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Assessment of Soil Contamination Caused by Municipal Solid Waste and Its Environmental Impacts

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Abstract - Municipal solid waste (MSW) has become one of the major anthropogenic factors contributing to soil degradation in urban and peri-urban environments. This study assesses the extent, sources, and environmental implications of soil contamination caused by improper MSW disposal. Field sampling and laboratory analyses were conducted to determine the concentrations of key pollutants, including heavy metals, organic residues, and physicochemical alterations in soils surrounding waste disposal sites. The obtained results indicate elevated levels of contaminants exceeding acceptable environmental standards, reflecting intensified anthropogenic pressure. Furthermore, the study highlights how such pollution negatively affects soil quality, microbial activity, nutrient cycles, and overall ecosystem stability. The findings underscore the urgent need for improved waste management strategies, environmental monitoring, and remediation efforts to mitigate the long-term ecological risks associated with MSW-induced soil contamination.

Keywords. Soil contamination; Municipal solid waste (MSW); Heavy metals; Environmental impact; Soil degradation; Ecosystem stability; Anthropogenic pollution; Waste management; Ecological risk assessment; Physicochemical properties.

INTRODUCTION

Soil fertility is directly related to its physicochemical properties, humus cover, organic and mineral substances, especially the number and biological activity of various beneficial microorganisms. In addition, it is necessary to purposefully select crops depending on the location of agriculture at different geographical latitudes, the peculiarities of its development, and the creation of modern harmless biotechnologies. The influence of soil pollutants on nitrogen-containing bacteria is insignificant, and an increase in their number leads to a decrease in soil contamination. Another group of soil microorganisms is very sensitive to household waste contamination, and their task is to preserve and restore soil fertility [*Abdraxmanov at al. 2023*]. Heavy metal pollution is a global issue due to health risks associated with metal contamination. Although many metals are essential for life, they can be harmful to man, animal, plant and microorganisms at toxic levels. Occurrence of heavy metals in soil is mainly attributed to natural weathering of metal-rich parent material and anthropogenic activities such as industrial, mining, agricultural activities. Here we review the effect of soil microbes on the biosorption and bioavailability of heavy metals; the mechanisms of heavy metals sequestration by plant and microbes; and the effects of pollution on soil microbial diversity and activities [*Nafiu Abdu at al. 2017; Xue-Ting Bai* at al. 2020]. It is known that household waste is completely different from industrial waste, industrial waste is easy to separate into fractions, while household waste is somewhat more difficult to separate into fractions due to its complex composition. For example, it contains various small fractions, heavy metals and various food residues, which, on the one hand, are of interest as secondary materials, and on the other hand, their separation using any mechanical devices is a complex process *[Juvalikyan X.S at al. 2009]*. The presence of heavy metals in the soil around household waste storage areas and landfills has been identified. High concentrations of heavy metals are characteristic of Mg, Zn, Cu, Mo, Se, Cd, and other elements. Copper, mercury, and sulfur are characterized by significantly higher concentrations compared to the maximum permissible concentration (MPC), while slightly higher concentrations of zinc, lead, chromium, copper, and tin decrease with distance from the polygon. The amount of heavy metals in the vertical cross-section of the soil cover is somewhat higher in the upper layers of the soil compared to the lower ones, which is explained by the fact that waste ash, rich in heavy metals, enters the soil cover

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through the atmosphere during the burning and open storage of waste. It is explained by an increase in the content of zinc, lead, chromium, and copper [*Jabbarov Z at al. 2024*]. The distribution of cadmium, lead and zinc in exchangeable, organic, and 2M HNO_3 -extractable fractions as well as the effect of heavy metal concentrations on soil microflora was investigated. Concentrations of all metals increased with decreasing distance from the source of contamination. The concentrations of Cd and Zn in exchangeable fraction were higher than in organically bound fraction, a reverse trend was found in Pb speciation. All measured parameters of soil microbial activity were affected by heavy metal concentrations. The decrease in CFU was most significant in the case of oligotrophic bacteria and spore-forming bacteria. Significant inhibition of C-biomass occurred in soils highly contaminated by heavy metals. The Cbiomass:Cox ratio decreased with increasing soil pollution. Generally, the values of enzymatic activities were highest in the soil above the source of contamination and they were decreased as approaching the source of contamination. Our results demonstrate that several parameters of microbial activity could be used as good indicators of increasing concentrations of Cd, Pb, and Zn in soil [*M. Šmejkalová at al. 2003; Mathiyazhagan Narayanan at al, 2023*]. When studying the effect of heavy metal speciation and presence on soil microbial activity along a Cu/Zn contamination gradient, it was found that the microbial biomass and enzyme activity of Cu and Zn contaminated soil changed. The results showed that microbial biomass was negatively affected by elevated metal levels. The ratio of microbial biomass-C (Cmic)/organic C (Corg) was closely related to heavy metal stress. There was a negative correlation between soil microbial biomass, phosphatase activity, and NH4NO3 heavy metal uptake. The activity of soil microorganisms can be predicted by empirical models with the presence of Cu and Zn [*Wang Yuan-peng at al, 2007*]. Studies were conducted to evaluate the effects of Cd, Cr, Cu, Ni, Pb or Zn on the decomposition of organic matter in the soil and their microflora. All metals inhibited the evolution of CO 2 from the two soils. Among the heavy metals, the effects of Cd, Cu and Ni were noted to be very significant, while Pb was the least significant. The toxicity of heavy metals to colony formation by soil bacteria was high for Cd and Cu, which significantly inhibited the evolution of CO 2 . The content of water-soluble heavy metals in the Gley soil was higher than in the light-colored Andosol, and the decrease in CO 2 evolution was associated with an increase in the content of water-soluble heavy metals divided by the ED 90 values of the heavy metals relative to colony formation by bacteria [*Hiroyuki Hattori, 1992*]. The effects of long-term heavy metal contamination on the soil biological processes and soil microbial communities were investigated in a typical electroplating site in Zhangjiakou, China. It was found that the soil of the electroplating plant at Zhangjiakou were heavily polluted by Cr, Cr (VI), Ni, Cu, and Zn, with concentrations ranged from 112.8 to 9727.2, 0 to 1083.3, 15.6 to 58.4, 10.8 to 510.0 and 69.6 to 631.6 mg/kg, respectively. Soil urease and phosphatase activities were significantly inhibited by the heavy metal contamination, while the microbial biomass carbon content and the bacterial community richness were much lower compared to noncontaminated samples, suggesting that the long-term heavy metal contamination had a severe negative effect on soil microorganisms [*Wen-Jing Gong at al, 2021*].The potential ecological risk index of six heavy metals to soils and the environment was evaluated as Cd > Cu > Pb > Ni > Zn > V. Cd had a high potential ecological risk, Cu had a medium potential ecological risk, and Zn, Pb, V, and Ni had a low potential ecological risk. The comprehensive evaluation result of the Hakanson potential ecological risk index showed that zone I had a high potential risk level, zones II, III, and IV had a medium risk level, and zones V, VI, and VII had a low level. In addition, Microbial Biomass Carbon (MBC) was evaluated to have a significant negative correlation or highly significant negative correlation with 6 heavy metals, and the microbial metabolic coefficient (MMC) was evaluated to have a significant positive correlation or highly significant positive correlation with 6 heavy metals [*Bi Tang at al, 2022; Ivan Sazykin at al, 2023*]. Soil heavy-metal pollution leads to excessive heavy metals in rice and other food crops, which has caused serious impacts on the ecological environment and on human health. In recent years, environmental friendly treatment methods that reduce the bioavailability of heavy metals in soil by soil microorganisms improving the tolerance of heavy metals in rice and reducing the transfer of heavy metals from the roots to the above-ground parts of rice have attracted much attention [*Jie Liu at al, 2011*]. At present, microorganisms tolerant to heavy metals mainly include bacteria and fungi, and their mechanisms include the adsorption of heavy metals by microorganisms, the secretion of growth-promoting substances (growth hormone, ACC deaminase, IAA), changing the physical and chemical properties of the soil and the composition of the microbial community, changing the transport mode of heavy metals in soil, the improvement of the antioxidant capacity of rice, etc [*Yangbin Mao at al, 2022*]. In areas of increased soil contamination with heavy metals (Cd, Pb, Zn, Cu), the ratio of microbial biomass carbon to oxidized carbon has significantly decreased [Michaela F. 2010].

Currently, the rapid development of time and the increasing activity of industrial enterprises are causing the increase in the amount of heavy metals in the soil [*Honghua Liu. At al. 2021*]. It is recognized by most scientists that the amount of heavy metals such as Sr, Cr, Pb, Zn, Cu, Mn in the composition of most polluted soils exceeds the permissible limit [*Elvira Dzhumelia at al. 2021; Alice Kicinska at al. 2023*].The pollution of the soil scattered around the household waste dump has an effect on its physical and chemical properties, a significant difference in the chemical composition of the soil has been detected, which causes

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the amount of heavy metals in the soil to exceed the specified norm. The concentration of heavy metals in landfill soils increased in the order of Fe>Pb>As>Zn>Cd [*Alex Amerh Agbeshiea. 2020*].

Accumulation of heavy metals in the soil as a result of pollution has a negative effect not only on the soil, but also on the plant and human body. In addition, it disrupts the nitrogen cycle mechanism in the soil and causes a decrease in the activity of soil enzymes [*Dinghua Peng. 2023*]. These pollutants enter or remain in the soil for a long time, and once they exceed the self-purification capacity of the soil, they will directly cause the pollution of farmland soil. Many pollutants into the soil will damage the soil ecological balance, soil beneficial organisms and microorganisms die, soil biological populations decrease, soil physical and chemical biological properties deteriorate, soil activity decreases, soil function becomes poor. Serious pollution will also make the soil lose production capacity and lose its value for agricultural use [*Hai Lin at al. 2022; Han Gui-Qi at al, 2012*]. Soil microbial metabolism plays an important role in nutrient cycling and biochemical processes of soil ecosystem. The results showed that soil microbial metabolism reflected by the ecoenzymatic activities had a significant response to soil heavy metals pollution. The metabolism was limited by soil carbon (C) and phosphorus (P) under varied heavy metal levels, and the increase of heavy metal concentration significantly increased the microbial C limitation, while had no effect on microbial P limitation. Microorganisms may increase the energy investment in metabolism to resist heavy metal stress and thus induce C release [*Mingzhe Xu at al. 2021*]. Long-term heavy metal exposure could decrease microbial biomass and activity by inhibiting community diversity, but did not significantly affect community composition. Notably, heavy metal pollution disturbed the relative abundance of several bacterial and fungus taxa, including Actinobacteria, Chloroflexi, Bacteroidetes, Ascomycota and Basidiomycota. Meanwhile, Pseudonocardiaceae, AD3, Latescibacteria, Apiotrichum and Paraboeremia were found only in polluted soil [*Yan Xie at al, 2021*]. Heavy metals (HMs) contamination around smelters poses serious stress to soil microbiome. However, the co-effect of multiple HMs and native vegetation rhizosphere on the soil ecosystem remains unclear. Herein, effects of high HMs level and the rhizosphere (*Tamarix ramosissima*) on soil bacterial community structure and metabolic profiles in sierozem were analyzed by coupling high-throughput sequencing and soil metabolomics. Plant roots alleviated the threat of HMs by absorbing and stabilizing them in soil. High HMs level decreased the richness and diversity of soil bacterial community and increased numbers of special bacteria. Plant roots changed the contribution of HMs species shaping the bacterial community. Cd and Zn were the main contributors to bacterial distribution in non-rhizosphere soil, however, Pb and Cu became the most important HMs in rhizosphere soil [*Fanghan Qian at al, 2022; Run Wang at al, 2023*]

Soil enzyme activities have been proposed as suitable indicators for assessing metal pollution, as they are susceptible to microbial changes induced by heavy metals and are related to soil nutrient cycling. We review the most common methods for assessing heavy metal pollution based on enzyme activity in experiments [*Yongxing Cui at al, 2021*]:

a) enzyme index,
b) combined enzyme index,
c) enzyme-based functional diversity index,
d) microbiological stress index
e) ecoenzymatic stoichiometry models.

We critically review the advantages and disadvantages of these methods based on their implementation complexity, performance, and ecological implications, and consider ways to improve future assessment systems. Some heavy metals have a negative impact on human health, damaging the kidneys, brain, intestines, lungs, liver and other organs of the human body. If people want to feel safe in their surroundings, the release of heavy metals into the environment must be strictly regulated [*Prodipto B.A. at al, 2024].*

Materials and Methods**

Study Area

The study was conducted in the vicinity of a municipal solid waste (MSW) disposal site located in the Ohangaron district. The soils of the study area are predominantly irrigated typical grey soils (bo‘z soils), which cover approximately 28–40% of the district's agricultural land. These soils are characterized by a medium loamy texture, low compaction, light grey color, and clod-like structure. Visual surveys revealed the presence of ash particles resulting from household waste combustion, fragments of glass, gravel, polyethylene residues, and white carbonate accumulations. Soil profiles were taken from agricultural fields where winter wheat and maize were cultivated, and biological traces such as insect burrows and plant roots were observed.

Soil Sampling

Soil samples were collected from two main sections (southern and eastern parts of the landfill) at varying depths ranging from surface layers (0–14 cm and 0–6 cm) to deeper horizons (up to 137 cm). Stainless-steel augers were used to avoid metal contamination during sampling. For each sampling point, three subsamples were combined to obtain composite samples. Control (background) samples were taken from non-contaminated locations sufficiently distant from the landfill.

Sample Preparation

All samples were air-dried, homogenized, and sieved through a 2 mm mesh. Prepared samples were stored in sealed polyethylene bags and transported for laboratory analysis. Visible anthropogenic fragments (glass, plastics, stones) were recorded but excluded from chemical analysis. Electrical conductivity (EC) was measured using a calibrated digital conductivity meter in a soil–water suspension (1:2.5). EC values were expressed in µS/cm and used as an indicator of soil salinity and ion concentration. The classification criteria applied were:

- 0–200 µS/cm – non-saline, non-polluted soil
- 200–400 µS/cm – moderate salinity or pollution
- >400 µS/cm – saline or polluted soil

These thresholds allowed for the identification of pollution accumulation in the upper soil layers.

Heavy Metal Determination

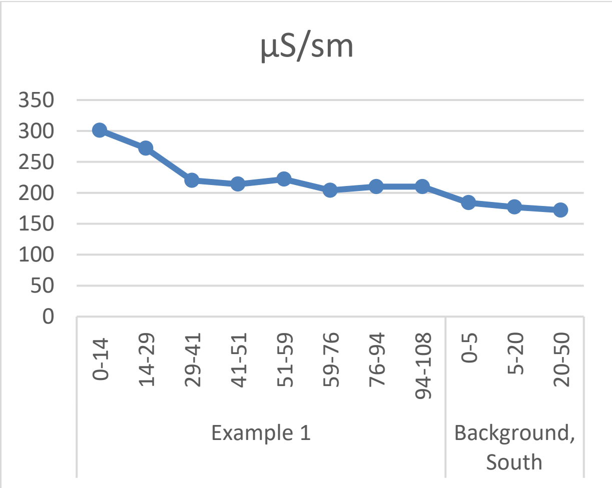
Concentrations of As, Cd, Cu, Ni, and Co were determined following acid digestion using HNO_3 and $HClO_4$ solutions. Heavy metals were quantified using Atomic Absorption Spectrophotometry (AAS). The obtained concentrations (Cb) were compared with Clarke values (Ci) to determine pollution intensity. Analytical precision was verified using standard reference materials. All analytical data were processed using MS Excel. Elemental concentrations, EC values, PI, IPI, E_ir, and RI indices were statistically compared between soil profiles and landfill sectors (southern, eastern, western, and central parts). Heavy metal distribution patterns were analyzed to determine pollution sources and depth-related trends.

Results

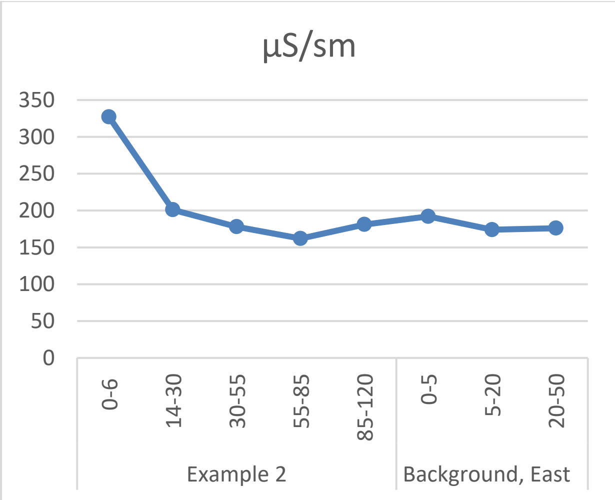
The soils of the study area mainly consist of irrigated typical gray soils, which account for 28–40% of the soils in the Ohangaron district. These soils are generally medium loamy, non-compacted, light gray in color, and possess a cloddy structure. Particles of ash formed as a result of solid waste combustion are present in the soil. Fragments of glass, gravel, and polyethylene are also encountered. White carbonate accumulations are visible. The site from which the soil profile was taken had previously been cultivated with winter wheat and maize, and traces of insect burrows and plant roots were observed. Transition to the next soil horizon was identified by a noticeable change in color.

Measurements of the soils' electrical conductivity (EC) were conducted. Electrical conductivity, expressed in µS/cm (microsiemens per centimeter), indicates the concentration of ions in the soil solution and is therefore used to determine the degree of soil salinity or contamination. EC values in uncontaminated soils are typically low because the amount of dissolved salts and ions is minimal. Accordingly, EC serves as an indicator of salinity and pollution levels.

In the upper horizon (0–14 cm), the EC value is 301 µS/cm, indicating moderate salinity or contamination in the surface layer. With increasing depth, EC values decrease. At 118–137 cm, EC is 145 µS/cm, showing that salinity and contamination are minimal in deeper layers. In Profile 1, salinity or contamination is mainly concentrated in the upper horizon, which may be associated with surface-level pollution sources, such as deposition of waste materials or ash.



Pic. 1. EC in soils of the southern part



Pic. 2. EC in the soils of the eastern part

Section 2 shows the presence of contamination or salinity in the upper layer (0-6 cm): EC 327 µS/cm. Electrical conductivity decreases sharply towards the lower layer. In the 85-120 cm layer, EC 181 µS/cm shows the presence of low contamination. In the 2nd section, as in the 1st section, the contamination in the upper layer is high, but significantly decreases downwards.

An increase in the content of heavy metals is observed in soils contaminated with household waste. In the studied territory, an increase in the content of As, Cd, Cu, Ni, and Co elements in the soils was also revealed. A large amount of these elements is dangerous for the soil, and the combined effect of As, Cd, Cu, Ni, and Co on the soil leads to a decrease in soil enzymatic activity (urease, catalase, dehydrogenase), a decrease in the diversity and biomass of microorganisms, an increase in the environmental hazard index (ERI), long-term soil degradation and a decrease in fertility, and an increase in the bioaccumulation potential of plants and groundwater. As a result of the studies, the Cu content in contaminated soils exceeded the natural clarke by 2-3 times - this indicates a moderate degree of soil contamination in both regions. In the sections taken from the southern part, the value of Cu is in the range of Kt ≈ 0.6-1.9, and in many places the element Cu is higher than the Clarke value. The Kc values of Co and Ni elements are about 0.8, and they are at the natural background level, i.e., household waste did not affect the composition of these elements.

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Soil pollution index PIi= Ci/Cclarke=Kk and integral pollution index
*IPI-n√ (PI1*Pi2*...*Pin) was determined using the formulas.*
Here;
PI is the average pollution load for each element:
IPI - indicates the average pollution load of all elements

These models determine the pollution coefficient for each element and allow for the integration of their overall environmental load. In the conducted studies, it was noted that the lowest integral pollution index (IPI) was obtained from the eastern part of the landfill (LPI-3-0.71), where the level of pollution is close to the level of the natural background. The highest IPI: in the western part of the outlet (LLC-1-1.15). Contamination with Cu, Co elements was observed here. This means that the environmental risk is moderate. Areas close to the center of the landfill (in samples MCHSHi-9, MCHG-1 and MCHG-3) are distinguished as active zones of heavy metal contamination. The Potential Economic (Environmental) Risk Index (PI) is a complex integrated indicator of heavy metal contamination with highly toxic and moderately toxic (As, Cd, Cu, Co, and Ni) elements, which together assesses the toxicity, concentration in the soil, and potential economic damage of this element.

As a result of the conducted research, the potential environmental hazard index of very hazardous and moderately hazardous heavy metals (As, Cd, Cu, Co, and Ni) was determined.

Table 1. Potential Environmental Hazard Index (IPI) for heavy metal As

№	Regions	Clarke concentration, C_i	Content in soil, C_b	Toxicity Coefficient(T_r)
1	MCHJ -1	176,2	103,6	10
2	MCHSha-1	169,7	99,84	30

This table contains the Clarke concentration (C_i), soil content (C_b), and toxicity coefficient (T_r) of the heavy metal As by region. Based on this data, we can analyze the pollution index (PI) and the environmental risk index (E_i^r), as well as the overall integrated environmental risk index (PI).

№	Region	C_i	C_b	T_r	$PI = C_b/C_i$	$E_ir = PI \times T_r$
1	MCHJ-1	176.2	103.6	10	0.588	5.88
2	MCHJ-fon	144.7	85.11	10	0.588	5.88
3	MCHSha-1	169.7	99.84	30	0.588	17.64
4	MCHSha-fon	167.8	98.71	5	0.588	2.94

In the obtained data, the values of PI (0.588) of Tl indicate that the soil is not contaminated with toxic elements. Eir values ranged from 0.59 to 17.64, with the highest toxic effect observed at MCHSHa-1 (E_i^r = 17.64). In all other regions, E_i^r is very low - in the environmentally safe range. The total integral index RI = 40, which belongs to the category of low environmental risk. Elements with a high toxicity coefficient (Tr = 30) had a significant effect on the analysis, but their quantity did not yet reach a dangerous level. Based on PI values, the Cd element is 3-5 times more abundant, while in other metals, PI < 1, i.e., at the background level. The Cd element for E_i^r has a highly toxic value in the range of E_i^r = 50-140. The PI index varies within the range of 57.9-146.8, indicating a low average risk level. Procedure according to the level of environmental risk:

As>Cd > Cu > Ni > Co

As a result of the research, the As element is the main source of environmental danger in the analyzed territories, the influence of other heavy metals is at the level of a natural background.

Table 2. Comprehensive Environmental Risk Index Table of Elements

Region	Cd	Cu	Co	Ni	RI ($\sum E_ir$)
MCHJ-1	109.5	1.8	1.75	1.86	116.2
MCHJ-fon	139.5	2.05	1.70	2.10	98.8
MCHSha-1	69.3	2.15	1.60	1.98	76.4
MCHSha-fon	69.3	3.35	1.85	2.46	70.4

As a result of the analysis, the highest RI of heavy metals is in MCHJ-2-146.8, which belongs to the zone of medium environmental risk. The lowest risk corresponds to the RI MCHShi -3-57.9 area. In all samples, the Cd element is the main source

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of high risk, accounting for 80-90% of Eir values. Heavy metals such as Cu, Co, Ni, Cr have very low Eir values, i.e., they are reflected at the natural background level.

DISCUSSION

The findings of this study demonstrate that municipal solid waste (MSW) disposal sites exert significant pressure on surrounding soil environments, resulting in both physicochemical deterioration and ecological imbalance. Elevated concentrations of heavy metals such as As, Cd, Cu, Ni, and Co indicate persistent pollution, which aligns with previous studies reporting that MSW leachates are major contributors to long-term soil contamination. The accumulation of these metals beyond permissible limits suggests restricted natural attenuation capacity and continuous anthropogenic input.

The observed decrease in soil pH and increase in electrical conductivity (EC) near waste disposal zones further confirm the infiltration of inorganic ions and acidic compounds from decomposing waste materials. Such physicochemical alterations negatively influence nutrient availability, microbial functioning, and overall soil fertility. The decline in organic matter content in contaminated soils may be attributed to inhibited microbial decomposition processes, underscoring the disruptive effect of toxic substances on soil biological activity.

Biological indicators, including reductions in urease and catalase activity, provide strong evidence of microbial stress induced by heavy metal toxicity and altered soil chemistry. These results are consistent with earlier research highlighting enzyme activity as a reliable biomarker for assessing soil health under pollution pressure. The reduced microbial biomass carbon (MBC) observed in this study reflects compromised nutrient cycling, which poses long-term risks for soil productivity and ecosystem sustainability.

Pollution indices (PI and ERI) calculated for the study area reveal moderate to high ecological risk levels, emphasizing the urgency of implementing effective waste management interventions. The strong positive correlations between heavy metal concentrations and pollution indices indicate that these contaminants are primary contributors to ecological hazards. Therefore, remediation measures—such as phytoremediation, engineered landfill systems, and regular environmental monitoring—are essential to mitigating the environmental impacts identified. Overall, the findings highlight the critical need for improved MSW handling practices and the integration of environmental protection policies to prevent further soil degradation. Without strategic intervention, the persistent accumulation of pollutants will continue to undermine soil health, ecosystem function, and public safety in the surrounding areas.

CONCLUSIONS

This study demonstrates that improper management and disposal of municipal solid waste (MSW) significantly contribute to soil contamination and environmental degradation in the surrounding areas. The elevated levels of heavy metals (Cd, Ni, Co, Cu) and altered physicochemical parameters (pH, EC, organic matter) indicate intense anthropogenic pressure and highlight the vulnerability of soils to persistent pollution. Moreover, reductions in microbial activity and enzyme functions, including urease and catalase activity, confirm the disruptive impacts of MSW leachates on soil biological processes.

The calculated pollution indices (PI and ERI) reveal moderate to high ecological risk, underscoring the need for urgent mitigation strategies. If left unaddressed, the continued accumulation of toxic substances will lead to long-term soil degradation, reduced ecosystem stability, and potential threats to human health. To minimize these impacts, the study recommends the adoption of improved waste management practices, such as engineered landfill systems, leachate treatment technologies, and regular environmental monitoring. Additionally, the implementation of remediation approaches—such as phytoremediation and soil amendment—can play a crucial role in restoring soil health and reducing ecological risks. Overall, the research highlights the necessity of integrating sustainable waste management policies and scientific monitoring to protect soil resources and ensure environmental safety in regions affected by MSW contamination.

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