Indonesian Journal of Environmental Management and Sustainability
e-ISSN:2598-6279 *p*-ISSN:2598-6260

Research Paper

Phytoremediation of Zinc (Zn) in Leachate-Contaminated Soil Using Vetiver (*Chrysopogon zizanioides*) with Compost Addition

Ameviana Fitri Noveira[1], Endah Dwi Hastuti[1*], Yulita Nurchayati[1]

[1] *Department of Biology, Faculty of Sains and Mathematic, Diponegoro University, Central Java, 50275, Indonesia*
***Corresponding author e-mail**: endahpdil@yahoo.com

Abstract
Soil contamination by zinc (Zn) derived from landfill leachate poses significant ecological risks, particularly in regions with limited waste management capacity such as Indonesia. The Jatibarang landfill in Semarang has reported soil Zn concentrations exceeding the Ecological Soil Screening Level, highlighting the need for sustainable remediation strategies. This study evaluated the stability of vetiver (*Chrysopogon zizanioides*)-based phytoremediation under varying plant densities and compost amendment in leachate-contaminated soil. A two-month greenhouse experiment was conducted using a 2 × 2 factorial completely randomised design with two planting densities (one and three plants per polybag) and two compost treatments (with and without compost). Parameters observed included soil Zn concentration, removal efficiency, bioconcentration factor (BCF), translocation factor (TF), plant biomass, and soil pH, analysed using two-way ANOVA ($\alpha = 0.05$). All treatments significantly reduced soil Zn concentrations from 174.41 mg/kg to 49.33-52.17 mg/kg, corresponding to removal efficiencies of 70.09-71.72%, with no statistically significant differences among treatment combinations. Zinc accumulation occurred predominantly in the roots, reflected by higher root BCF values and TF values generally below one, confirming phytostabilisation as the dominant remediation mechanism. These findings indicate that vetiver-based phytoremediation provides a stable and reliable strategy for controlling Zn mobility in landfill leachate-contaminated soils, supporting its application as a sustainable soil management approach.

Keywords
Zinc, Phytoremediation, Vetiver (*Chrysopogon zizanioides*), Landfill Leachate, Phytostabilisation

Received: 10 December 2025, Accepted: 18 february 2026
https://doi.org/10.26554/ijems.2026.10.2.70-78

1. INTRODUCTION

The increasing generation of municipal solid waste has become a major environmental challenge associated with population growth, urbanisation, and changing consumption patterns. Globally, waste generation is projected to increase substantially in the coming decades, placing increasing pressure on waste management systems, particularly in developing countries (Khan et al., 2022). In many developing regions, limited technical capacity and financial constraints have resulted in unsanitary disposal practices, including open dumping, which poses long-term risks to soil and groundwater quality. In Indonesia, limited waste management capacity has intensified the risk of environmental contamination, especially in areas surrounding landfill sites (Ermilinda et al., 2022). Although national waste management policies promote improved landfill governance, operational and institutional limitations remain significant, underscoring the need for remediation strategies that are technically feasible, economically viable, and adaptable to local conditions.

The Jatibarang landfill in Semarang City, Central Java, Indonesia, represents one of the most critical waste management hotspots, receiving approximately 800-900 tonnes of waste per day, equivalent to nearly 70% of the city's total waste generation (Hasthi et al., 2023; Saputra et al., 2020). The continued application of open dumping practices and inadequate leachate management systems increases the potential for leachate infiltration into surrounding soils and groundwater (Satriani et al., 2025). Landfill leachate contains a complex mixture of contaminants, including heavy metals such as zinc (Zn), cadmium (Cd), and lead (Pb), which are persistent, toxic, and capable of accumulating in soils (Bouzayani et al., 2014; Rezapour et al., 2018). Among these, Zn warrants particular attention due to its relatively high mobility under fluctuating environmental conditions and its dual function as an essential micronutrient at low concentrations but a phytotoxic element at elevated levels.

Previous assessments have reported that Zn concentrations in soils surrounding the Jatibarang landfill exceed the Ecological Soil Screening Level (Eco-SSL) threshold of 160 mg/kg (EPA, 2007), indicating potential ecological risk.

Elevated Zn concentrations may inhibit microbial activity, alter enzymatic processes, and interfere with nutrient cycling, thereby reducing soil fertility and ecological resilience. Exceedance of the Eco-SSL threshold reflects more than regulatory non-compliance; it indicates potential disruption of soil ecosystem functions. In landfill-affected soils, increased Zn mobility further elevates the risk of groundwater contamination and entry into agricultural food chains, posing broader environmental and public health concerns.

The environmental behaviour of Zn in landfill-affected soils is governed by complex soil-solution interactions. Zn speciation, solubility, and bioavailability are strongly influenced by pH, redox potential, dissolved organic matter (DOM), clay mineral composition, and cation exchange capacity (CEC). Variations in pH can significantly alter Zn solubility, with lower pH generally increasing Zn mobility and bioavailability, while higher pH promotes adsorption and precipitation processes (Wu et al., 2026). In addition, redox conditions influence metal transformation pathways and interactions with soil constituents. The presence of dissolved organic matter plays a dual role in regulating Zn dynamics, as DOM can form soluble organo-metal complexes that enhance Zn mobility or, alternatively, facilitate immobilisation through adsorption and complexation with humic substances (Wei et al., 2021; Duan et al., 2024). Organic matter quality and composition further determine the strength of Zn binding, affecting its partitioning between solid and solution phases (Medyńska-Juraszek et al., 2020). Moreover, soil mineral components and surface functional groups contribute to Zn retention through cation exchange and surface complexation mechanisms (Lacalle et al., 2023). These dynamic and interrelated processes complicate remediation efforts in landfill-impacted soils and require strategies capable of functioning effectively under chemically heterogeneous conditions.

Conventional remediation technologies for heavy metal-contaminated soils, such as soil washing, solidification/stabilisation, and membrane-based treatments, are often costly, technically demanding, and may generate secondary waste (Yang et al., 2019; Kaparwan et al., 2020). These limitations have driven increasing interest in environmentally friendly and cost-effective alternatives, among which phytoremediation has emerged as a promising strategy. Phytoremediation utilises plants to immobilise, stabilise, or remove contaminants through natural biological processes, making it particularly suitable for large-scale and long-term remediation of contaminated land (Wei et al., 2021). Compared with conventional physicochemical approaches, phytoremediation offers lower operational costs, minimal site disturbance, and the potential to simultaneously improve soil structure and ecological function. However, for phytoremediation to be effectively implemented in chemically complex environments such as landfill-impacted soils, its performance must remain mechanistically stable under variable agronomic and soil management conditions. Therefore, evaluating the robustness of plant-based remediation systems under different planting densities and organic amendment regimes is critically important to ensure reliable field-scale application. Vetiver (*Chrysopogon zizanioides*) is a perennial grass widely recognised for its high tolerance to extreme environmental conditions and its ability to survive in soils contaminated with heavy metals. Numerous studies have demonstrated the effectiveness of vetiver in reducing Zn contamination in soil and water systems (Gautam and Agrawal, 2017; Masinire et al., 2021; Angelova, 2025). Generally reported is that Zn accumulation in vetiver occurs predominantly in the root system, with limited translocation to aboveground tissues, as reflected by relatively high root bioconcentration factors (BCF) and low translocation factors (TF) (Mahmoudpour et al., 2021). These characteristics indicate that phytostabilisation is the dominant remediation mechanism, which is advantageous for limiting metal mobility and reducing ecological risks (Kamal and Alali, 2025). Phytostabilisation is particularly relevant in landfill environments, where preventing metal migration to groundwater and adjacent ecosystems is a primary remediation objective.

In addition to plant species selection, agronomic factors such as plant density and the application of organic amendments can influence heavy metal dynamics in soil-plant systems. Increased plant density can enhance total root biomass and rhizosphere interactions, thereby strengthening metal retention in the root zone (Qin et al., 2021). Organic amendments such as compost can modify soil physicochemical properties, including organic matter content and cation exchange capacity, and influence heavy metal bioavailability through complexation and adsorption mechanisms (Piccolo et al., 2019; Medyńska-Juraszek et al., 2020; Lacalle et al., 2023). However, the combined effects of plant density and compost amendment on heavy metal remediation have produced variable outcomes and remain insufficiently understood, particularly in chemically complex environments such as landfill leachate-contaminated soils.

Despite the extensive body of research on vetiver-based phytoremediation, existing studies have primarily focused on metal accumulation or removal efficiency under fixed experimental conditions, with limited attention given to the stability and robustness of remediation mechanisms under variable agronomic management. In particular, empirical evidence regarding the combined effects of plant density and compost amendment on Zn remediation behaviour in landfill leachate-contaminated soils remain scarce, despite the presence of dissolved organic matter and complex soil-solution interactions that may strongly influence Zn mobility (Duan et al., 2024; Wei et al., 2021). Consequently, it remains unclear whether vetiver-based phytoremediation maintains consistent performance and mechanistic dominance when key planting variables are altered, as would occur under realistic field-scale applications.

Therefore, this study aims to evaluate the stability of Zn phytoremediation using vetiver under varying planting densities and compost addition in leachate-contaminated soil at the Jatibarang landfill. The investigation focuses not only on changes in soil Zn concentration but also on Zn accumulation patterns in plant roots and shoots, alongside analysis of bioconcentration factors (BCF) and translocation factors (TF) to identify the dominant remediation mechanism. By integrating agronomic management variables with mechanistic analysis of Zn dynamics, this study provides a more comprehensive scientific basis for sustainable heavy metal management in landfill environments, particularly in developing countries facing similar waste management challenges.

2. EXPRIMENTAL SECTION

2.1 Materials

The main materials used in this study were leachate-contaminated soil collected from the Jatibarang landfill, Semarang City, Central Java, Indonesia, and vetiver plants (*Chrysopogon zizanioides* (L.) Roberty) approximately two weeks old. The vetiver seedlings were obtained from the Research and Development Center for Medicinal Plants and Traditional Medicine (B2P2TOOT), Karanganyar, Indonesia.

Compost was used as an organic soil amendment, derived from goat manure. Based on published literature, goat manure compost is generally characterised by a high organic matter content, near-neutral to slightly alkaline pH, and relatively stable organic compounds. These properties are known to improve soil structure, increase cation exchange capacity (CEC), and influence heavy metal behaviour through adsorption and organic complexation mechanisms, thereby potentially reducing metal bioavailability and supporting phytostabilisation processes in contaminated soils (Tamma et al., 2025). Chemicals used for zinc (Zn) analysis included analytical-grade nitric acid (HNO_3) and hydrochloric acid (HCl).

2.2 Methods

2.2.1 Experimental Design

The phytoremediation experiment employed a 2 × 2 factorial completely randomised design (CRD) with two factors: plant density and compost addition. Plant density consisted of two levels, namely one plant per polybag (D1) and three plants per polybag (D2). Compost treatment also consisted of two levels: without compost (K0) and with compost addition (K1).

Each treatment combination was replicated six times, resulting in a total of 24 experimental units. Plant growth parameters were observed in all experimental units, while soil Zn analysis was conducted on three randomly selected replicates per treatment.

2.2.2 Phytoremediation Procedure

The phytoremediation process was conducted using ±2-week-old vetiver plants planted in polybags containing leachate-contaminated soil. For the compost treatment (K1), 0.5 kg of compost was thoroughly homogenized with 2.5 kg of contaminated soil, corresponding to a compost proportion of 20% (w/w). In contrast, the control treatment (K0) consisted of 3.0 kg of contaminated soil without compost addition. The total growth medium in each polybag was maintained at 3.0 kg to ensure uniform experimental conditions across treatments.

Vetiver plants were grown in the greenhouse for a period of two months. During the experimental period, plants were irrigated regularly with clean water to maintain soil moisture near field capacity. No inorganic fertilisers were applied throughout the experiment to avoid external nutrient interference with Zn uptake and stabilisation processes.

Figure 1. Vetiver Grass (*Chrysopogon zizanioides*) Grown in Polybags as Experimental Units in the Phytoremediation Study of Zn Contaminated Soil

2.2.3 Zinc (Zn) Analysis in Soil and Plant Tissues

Soil samples were air-dried at room temperature and sieved through a 2 mm mesh prior to analysis. Total Zn in soil was determined using the aqua regia digestion method with a mixture of nitric acid (HNO_3) and hydrochloric acid (HCl) (Park et al., 2011). The digestion process was continued until a clear solution was obtained, after which the digest was cooled, diluted with distilled water to a known volume, and analysed for Zn concentration using AAS.

Plant samples were separated into roots and shoots, thoroughly washed with tap water followed by distilled water to remove adhering soil particles, and oven-dried at 60-70 °C until constant weight. This procedure refers to the method of plant sample preparation for heavy metal analysis as reported by Asikin et al. (2023). Dried plant tissues were ground to a homogeneous powder and digested

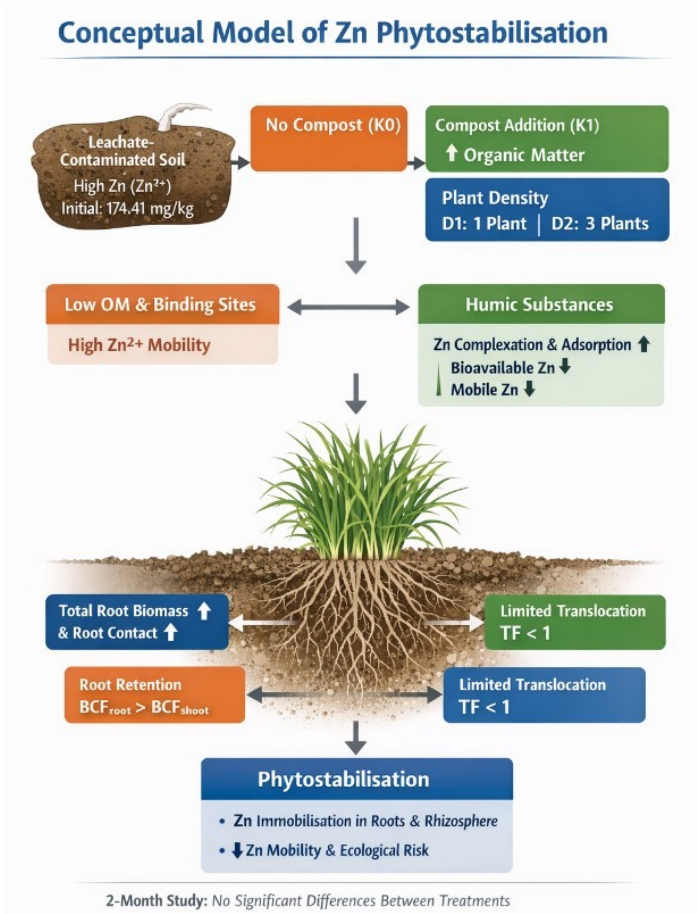

Figure 2. Conceptual Model of Zn Phytostabilisation Mechanism Under Compost Amendment and Plant Density Variation; The Model Integrates Soil Chemical Processes and Plant Physiological Responses, Illustrating How Compost Addition Enhances Zn Complexation and Adsorption, while Vetiver Roots Retain Zn Predominantly in Belowground Tissues (BCF Root > BCF Shoot; TF < 1), Confirming Phytostabilisation as the Dominant Mechanism. Plant Density Influences Total Root Biomass but did not Significantly Alter Zn Removal Under the Experimental Timeframe

using nitric acid (HNO_3). The resulting digest solutions were diluted to a fixed volume with distilled water and analysed for Zn concentration using AAS (Pan et al., 2010). Zinc concentrations were expressed in mg/kg dry weight. Instrument calibration was performed using standard Zn solutions prior to analysis.

2.2.4 Bioconcentration and Translocation Factors

The bioconcentration factor (BCF) and translocation factor (TF) were calculated to evaluate Zn uptake and distribution within the plant. BCF was calculated as the ratio of Zn concentration in plant tissue (root or shoot) to Zn concentration in soil, while TF was calculated as the ratio of Zn concentration in shoots to that in roots. Bioconcentration factor (BCF) and translocation factor (TF) are widely applied indices to assess metal uptake, accumulation, and distribution in phytoremediation studies (Wei et al., 2021).

2.2.5 Data Analysis

All data were analysed using two-way analysis of variance (ANOVA) at a 95% confidence level ($\alpha = 0.05$) to evaluate the effects of plant density, compost addition, and their interaction. When significant differences were detected, Duncan's Multiple Range Test (DMRT) was applied as a post-hoc test. Statistical analyses were performed using appropriate statistical software.

3. RESULT AND DISCUSSION

3.1 Zinc Concentration in Soil and Removal Efficiency

The analysis of variance (ANOVA) showed that plant density, compost addition, and their interaction did not have a statistically significant effect on soil Zn concentration or Zn removal efficiency ($p > 0.05$). Nevertheless, a consistent decrease in soil Zn concentration was observed across all treatments after the phytoremediation period (Table 1).

Table 1. Zn Content in Soil and Zn Reduction Efficiency in Soil Contaminated by Leachate from the Jatibarang Landfill with Plant Density and Compost Treatment

Parameter	Treatment	D1	D2	Mean D
Soil Zn Content (mg/kg)	K0 (control)	52.17 ± 1.81	49.33 ± 5.88	50.75 ± 4.19
	K1 (compost)	50.50 ± 2.68	49.45 ± 3.01	49.97 ± 2.61
Efficiency Zn reduction (%)	K0	70.09 ± 1.03	71.72 ± 3.37	70.90 ± 2.40
	K1	71.05 ± 1.53	71.65 ± 1.73	71.35 ± 1.50

Notes: K0 = without compost; K1 = compost addition; D1 = one plant per polybag; D2 = three plants per polybag. Values are presented as mean ± standard deviation (n = 3 for soil analysis)

The initial Zn concentration in the contaminated soil was 174.41 mg/kg, exceeding the Ecological Soil Screening Level (Eco-SSL) of 160 mg/kg. After two months of phytoremediation, soil Zn concentrations decreased to a range of 49.33-52.17 mg/kg, corresponding to Zn removal efficiencies of 70.09-71.72%. These results indicate that all treatment combinations were capable of substantially reducing Zn levels in leachate-contaminated soil, although the magnitude of reduction did not differ significantly among treatments.

Soil Zn concentrations tended to be slightly lower at higher plant density (D2) than at lower density (D1), and in treatments with compost addition (K1) compared to those without compost (K0). However, these differences were not statistically significant and should therefore be interpreted as general trends rather than treatment-driven effects.

3.2 Bioconcentration Factor (BCF) and Translocation Factor (TF)

The ANOVA results indicated that plant density, compost addition, and their interaction had no significant effect on root BCF, shoot BCF, or translocation factor (TF) values ($p > 0.05$) (Table 2). Across all treatments, similar patterns of Zn distribution between soil, roots, and shoots were observed.

Root BCF values were generally higher than shoot BCF values, while TF values were mostly below 1, indicating limited translocation of Zn from roots to shoots. This pattern suggests that Zn accumulation predominantly occurred in the root system across all treatment combinations. Although treatments with higher plant density (D2) and compost addition (K1) tended to show slightly lower TF values and higher root BCF values, these differences were not statistically significant. Overall, the results indicate that variations in plant density and compost addition did not substantially alter Zn uptake or translocation behaviour under the experimental conditions.

3.3 Root and Shoot Dry Weight

Plant density had a significant effect on root and shoot dry weight ($p < 0.05$), whereas compost addition and its interaction with plant density did not show significant effects on these parameters (Table 3). Root dry weight was significantly higher in treatments with three plants per polybag (D2) compared to those with one plant per polybag (D1). Similarly, shoot dry weight was also greater at higher plant density. These results indicate that increased plant density enhanced total biomass production, primarily due to the greater number of individual plants per experimental unit. Although compost-treated plants (K1) tended to exhibit higher root and shoot dry weights than plants grown without compost (K0), these differences were not statistically significant.

3.4 Soil pH

The initial soil pH was uniform across all treatments (pH 6.0), indicating homogeneity of the growing medium prior to the experiment. At the end of the phytoremediation period, soil pH values ranged from 6.7 to 6.9 (Table 4). ANOVA results showed that plant density, compost addition, and their interaction did not significantly affect soil pH ($p > 0.05$). Minor variations in pH among treatments were observed but remained within a near-neutral range.

3.5 Stability of Zn Reduction in Leachate-Contaminated Soil

The results of this study demonstrate that vetiver (*Chrysopogon zizanioides*) was consistently able to reduce Zn concentrations in leachate-contaminated soil, regardless of variations in plant density and compost addition. Although statistical analysis indicated no significant effects of these treatments on soil Zn concentration or removal efficiency, the substantial decrease in Zn levels observed across all treatments indicates that the phytoremediation process remained stable during the experimental period.

The reduction of soil Zn from an initial concentration of 174.41 mg/kg to approximately 49.33-52.17 mg/kg after two months suggests that vetiver can effectively control Zn contamination in landfill-impacted soils. Similar reductions have been reported in previous studies examining vetiver-based phytoremediation in contaminated soils and wastewater systems (Gautam and Agrawal, 2017; Angelova, 2025). Importantly, the absence of significant differences among treatments suggests that Zn reduction by vetiver is not strongly dependent on plant density or compost addition within the tested range, highlighting the robustness of the remediation process.

Table 2. BCF Root, BCF Shoot, and TF Values in Soil Contaminated by Leachate from the Jatibarang Landfill with Plant Density and Compost Treatment

Variable	Treatment	D1	D2	Mean D
BCF Root	K0	0.96 ± 0.31	1.55 ± 0.11	1.26 ± 0.39
	K1	1.11 ± 0.21	1.20 ± 0.51	1.15 ± 0.35
BCF Shoot	K0	1.03 ± 0.39	1.07 ± 0.18	1.05 ± 0.27
	K1	0.97 ± 0.39	0.82 ± 0.07	0.89 ± 0.26
TF	K0	1.28 ± 0.99	0.68 ± 0.09	0.98 ± 0.71
	K1	0.93 ± 0.51	0.76 ± 0.28	0.85 ± 0.38

Notes: BCF = bioconcentration factor; TF = translocation factor. Values are expressed as mean ± standard deviation

Table 3. Dry Weight of Root and Shoot on Soil Contaminated by Leachate from Jatibarang Landfill with Treatment of Plant Density and Compost

Variable	Treatment	D1	D2	Mean D
Dry Weight of Root	K0	6.59 ± 2.93	12.35 ± 5.52	9.47 ± 5.17
	K1	7.12 ± 2.83	18.84 ± 8.58	12.98 ± 8.63
Dry Weight of Shoot	K0	23.19 ± 11.52	35.95 ± 7.45	29.57 ± 11.40
	K1	21.50 ± 8.46	41.67 ± 5.28	31.59 ± 12.50

Notes: Different superscript letters within the same row indicate significant differences at $p < 0.05$ (DMRT). Values are presented as mean ± standard deviation ($n = 6$)

3.6 Dominance of Phytostabilisation Mechanisms

Across all treatments, Zn accumulation was predominantly observed in the root system, as reflected by higher root bioconcentration factor (BCF) values compared to shoot BCF values, along with translocation factor (TF) values generally below one. This distribution pattern indicates that phytostabilisation was the dominant remediation mechanism, characterised by the retention and immobilisation of Zn in the root zone rather than its translocation to aboveground tissues.

These findings are consistent with previous reports showing that vetiver tends to immobilise heavy metals in its extensive root system, thereby limiting metal mobility and reducing ecological risks (Mahmoudpour et al., 2021; Kamal and Alali, 2025). The persistence of low TF values across different plant densities and compost treatments further supports the conclusion that the phytostabilisation mechanism remained mechanistically stable under varying agronomic conditions.

Although treatments with higher plant density and compost addition showed slight trends toward increased root BCF and reduced TF, these differences were not statistically significant. Therefore, these patterns should be interpreted as indicative of mechanistic consistency rather than treatment-induced enhancement of Zn uptake or translocation.

3.7 Influence of Plant Density on Biomass Production

Plant density significantly affected root and shoot biomass, with higher density treatments producing greater total biomass per experimental unit. This result is consistent with previous studies reporting increased total biomass at higher planting densities due to the presence of more individuals contributing to overall growth (Qin et al., 2021; Shao et al., 2024). In the context of phytoremediation, increased root biomass at higher plant density may enhance root-soil contact and rhizosphere activity, potentially supporting greater metal retention in the root zone. However, in the present study, the increase in biomass did not translate into significantly higher Zn removal or altered Zn distribution patterns. This finding suggests that while biomass production is influenced by plant density, the Zn phytoremediation mechanism itself remains largely independent of biomass variation within the tested density range.

3.8 Role of Compost Addition in Zn Behaviour

Compost addition did not significantly affect soil Zn concentration, Zn removal efficiency, BCF, TF, or plant biomass during the experimental period. This result suggests that the compost dose and duration applied were insufficient to induce measurable changes in Zn bioavailability or plant uptake patterns within the two-month timeframe.

Nevertheless, the slightly lower TF and BCF values observed in compost-treated soils indicate a tendency toward reduced Zn mobility and uptake, which may be attributed to organic complexation between Zn ions and humic substances in compost. Similar immobilisation effects of organic amendments have been reported in previous studies, particularly through increases in soil organic matter and cation exchange capacity (Piccolo et al., 2019; Medyńska-Juraszek et al., 2020). However, since these trends were not statistically

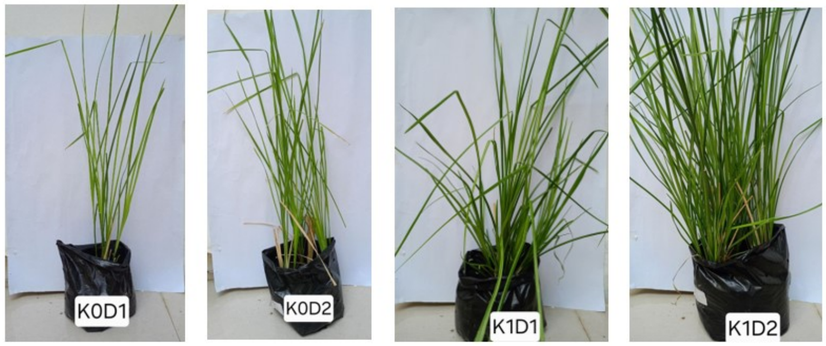

Figure 3. Vetiver Treatment K0D1, K0D2, K1D1, K1D2

supported, they should be interpreted cautiously.

The lack of significant compost effects may also be related to the gradual decomposition rate of organic amendments, suggesting that longer experimental durations may be required to fully capture their influence on Zn stabilisation in leachate-contaminated soils.

Table 4. Soil pH Contaminated by Leachate from Jatibarang Landfill at the End of Observation with Plant Density and Compost Treatment

Treatment	D1	D2	Mean D
K0	6.8	6.9	6.8
K1	6.9	6.9	6.8

3.9 Implications for Field-Scale Phytoremediation

A key contribution of this study lies in demonstrating the stability of Zn phytoremediation mechanisms under variable agronomic conditions rather than identifying treatment-specific enhancements. The consistent dominance of phytostabilisation across all treatments indicates that vetiver-based remediation may be reliably applied in landfill environments where plant density and organic matter inputs are likely to vary. From a practical perspective, this robustness is advantageous for field-scale implementation, as it reduces the need for precise optimisation of planting density or compost application to achieve effective Zn stabilisation. However, it should be noted that this study was conducted under controlled greenhouse conditions and over a relatively short duration. Therefore, future studies should incorporate longer-term experiments, measurements of bioavailable Zn fractions, and assessments of Zn concentrations in soil pore water or leachate to further validate the stability of phytostabilisation under field conditions.

In the K0D1 treatment (without compost, low planting density), relatively lower root BCF values and TF values approaching or exceeding 1 indicate a greater tendency for Zn translocation to aboveground tissues. This pattern may reflect the persistence of Zn in a more bioavailable form under conditions lacking organic amendments. In the absence of additional organic matter, Zn is more likely to remain in a mobile ionic form, potentially increasing oxidative stress and reducing photosynthetic efficiency (Lacalle et al., 2023). The relatively stable soil pH observed in this treatment may have further maintained Zn solubility.

Under higher planting density without compost (K0D2), total biomass increased at the population level; however, this increase did not correspond to substantial changes in BCF or TF values. This suggests that increasing plant density alone, without modification of soil chemical properties, may be insufficient to significantly alter Zn stabilisation patterns. Competition for nutrients at higher density may also influence plant physiological responses, while Zn availability in soil remains relatively high (Qin et al., 2021).

In compost-amended treatments, particularly K1D1 (compost with low density), tendencies toward increased root biomass and lower TF values were observed. Compost addition may contribute to Zn immobilisation through organic matter complexation and adsorption mechanisms, thereby reducing the bioavailable fraction (Park et al., 2011). However, given that differences among treatments were not statistically significant, these observations should be interpreted as indicative trends rather than definitive treatment effects.

Similarly, in K1D2 (compost with high density), root BCF values exceeding 1 and TF values below 1 further support the predominance of Zn retention in the root system. The combination of organic amendment and increased root biomass may enhance root-soil contact and Zn binding capacity. Nevertheless, as overall treatment effects were not statistically significant, the dominant phytostabilisation mechanism appears to remain consistent across planting densities and compost treatments within the experimental timeframe (Qin et al., 2021).

4. CONCLUSIONS

This study demonstrates that vetiver (*Chrysopogon zizanioides*) effectively and consistently reduces Zn concentrations in leachate-contaminated soil from the Jatibarang landfill, regardless of variations in planting density and compost amendment. All treatment combinations achieved substantial Zn reduction, while differences in agronomic management did not significantly influence soil Zn concentration, BCF, or TF values, indicating mechanistic stability of the phytoremediation process. The predominance of Zn accumulation in roots, supported by higher root BCF values and TF values below one, confirms phytostabilisation as the dominant remediation pathway. These results suggest that vetiver-based phytoremediation represents a robust, environmentally friendly strategy for long-term stabilisation and mobility control of Zn in landfill-impacted soils, particularly in developing regions where cost-effective and scalable remediation approaches are required.

5. ACKNOWLEDGEMENT

The author would like to thank the Faculty of Science and Mathematics, Diponegoro University, for providing greenhouse and laboratory facilities. Thanks, are also extended to the Laboratory of Plant Structure and Function, Diponegoro University, and the Integrated Laboratory of the Faculty of Mathematics and Natural Sciences, Semarang State University, for their assistance in analysing zinc (Zn) content. Thanks are also extended to the management of the Jatibarang Landfill, Semarang City, for their permission and support during soil sampling.

REFERENCES

Angelova, V. (2025). Evaluation of Phytoremediation Potential of Vetiver Grass (*Chrysopogon zizanioides* L.) Grown on Contaminated Soils in Bulgaria. *Nature Environment and Pollution Technology*, **24**(3); Article D1734

Asikin, A., L. Hoon, and F. Metali (2023). Comparative Assessment of the Heavy Metal Phytoextraction Potential of Vegetables from Agricultural Soils: A Field Experiment. *Heliyon*, **9**(2); e13547

Bouzayani, F., A. Aydi, and T. Abichou (2014). Soil Contamination by Heavy Metals in Landfills: Measurements from an Unlined Leachate Storage Basin. *Environmental Monitoring and Assessment*, **186**(8); 5033–5040

Duan, S., L. Peng, W. Chen, K. K. Kwakye, K. Zhou, and C. Teng (2024). Spectroscopic Insights into the Binding Characteristics of Heavy Metals to Dissolved Organic Matter in Landfill Leachate. *Chemosphere*, **352**; 141433

EPA, U. (2007). Ecological Soil Screening Levels for Manganese, Interim Final, OSWER Directive 9285.7-71. *US EPA, Washington, DC*

Ermilinda, M., R. Werdiningsih, and A. T. Winarn (2022). Implementasi Perda Nomor 6 Tahun 2012 Tentang Pengelolaan Sampah (Studi Kasus Pengelolaan Sampah Kota Semarang). *Jurnal Pendidikan dan Konseling*, **4**(5); 5716–5724 (in Indonesia)

Gautam, M. and M. Agrawal (2017). Phytoremediation of Metals Using Vetiver (*Chrysopogon zizanioides* (L.) Roberty) Grown under Different Levels of Red Mud in Sludge Amended Soil. *Journal of Geochemical Exploration*, **182**; 218–227

Hasthi, S., L. Budiati, and R. Setiadi (2023). Study of Waste Management at the Jatibarang Landfill, Semarang City. In *Proceedings of the International Conference On Multidisciplinary Studies (ICOMSI 2022)*. Springer Nature, page 102

Kamal, M. A. and A. F. Alali (2025). Kinetic Modeling of Heavy Metal Uptake and Translocation in *Brassica juncea* L. for Phytoremediation Engineering. *Discover Environment*, **3**; 296

Kaparwan, D., N. S. Rana, and B. P. Dhyani (2020). Heavy Metals Toxicity in Agricultural Soils: Critical Review of Possible Sources, Influence on Soil Health and Remedial Measures to Remove, Reduce, and Stabilize Contaminants in Soil. *International Journal of Current Microbiology and Applied Sciences*, **9**(6); 1467–1482

Khan, A. H., E. A. López-Maldonado, N. A. Khan, L. J. Villarreal-Gómez, F. M. Munshi, A. H. Alsabhan, and K. Perveen (2022). Current Solid Waste Management Strategies and Energy Recovery in Developing Countries-State of Art Review. *Chemosphere*, **291**; 133088

Lacalle, R. G., M. Bernal, M. J. Álvarez-Robles, and R. Clemente (2023). Phytostabilization of Soils Contaminated with As, Cd, Cu, Pb and Zn: Physicochemical, Toxicological and Biological Evaluations. *Soil & Environmental Health*, **1**(2); 100014

Mahmoudpour, M., S. Gholami, M. Ehteshami, and M. Salari (2021). Evaluation of Phytoremediation Potential of Vetiver Grass (*Chrysopogon zizanioides* (L.) Roberty) for Wastewater Treatment. *Advances in Materials Science and Engineering*, **2021**(1); 3059983

Masinire, F., D. O. Adenuga, S. M. Tichapondwa, and E. M. N. Chirwa (2021). Phytoremediation of Cr(VI) in Wastewater Using the Vetiver Grass (*Chrysopogon zizanioides*). *Minerals Engineering*, **172**; 107141

Medyńska-Juraszek, A., M. Bednik, and P. Chohura (2020). Assessing the Influence of Compost and Biochar Amendments on the Mobility and Uptake of Heavy Metals by Green Leafy Vegetables. *International Journal of Environmental Research and Public Health*, **17**(21); 7861

Pan, Y., H. Wang, Z. Gu, G. Xiong, and F. Yi (2010). Accumulation and Translocation of Heavy Metals by Macrophytes. *Shengtai Xuebao / Acta Ecologica Sinica*, **30**; 6430–6441

Park, J. H., D. Lamb, P. Paneerselvam, G. Choppala, N. Bolan, and R. Naidu (2011). Role of Organic Amendments on the Remediation of Metal(loid)-Contaminated Soils. *Journal of Hazardous Materials*, **185**(2–3); 549–574

Piccolo, A., R. Spaccini, A. De Martino, F. Scognamiglio, and V. Di Meo (2019). Soil Washing with Solutions of Humic Substances from Manure Compost Removes Heavy Metal Contaminants as a Function of Humic Molecular Composition. *Chemosphere*, **225**; 150–156

Qin, Y., X. Shi, Z. Wang, C. Pei, M. Cao, and J. Luo (2021).

Influence of Planting Density on the Phytoremediation Efficiency of *Festuca arundinacea* in Cd-Polluted Soil. *Bulletin of Environmental Contamination and Toxicology*, **107**(1); 154–159

Rezapour, S., A. Samadi, I. K. Kalavrouziotis, and N. Ghaemian (2018). Impact of the Uncontrolled Leakage of Leachate from a Municipal Solid Waste Landfill on Soil in a Cultivated-Calcareous Environment. *Waste Management*, **82**; 51–61

Saputra, W. A., O. Setiani, and M. Raharjo (2020). Water Quality and Pollution Index of Kreo and Garang River from Jatibarang Landfill in Semarang City. *E3S Web of Conferences*, **202**; 05018

Satriani, E., R. I. Putra, M. Herizon, and S. P. Utama (2025). Studi Literatur: Pencemaran TPA Air Sebakul dan Pemanfaatan Sampah Organik Rumah Tangga dengan Biogas. *INSOLOGI: Jurnal Sains dan Teknologi*, **4**(3); 354–366 (in Indonesia)

Shao, H., X. Wu, J. Duan, F. Zhu, H. Chi, J. Liu, W. Shi, Y. Xu, Z. Wei, and G. Mi (2024). How Does Increasing Planting Density Regulate Biomass Production, Allocation, and Remobilization of Maize Temporally and Spatially: A Global Meta-Analysis. *Field Crops Research*, **315**; 109430

Tamma, A. A., K. Lejcuś, W. Fiałkiewicz, and D. Marczak (2025). Advancing Phytoremediation: A Review of Soil Amendments for Heavy Metal Contamination Management. *Sustainability*, **17**(13); 5688

Wei, Z., H. Gu, Q. V. Le, W. Peng, S. S. Lam, Y. Yang, C. Li, and C. Sonne (2021). Perspectives on Phytoremediation of Zinc Pollution in Air, Water and Soil. *Sustainable Chemistry and Pharmacy*, **24**; 100550

Wu, Y., Z. Zeng, R. Teng, J. Yu, G. Guo, P. Huang, Z. Huang, and S. Deng (2026). pH-Dependent Overestimation of Heavy Metals Mobility Risk in Soils: Implications for Soil Quality Assessment. *Journal of Hazardous Materials*, **501**; 140792

Yang, X., S. Zhang, J. Mei, and L. Liu (2019). Preparation and Modification of Biochar Materials and Their Application in Soil Remediation. *Applied Sciences*, **9**(7); 1365

