DOI: 10.29050/harranziraat.1658095
Harran Tarım ve Gıda Bilimleri Derg. 2025, 29(2): 369-382

Research Article/Araştırma Makalesi

Effects of compost application on sunflower (*Helianthus annuus* L.) yield and some soil enzyme activities in heavy metal-contaminated soils

Ağır metal içeren topraklarda kompost kullanımının ayçiçeği (Helianthus annuus L.) verimi ve bazı toprak enzim aktivitesine etkisi

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To cite this article:
Firat Z., Cun S. & Ramazanoglu E. (2025). Effects of Compost Application on Sunflower (*Helianthus annuus* L.) Yield and Some Soil Enzyme Activities in Heavy Metal-Contaminated Soils. Harran Tarım ve Gıda Bilimleri Dergisi, 29(2): 369-382

DOI: 10.29050/harranziraat.1658095

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Received Date:
14.03.2025
Accepted Date:
02.06.2025

ABSTRACT

Heavy metal accumulation in soils causes environmental pollution, negatively affecting soil microbiota and limiting plant growth and development. This study investigated the effects of different compost doses (0, 1.5%, 3%, and 4.5%) on sunflower (*Helianthus annuus* L.) growth and soil enzyme activities under high heavy metal content soil conditions. The experiment was conducted with three replications, and morphological plant characteristics (plant height, number of nodes, root length, fresh and dry weights), and soil enzyme activities (catalase, urease, dehydrogenase), were analyzed. The results showed that compost applications significantly affected plant growth and soil enzyme activities. The 1.5% compost dose yielded the best results for plant height, root length, and fresh and dry weights, whereas root length, number of nodes, root weights, and catalase and dehydrogenase enzyme activities reached their highest levels at the 4.5% compost dose. These findings suggest that compost can enhance plant growth and improve soil biological activity in heavy metal-contaminated soils. Specifically, the 1.5% compost dose promoted plant growth, while the 4.5% dose increased soil enzyme activities.

Keywords: Compost, Sunflower, Heavy metal, Soil enzyme activity, Plant growth

ÖZ

Ağır metal birikimi topraklarda çevresel kirliliğe yol açmakta, toprak mikrobiyotasını olumsuz etkilemekte, bitki büyümesini ve gelişimini sınırlamaktadır. Bu çalışmada, yüksek ağır metal içeriğine sahip toprak koşullarında ayçiçeği (*Helianthus annuus* L.) büyümesi ve toprak enzim aktiviteleri üzerine farklı kompost dozlarının (0, %1.5, %3 ve %4.5) etkileri incelenmiştir. Deneme, üç tekerrürlü olarak gerçekleştirilmiş ve morfolojik bitki özellikleri (bitki boyu, boğum sayısı, kök uzunluğu, yaş ve kuru ağırlıklar) ile toprak enzim aktiviteleri (katalaz, üreaz, dehidrogenaz) analiz edilmiştir. Sonuçlar, kompost uygulamalarının hem bitki büyümesini hem de toprak enzim aktivitelerini önemli ölçüde etkilediğini göstermiştir. %1.5 kompost dozu, bitki boyu, kök uzunluğu ve yaş ile kuru ağırlıklar için en iyi sonuçları verirken, kök uzunluğu, boğum sayısı, kök ağırlıkları ve katalaz ile dehidrogenaz enzim aktiviteleri %4.5 kompost dozunda en yüksek seviyelere ulaşmıştır. Bu bulgular, kompostun ağır metal ile kirlenmiş topraklarda bitki büyümesini artırabileceğini ve toprak biyolojik aktivitelerini iyileştirebileceğini göstermektedir. Özellikle %1.5 kompost dozu bitki büyümesini teşvik ederken, %4.5 dozunun toprak enzim aktivitelerini artırdığı görülmüştür.

Anahtar Kelimeler: Kompost, Ayçiçeği, Ağır metal, Toprak enzim aktivitesi, Bitki büyümesi

Introduction

Phosphate mining worldwide leads to the formation of hazardous waste types such as low-grade phosphorites, acid mine drainage, and phosphogypsum. These wastes are among the most environmentally harmful materials due to their content of heavy metals, including cadmium (Cd), mercury (Hg), lead (Pb), chromium (Cr), nickel (Ni), uranium (U), thorium (Th), and radium-256 (^{256}Ra) (Tayibi et al., 2009). These toxic elements accumulate in the soil and, under intense chemical weathering, leach into surrounding water bodies, causing toxicity in plants, animals, and humans (Reta et al., 2018; Afshan et al., 2019; Khelifi et al., 2020). Contaminated irrigation water further exacerbates this issue, as heavy metals like Cd and Pb directly inhibit seed germination and early seedling growth in crops (Uslu et al., 2025). The primary source of toxic metals in agricultural soils is phosphate fertilizers. The type and concentration of heavy metals in phosphate fertilizers depend on the metal content of the raw phosphate rock used (Tayibi et al., 2009). In nature, phosphate rock is predominantly found in the form of the apatite mineral, which is classified into different types based on its anion and cation composition, including carbonate apatite, fluorapatite, chlorapatite, hydroxyapatite, and sulfate apatite. Among these, fluorapatite is the most commonly used type in phosphate fertilizer production (Sezen, 1995).

In this regard, sunflower (*Helianthus annuus* L.), a widely cultivated crop in agricultural production, is a crucial plant for investigating the effects of phosphate fertilizer applications. Due to its broad phenotypic adaptability, sunflower is extensively grown in several countries, including Russia, Ukraine, the United States, Argentina, and China (Kostenkova et al., 2019). Its seeds are particularly valued for their high nutritional content, especially in terms of oil composition, and they also exhibit medicinal properties (Adeleke and Babalola, 2020). Previous studies show that Phosphorus (P) fertilization of sunflowers accelerates plant growth and increases sunflower yield (Abbadi and Gerendás, 2011; Sadozai et al., 2013). Phosphorus is particularly essential for the plant until the seed-filling stage, with remobilization rates from leaves and stems to maturing achenes ranging between 30% and 60%. Notably, phosphorus deficiency at the onset of the vegetative growth stage leads to adverse effects such as growth retardation, delayed flowering, poor achene filling, and reduced oil content (Mello Prado and Moreira Leal, 2006).

However, considering the environmental impacts of heavy metals contained in phosphate fertilizers, the use of organic materials as an alternative to mineral fertilizers is becoming increasingly important for enhancing soil fertility in sunflower cultivation. In addition to improving crop productivity, organic-based fertilizers play a crucial role in sustainable agriculture by enhancing soil health and mitigating environmental effects (Ramazanoglu, 2024). In this context, compost is recognized as a significant nutrient source for various crops. As an organic amendment, compost is a valuable resource that improves soil quality and enhances agricultural production (Tian et al., 2016).

This study aims to investigate the effects of compost application on the growth and development of sunflower plants cultivated in soils obtained from phosphate mining sites, as well as its impact on selected soil enzyme activities.

Materials and Methods

Experimental site and design

This research was carried out in a greenhouse environment within the research and application area of the Field Crops Department at Harran University's Faculty of Agriculture. The experimental setup was initiated on July 15, 2024, and continued until the plants reached the flowering stage, at which point they were harvested. The study followed a randomized complete block design with three replications, utilizing plastic pots for the cultivation process.

Soil collection and characteristics

The soil used in the experiment was collected from an agricultural field located within the Mazıdağı phosphate mining site in Karataş village, Mazıdağı district, Mardin Province (37°29'49.02" N, 40°20'35.70" E) (Figure 1). Due to limited irrigation in the region, this land is primarily used for wheat cultivation during the winter months. The chemical properties of the experimental soil were analyzed, and the results are presented in Table 1.

Table 1. Some chemical analysis results of the study soil.

pH (1:2.5 v/w)	EC (1:5 v/w) (dS m^{-1})	Lime (%)	Organic Matter (%)
7.68	0.15	13.44	0.72

The soil pH was determined as 7.68, indicating a slightly alkaline reaction. The electrical conductivity (EC) was measured as 0.15 dS m^{-1}, showing that the soil had no salinity issues. The lime content was determined as 13.44%, classifying the soil as calcareous. The organic matter content was measured as 0.72%, indicating a low organic matter level. The total heavy metal concentrations in the experimental soil were analyzed, and the results are presented in Table 2. When compared to the limit values set by the World Health Organization (WHO), it was observed that the concentrations of Cd (6.47 mg kg^{-1}), Cr (113.34 mg kg^{-1}), and Ni (100.17 mg kg^{-1}) exceeded the WHO threshold limits.

Table 2. Total heavy metal concentration of the experimental soil (mg kg^{-1}).

	Cd	Cr	Ni	Cu	Pb
Soil	6.47	113.34	100.17	37.45	9.03
WHO limit Value	3	100	50	100	100

WHO: World Healty Orrganizasyon.

In particular, the cadmium (Cd) concentration exceeded the WHO limit of 3 mg kg^{-1} by more than twofold, while chromium (Cr) and nickel (Ni) concentrations were also found to be above the WHO limits of 100 mg kg^{-1} and 50 mg kg^{-1}, respectively. On the other hand, the concentrations of copper (Cu) and lead (Pb) remained below the WHO limit of 100 mg kg^{-1}. These findings indicate that the experimental soil has particularly high accumulations of cadmium, chromium, and nickel.

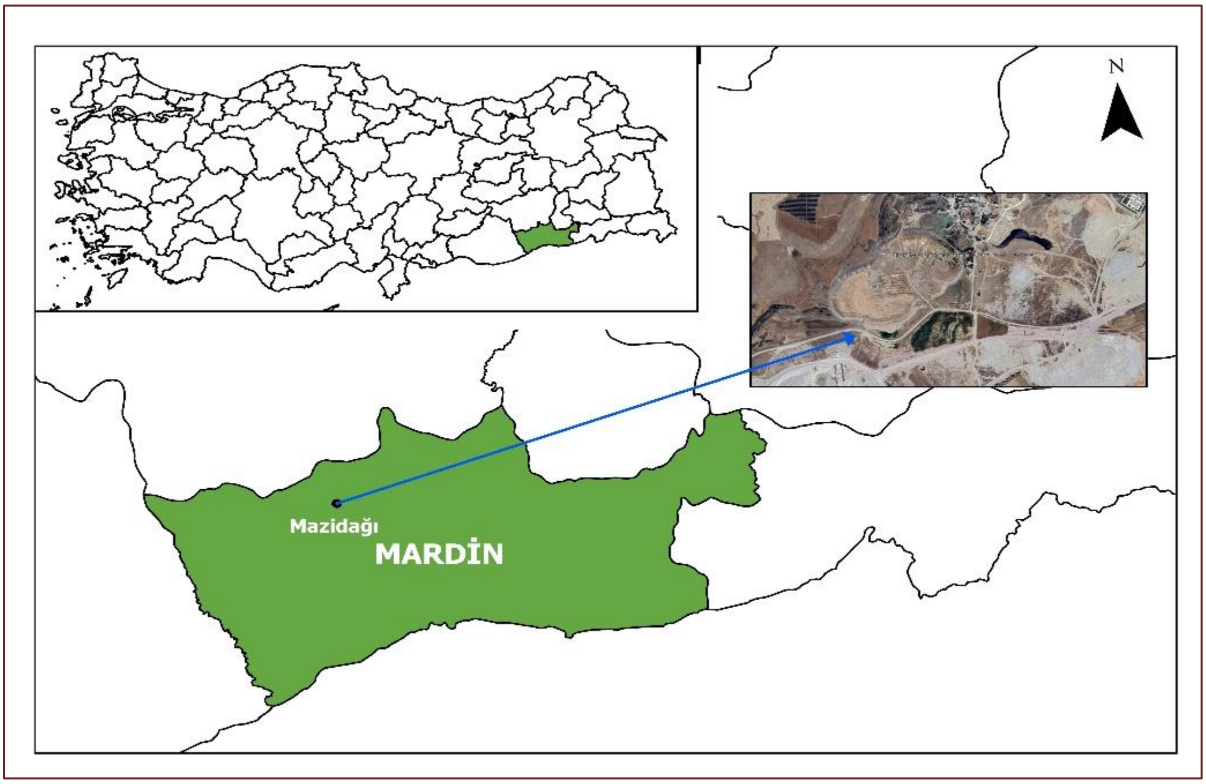

Figure 1. Sampling location of the soil used in the experiment.

Plant material and fertilization

The Suomi sunflower variety was used as the plant material. Fertilization was performed at the time of sowing with 10 kg P da^{-1} (18% N – 46% P DAP), while 15 kg N da^{-1} (46% N Urea) was applied as a topdressing fertilizer.

Experimental setup

The collected soil was placed into 5 kg capacity plastic pots, and compost was applied at rates of 1.5%, 3%, and 4.5%, except for the control treatment, at the time of sowing. Five seeds were sown in each pot, and after emergence, thinning was performed to leave one plant per pot.

Measured parameters

At the flowering stage, the experiment was terminated, and various plant growth parameters were analyzed. These parameters included plant height (cm), number of nodes, root length (cm), fresh biomass of the plant and root (g), and dry biomass of the plant and root (g). Additionally, soil enzyme activities, including catalase, urease, and dehydrogenase, were measured to assess the effects of compost application on soil biological activity.

Soil analysis

The soil reaction (pH) was analyzed using a 1:2.5 soil-to-water suspension, whereas the electrical conductivity (EC) was assessed in a 1:5 soil-to-water mixture. The pH measurement was performed using a pH meter after the suspension was shaken for a specific period and allowed to settle (Jackson, 1958). EC measurement was conducted using a conductivity meter (EC meter) after filtering the suspension. Calcium carbonate ($CaCO_3$) content was determined using the Scheibler calcimeter method, in which the soil sample reacts with hydrochloric acid (HCl), and the amount of carbon dioxide (CO_2) gas released is measured to calculate the lime content in the soil (Allison and Moodie, 1965). Organic matter content was determined using the wet combustion method. In this method, soil organic matter is oxidized using a mixture of potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4). The resulting color change in the solution was analyzed by titration to calculate the organic matter content (Nelson and Sommer, 1982).

Enzyme analysis

Soil enzyme activity assessments were

performed to evaluate dehydrogenase, urease, and catalase activities. Dehydrogenase activity was quantified using a spectrophotometric method, measuring triphenyl formazan (TPF) production following a 24-hour incubation at 25°C, with absorbance recorded at 485 nm (Tabatabai, 1982). Urease activity was determined based on the spectrophotometric detection of ammonium ions (NH_4^+) released as a result of urea hydrolysis, following a one-hour incubation at 37°C (Tabatabai and Bremner, 1972). Catalase activity was analyzed by measuring the oxygen released from the reaction of soil samples with hydrogen peroxide (H_2O_2) using spectrophotometric methods. These enzyme activities were assessed to evaluate soil microbial activity and biochemical processes (Beck, 1971).

Statistical analysis

The experimental parameters were reported as the arithmetic mean of three replicates. To identify statistically significant differences among the three treatments, ANOVA tests were applied at a significance level of $P < 0.05$. All statistical evaluations were carried out using the SPSS software package (version 20).

Results and Discussion

Plant height (cm)

In the study, statistically significant differences were observed among treatments in terms of plant height ($P < 0.05$). The control group (57.0 cm) had the lowest plant height among all treatments (Figure 2). Among the compost treatments, the shortest plant height was recorded in the 4.5% compost application (76.33 cm), while the tallest plant height was observed in the 1.5% compost application (81.0 cm). Compared to the control group, the increase in plant height due to compost applications was 42.10% for the 1.5% compost treatment, 35.66% for the 3% compost treatment, and 33.91% for the 4.5% compost treatment (Figure 3).

Figure 2. Comparison of plant growth under different treatments after harvest.

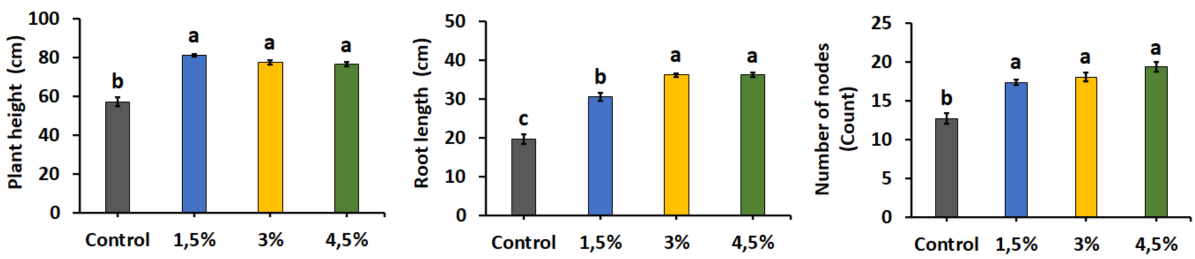

Figure 3. Effects of different compost application rates on plant height, root length, and number of nodes.

Root length (cm)

Statistical analyses revealed significant differences among compost treatments in terms of root length ($P < 0.05$). The control group (19.66 cm) had shorter root lengths compared to the compost-treated groups. Among the compost applications, the shortest root length was recorded in the 1.5% compost treatment (30.50 cm), while the longest root length was observed in the 4.5% compost treatment (36.16 cm). Compared to the control group, the increase in root length due to compost applications was 55.14% for the 1.5% compost treatment, 83.62% for the 3% compost treatment, and 83.93% for the 4.5% compost treatment (Figure 3).

Number of nodes (count)

Statistical analyses showed significant differences among compost treatments in terms of the number of nodes ($P < 0.05$). The control group (12.66 count) had the lowest number of nodes among all treatments. Among the compost applications, the lowest number of nodes was recorded in the 1.5% compost treatment (17.33 count), while the highest number of nodes was observed in the 4.5% compost treatment (19.33 count). Compared to the control group, the increase in the number of nodes due to compost applications was 36.89% for the 1.5% compost treatment, 42.18% for the 3% compost treatment, and 52.69% for the 4.5% compost treatment (Figure 3).

Plant fresh weight (g)

Statistical analyses revealed significant differences among compost treatments in terms of plant fresh weight ($P < 0.05$). Sunflower plants grown in the control group (33.14 g) had a lower fresh weight compared to those in the compost-treated groups. Among the compost applications, the lowest plant fresh weight was recorded in the 4.5% compost treatment (41.34 g), while the highest plant fresh weight was observed in the 1.5% compost treatment (49.08 g) (Figure 4). Compared to the control group, the increase in plant fresh weight due to compost applications was 48.10% for the 1.5% compost treatment, 37.15% for the 3% compost treatment, and 24.74% for the 4.5% compost treatment (Figure 4).

Plant dry weight (g)

Statistical analyses revealed significant differences among compost treatments in terms of plant dry weight ($P < 0.05$). Sunflower plants grown in the control group (5.77 g) had a lower dry weight compared to those in the compost-treated groups. Among the compost applications, the lowest plant dry weight was recorded in the 4.5% compost treatment (7.75 g), while the highest dry weight was observed in the 1.5% compost treatment (8.86 g) (Figure 4). Compared to the control group, the increase in plant dry weight due to compost applications was 53.55% for the 1.5% compost treatment, 40.38% for the 3% compost treatment, and 34.32% for the 4.5% compost treatment. The highest increase in dry weight was observed in the 1.5% compost treatment, while the lowest increase was recorded in the 4.5% compost treatment (Figure 4).

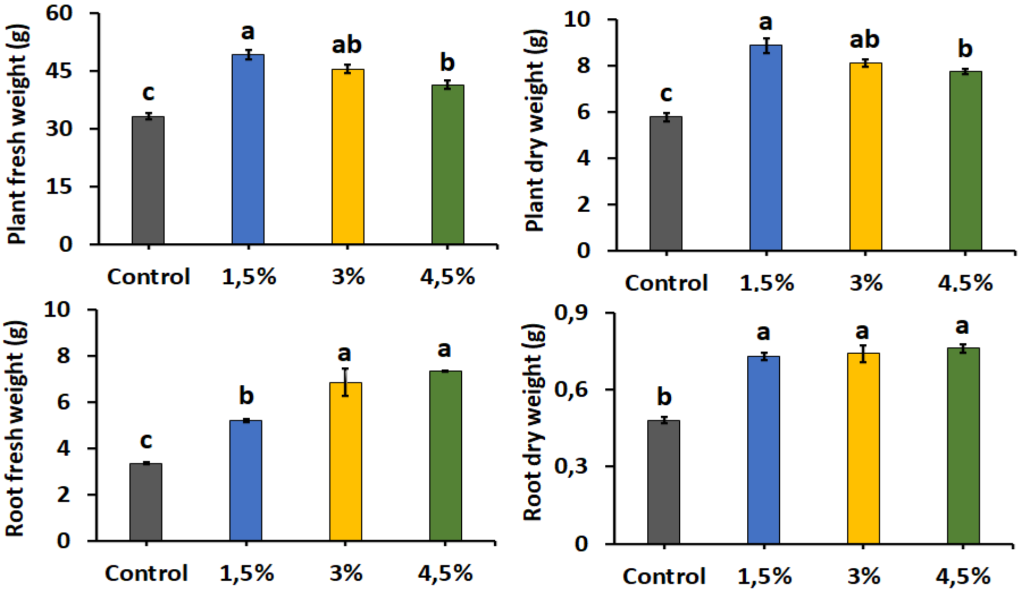

Figure 4. Effects of different compost application rates on plant fresh and dry weight, as well as root fresh and dry weight.

Root fresh weight (g)

Statistical analyses revealed significant differences among compost treatments in terms of root fresh weight ($P < 0.05$). The control group (3.33 g) had a lower root fresh weight compared to the compost-treated groups. Among the compost applications, the lowest root fresh weight was recorded in the 1.5% compost treatment (5.20 g), while the highest value was observed in the 4.5% compost treatment (7.33 g) (Figure 4). Compared to the control group, the increase in root fresh weight due to compost applications was 56.16% for the 1.5% compost treatment, 105.71% for the 3% compost treatment, and 120.12% for the 4.5% compost treatment (Figure 4).

Root dry weight (g)

Statistical analyses revealed significant differences among compost treatments in terms of root dry weight ($P < 0.05$). The control group (0.48 g) had the lowest root dry weight among all treatments. Among the compost applications, the lowest root dry weight was recorded in the 1.5% compost treatment (0.73 g), while the highest value was observed in the 4.5% compost treatment (0.76 g) (Figure 4). Compared to the control group, the increase in root dry weight due to compost applications was 52.08% for the 1.5% compost treatment, 54.17% for the 3% compost treatment, and 58.33% for the 4.5% compost treatment (Figure 4).

Catalase enzyme activity

Statistical analyses revealed significant differences among compost treatments in terms of catalase (CAT) enzyme activity ($P < 0.05$). The control group (143.33 ml O_2 g^{-1} dm 5 min^{-1}) exhibited the lowest catalase enzyme activity among all treatments. Among the compost applications, the lowest catalase enzyme activity was recorded in the 1.5% compost treatment (160.0 ml O_2 g^{-1} dm 5 min^{-1}), while the highest value was observed in the 4.5% compost treatment (163.33 ml O_2 g^{-1} dm 5 min^{-1}) (Figure 5). Compared to the control group, the increase in catalase enzyme activity due to compost applications was 11.63% for the 1.5% compost treatment, 12.10% for the 3% compost treatment, and 13.95% for the 4.5% compost treatment. The highest increase in catalase enzyme activity was observed in the 4.5% compost treatment, while the lowest increase was recorded in the 1.5% compost treatment (Figure 5).

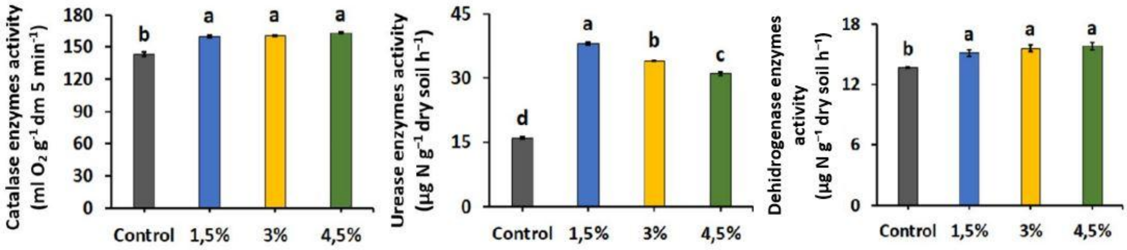

Figure 5. Effects of different compost application rates on soil catalase, urease, and dehydrogenase enzyme activities.

Urease enzyme activity

Statistical analyses revealed significant differences among compost treatments in terms of urease enzyme activity ($P < 0.05$). The control group (16.03 µg N g^{-1} dry soil h^{-1}) exhibited the lowest urease enzyme activity compared to the compost-treated groups. Among the compost applications, the lowest urease enzyme activity was recorded in the 4.5% compost treatment (31.06 µg N g^{-1} dry soil h^{-1}), while the highest value was observed in the 1.5% compost treatment (38.08 µg N g^{-1} dry soil h^{-1}) (Figure 5). Compared to the control group, the increase in urease enzyme activity due to compost applications was 137.55% for the 1.5% compost treatment, 112.60% for the 3% compost treatment, and 93.76% for the 4.5% compost treatment. The highest increase in urease enzyme activity was observed in the 1.5% compost treatment, while the lowest increase was recorded in the 4.5% compost treatment (Figure 5).

Dehydrogenase enzyme activity

Statistical analysis demonstrated significant variations in dehydrogenase enzyme activity across the compost treatments ($P < 0.05$). The control group exhibited the lowest dehydrogenase activity (13.68 µg TPF g^{-1} dry soil 24 h^{-1}), whereas compost applications resulted in increased enzyme activity. Among the compost treatments, the lowest dehydrogenase activity was detected in the 1.5% compost application (15.13 µg TPF g^{-1} dry soil 24 h^{-1}), while the highest activity was measured in the 4.5% compost treatment (15.80 µg TPF g^{-1} dry soil 24 h^{-1}) (Figure 5). When compared to the control, dehydrogenase activity increased by 10.60% in the 1.5% compost treatment, 13.89% in the 3% compost treatment, and 15.50% in the 4.5% compost treatment. The greatest enhancement in enzyme activity was observed in the 4.5% compost treatment, whereas the smallest increase was recorded in the 1.5% compost treatment (Figure 5).

Effects of application levels on parameters: Heatmap

The heatmap, created to evaluate the effects of compost applications on plant growth parameters and soil enzyme activities, visualizes the impact of different compost doses on various growth and biochemical parameters (Figure 6). The heatmap includes plant height, root fresh and dry weight, plant fresh and dry weight, number of nodes, root length, as well as catalase, urease, and dehydrogenase enzyme activities. In the heatmap, the color scale represents values; blue tones indicate low levels, while green tones represent high levels. Accordingly, the variations in parameters under different compost ratios were assessed.

First, the control group had the lowest values in all parameters, which is represented by blue tones. This indicates that plant growth and soil biological activity were at lower levels in soils without compost application. In contrast, compost-treated groups exhibited higher values, particularly in plant growth and soil enzyme activities, supporting the idea that compost enhances soil fertility and biological activity.

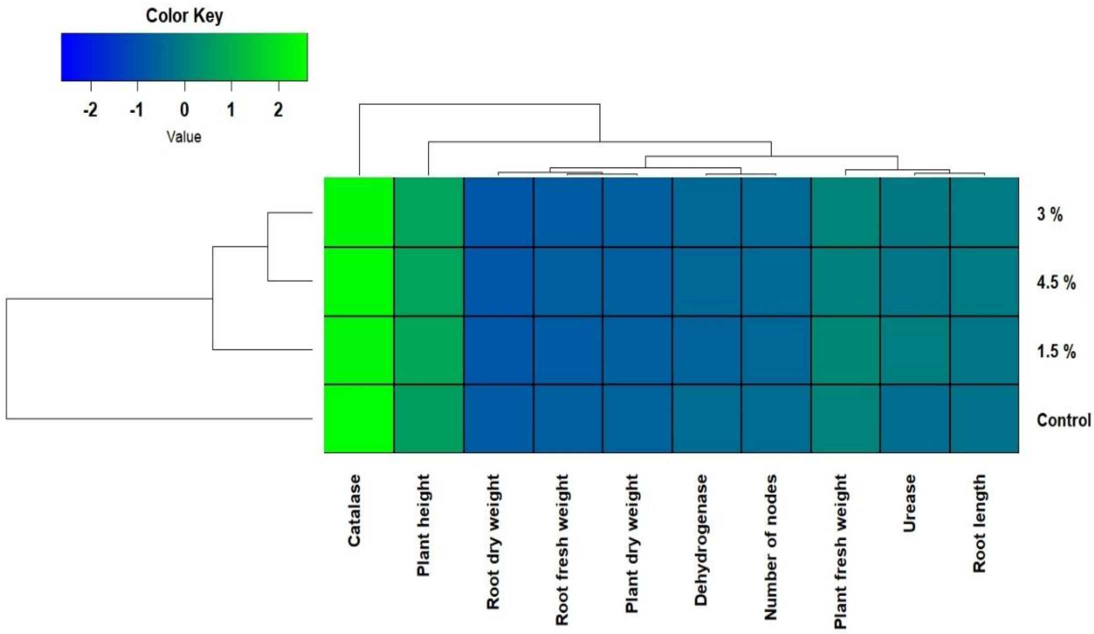

Figure 6. Heatmap showing the correlation coefficients between the analyzed parameters.

Especially, catalase enzyme activity was measured at higher levels compared to other parameters and was represented by green tones in the heatmap. This indicates that compost applications enhanced soil microbial activity and contributed to the reduction of oxidative stress in the soil (Tartoura et al., 2014). Comparisons among compost treatments revealed that growth parameters such as plant height, root length, and number of nodes increased with compost applications. However, the highest compost application rate (4.5%) did not always yield the best results. For instance, parameters such as plant fresh and dry weight, root fresh and dry weight showed higher values in the 1.5% and 3% compost treatments (Adugna 2016). This suggests that as the compost rate increases, some growth parameters may be suppressed, or the benefits of compost may diminish beyond a certain level.

From the perspective of soil enzyme activities, dehydrogenase and urease enzyme activities also increased with compost applications. Dehydrogenase enzyme serves as an indicator of microbial respiration and biological activity in the soil, and significant increases were recorded with compost treatments. Similarly, urease enzyme, which plays a crucial role in the nitrogen cycle, demonstrated that compost applications accelerated soil biochemical processes. Overall, these findings indicate that compost applications promote plant growth, enhance soil enzyme activities, and improve soil biological productivity. However, an increase in compost quantity did not always result in a directly proportional improvement across all parameters, as lower compost rates (1.5% and 3%) produced better results for certain growth parameters.

Data clustering technique: Correlation graphs

A strong positive correlation was found between plant height and root length ($r = 0.84$; $p < 0.01$). This relationship indicates that the growth of stems and leaves during the plant's development process is directly linked to the elongation of the root system. This finding suggests that under conditions where the plant exhibits uniform growth, the root system also develops in parallel (Forde and Lorenzo, 2001; Gregory 2006). Consequently, an increase in plant height may serve as a significant determinant of root development.

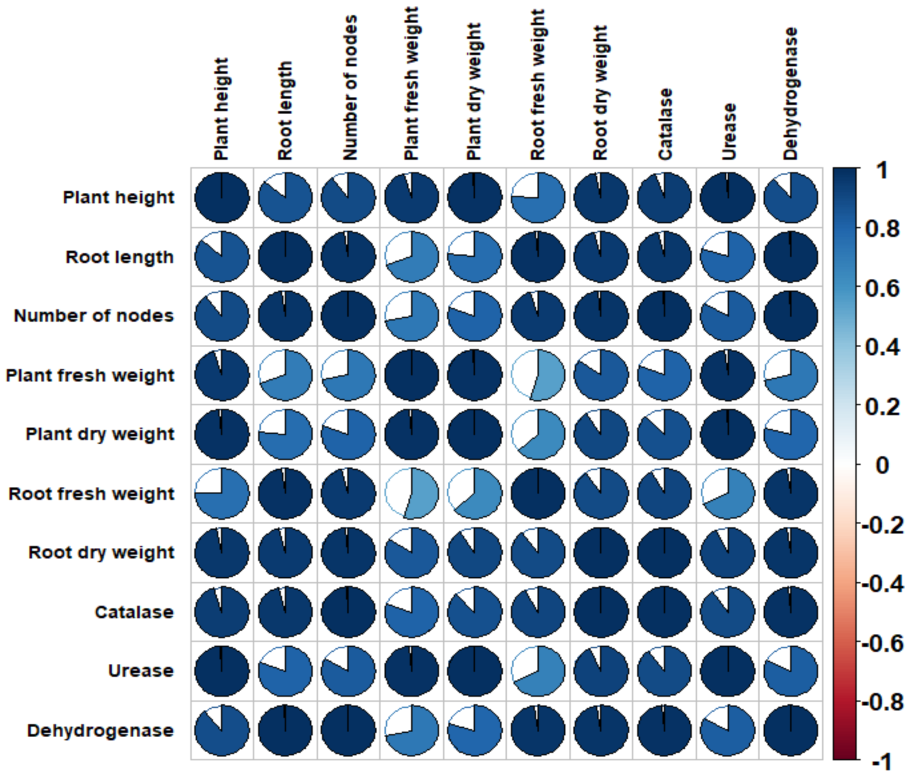

Figure 7. Correlation graph showing the relationships between the analyzed parameters. (Blue color represents positive correlations, while red and orange colors indicate negative correlations. The intensity of the colors represents the strength of the correlation, and the size of the circles indicates statistical significance.)

A strong positive correlation was found between plant fresh weight and dry weight (r = 0.97; p < 0.01) as well as between root fresh weight and dry weight (r = 0.89; p < 0.01). This result indicates that as plant and root fresh weights increase, dry matter content also increases accordingly. In other words, plants with higher fresh weights are expected to yield greater dry matter content after drying. In terms of root length, a significant correlation was observed with both root fresh and dry weights. As root length increased, root biomass also increased, suggesting that plants with more developed root systems could extend further into the soil and store more water and nutrients (Figure 7).

When examining soil biochemical properties, catalase, urease, and dehydrogenase enzyme activities were found to have strong correlations with plant growth parameters. In particular, catalase enzyme activity showed a strong correlation with plant height (r = 0.92; p < 0.01) and root length (r = 0.94; p < 0.01). Additionally, a positive correlation was identified between urease enzyme activity and plant height (r = 0.97; p < 0.01). Regarding dehydrogenase enzyme activity, a significant correlation with root length (r = 0.90; p < 0.01) was observed. These findings suggest that increased soil enzyme activity is directly linked to enhanced plant height, root length, and overall biomass accumulation (Figure 7).

Mining activities have generated an estimated 5 to 14 million tons of mining waste in recent years (Schoenberger, 2016). These wastes are characterized by low organic matter content, insufficient nutrient levels, high metal concentrations, and acidic pH, which collectively exacerbate soil degradation. Consequently, these adverse conditions promote erosion and negatively impact vegetation and soil microbial activity (Lima et al., 2016). Given the increasing concerns regarding soil contamination and degradation, the application of organic amendments has gained prominence as an effective remediation strategy. In particular, compost has been recognized as a cost-effective and sustainable soil amendment. Numerous studies have demonstrated that compost enhances soil quality by increasing organic matter content and improving plant growth conditions (Lu et al., 2014; Białobrzewski et al., 2015).

In this study, compost was applied to sunflower plants at rates of 1.5%, 3%, and 4.5%, and its effects on plant growth were evaluated. The findings indicate statistically significant differences ($p<0.05$) among the treatments in terms of plant height, root length, fresh and dry biomass of both shoots and roots. Additionally, a significant variation in the number of nodes was observed ($p<0.05$). The highest plant height was recorded at the 1.5% compost application rate, while the longest root length and highest number of nodes were observed at the 4.5% compost application rate. These results suggest that lower compost doses create more favorable conditions for overall plant growth, whereas higher compost doses promote root development and internode formation. However, excessive compost application may limit plant growth, potentially due to nutrient oversupply or the redistribution of resources toward root development rather than shoot elongation.

Compost applications are widely recognized for not only promoting plant growth but also contributing significantly to the immobilization of heavy metals. Owing to its rich organic matter content, compost interacts with heavy metals to form stable complexes, thereby lowering their bioavailability (Irfan et al., 2021). Consequently, the potential toxicity of heavy metals**,** which could otherwise impede plant development is effectively mitigated. Moreover, compost has been shown to elevate soil pH, leading to a reduction in heavy metal solubility and promoting their conversion into more stable, less mobile forms (Liang et al., 2017). This transformation significantly restricts heavy metal mobility, thereby limiting their absorption by plants (Beesley et al., 2010). Additionally, the combination of compost with biochar has been reported to enhance its metal-binding efficiency, resulting in greater stabilization and improved nutrient dynamics in the soil (Tang et al., 2014; Uslu et al., 2020).

The positive effects of compost on plant growth have been confirmed by numerous studies. Canellas and Olivares (2014) reported that organic materials, particularly compost, support biochemical, morphological, and physiological processes due to their rich nutrient content. It has been documented that sunflower growth significantly improves in soils rich in organic matter (Beesley et al., 2010). Similarly, Zaman et al. (2018) demonstrated that compost applications increase both fresh and dry biomass in sunflowers. Furthermore, various studies have verified that compost ensures a consistent supply of nutrients to plant tissues and contributes to a significant increase in biomass production (Abdella et al., 2018; Lwin et al., 2018; Nwamezie, 2018).

From a soil biochemical perspective, significant differences were observed among catalase, urease, and dehydrogenase enzyme activities ($p<0.05$). The highest catalase and dehydrogenase enzyme activities were recorded at the 4.5% compost application rate, whereas the highest urease activity was observed at the 1.5% compost dose. It is well established that enzymatic activity in soil is directly related to the existing microbial population, the availability of nutrients, and root exudates (Caldwell, 2005; Moreno-Espíndola et al., 2018). Compost applications were found to enhance catalase and dehydrogenase enzyme activities; however, a distinct trend was noted for urease activity. Specifically, urease activity was higher at lower compost application rates, whereas increasing compost doses led to a reduction in its activity. This finding suggests that while higher compost doses promote certain enzymatic activities, they may suppress urease activity to a certain extent (García-Gil et al., 2000; Lakhdar et al., 2010).

In conclusion, compost applications have significant effects on sunflower growth, soil microbial activity, and heavy metal immobilization. The influence of different compost doses on plant growth and enzymatic activities varies. While lower compost doses are advantageous in terms of promoting plant height and urease activity, higher doses support root development as well as catalase and dehydrogenase activities. Therefore, determining and applying appropriate compost doses in areas affected by mining activities is crucial, as compost serves as an effective soil amendment that enhances both plant growth and soil quality.

Conclusion

This study demonstrated that compost application positively affects sunflower growth and soil enzyme activities in heavy metal-contaminated soils. The 1.5% compost dose improved plant height and biomass, while the 4.5% dose enhanced root development and catalase and dehydrogenase enzyme activities. Compost also contributed to heavy metal immobilization by forming stable complexes with metals, thereby reducing their bioavailability and potential toxicity. However, excessive compost doses did not always yield greater benefits, indicating the need for optimized application rates. Overall, compost is an effective soil amendment for improving plant growth and soil health in contaminated soils. Future research should explore long-term applications to further understand its effects on soil quality and plant development.

Conflict of Interest

The authors declare that there is no conflict of interest between them.

Author contributions

The authors declare that they contributed equally to the article.

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