in roots, and improved phytostabilization potential. Generally, there was no significant difference between 15 % and 30 % compost amendment, suggesting that the lower rate may be sufficient for optimal phytostabilization. The results show that As, Cr, Mn, and Ni were accumulated more in the roots than in the leaves. Notably, MLE application promoted biomass growth while minimizing the uptake of As, Cr, Mn and Ni to the roots, yet MLE effect on metal accumulation in the leaves was generally insignificant. Furthermore, Pb was below detection in the leaves and roots of vetiver across the treatments, highlighting the plant's ability to exclude this toxic metal. These findings have significant implications for sustainable tailings management, pollutant mitigation, and potential bioenergy production and carbon sequestration, supporting a circular economy approach that promotes sustainability. Future research should focus on long-term evaluation of vetiver grass phytostabilization potential and exploring the feasibility of bioenergy production and carbon sequestration.

NBS Impacts statement

This study focuses on the potential of mine waste to contribute to these solutions when viewed as a valuable resource rather than a waste product. Planting bioenergy crops such as vetiver grass on mine tailings, instead of merely revegetating for cover, can generate bioenergy, promoting cleaner energy production and a just energy transition. Grass species, such as vetiver grass, exhibit high carbon sequestration potential compared to traditional cover grasses, enhancing carbon sequestration capabilities. Furthermore, as the mining industry declines in South Africa, resulting in job losses, repurposing mine tailings for agricultural use can foster a new agricultural economy. Using compost and biostimulants also promote environmental friendly practices.

CRediT authorship contribution statement

N Mlalazi: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **L Chimuka:** Visualization, Supervision, Resources, Methodology, Funding acquisition. **M D Simatele:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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