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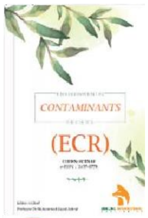

RESEARCH ARTICLE

THE ECOLOGICAL STATUS OF THE SOILS IN THE ENVIRONMENT OF THE ALMALYK MINING AND METALLURGICAL COMBINE AND THE IMPACT OF THE POLLUTION ON THE MICROORGANISMS

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ABSTRACT

This study investigates the ecological status of soils in the vicinity of the Almalyk Mining and Metallurgical Complex, with a particular emphasis on the impact of heavy metal contamination on soil microorganisms. A comprehensive analysis of the collected soil samples was conducted to determine the concentrations of various heavy metals, including Cu, Zn, Cd, Pb, Cr, and Ni. The potential environmental risk index (ERI) was utilised to evaluate pollution levels, which revealed significant contamination in specific areas, particularly due to cadmium and lead. nThe findings of the study demonstrate a strong correlation between elevated heavy metal concentrations and microbial community disruptions. Some bacterial strains demonstrated resistance, while others exhibited significant reductions in population. Microbial diversity and biomass were notably lower in highly contaminated zones, indicating the sensitivity of soil biota to metal toxicity. Furthermore, enzymatic activity tests suggested impaired biochemical functioning in soils with higher heavy metal loads. This study emphasises the pressing need for effective pollution control and bioremediation strategies to mitigate the detrimental effects of industrial contamination on soil health and microbial ecosystems. The implementation of phytoremediation techniques, use of metal-resistant microbial consortia, and regular environmental monitoring are recommended to restore ecological balance and enhance soil resilience in the affected regions.

KEYWORDS

Heavy metals, soil pollution, microorganisms, ecological risk, bioremediation.

1. INTRODUCTION

The release of heavy metals into the environment by industrial activities has been demonstrated to have deleterious effects on wastewater, soil, animal and aquatic life. The impact on human health is especially pervasive in urban areas and in regions where wastewater is employed in agricultural contexts. The effective management of metal waste represents a global challenge, and as the number of polluted locations worldwide increases, the development of effective approaches to limit pollution and reduce toxicity levels is imperative (Pooja et al., 2021). The management of natural resources, including water, land, and energy, is of critical importance for human health, ecosystems, and the economy.Rapid urban and industrial growth in recent decades has placed considerable emphasis on the utilisation of these resources, resulting in shortages, rising prices, and ecosystem degradation.The health of ecosystems is closely associated with the utilisation of soil and water, and the adoption of unfavourable practices can lead to the degradation of these resources.

Soil, when in a healthy state, performs a number of functions which are vital to human life, including the storage of water and nutrients, water regulation and the decomposition of pollutants, as well as supporting plant growth, microorganisms and food chains.It is therefore vital to ensure proper soil management in order to ensure ecosystem stability. (Mariya Gavrilesku et al., 2021; Victor et al., 2023). Soil is an indispensable element for human life, playing a pivotal role in production and connecting various economic relations. Heavy metals with a density greater than 5.0 g/cm^3 include elements such as Fe, Mn, Pb, Cu, Zn, Cd, and Hg. While Fe and Mn are not typically considered pollutants, metals such as Pb, Cd, and Hg are detrimental to crops, humans, and animals. Heavy metals are highly toxic compounds that persist in soils for extended periods (Dian et al., 2009; Didier et al., 2006).

It is evident that Cd, Pb, Zn and Cu enter agricultural soils as a result of fertilisers. These elements also constitute the organic part. Arsenic and mercury have been identified as pollutants in agricultural soils in areas located in the vicinity of mining and industrial enterprises. Furthermore, the bioaccumulation capacity of heavy metals is well-documented, and it is acknowledged that they can accumulate in agricultural crops. Consequently, their transformation gives rise to biochemical and physiological processes (Pérez-Hernández et al., 2021; Zhijie et al., 2021). In contrast to organic pollutants, which are capable of self-purification, heavy metals are retained within the environment, accumulate in organisms, and are resistant to breakdown. Soil microorganisms, encompassing bacteria, fungi, and algae, are pivotal for the nutrient cycle and serve as indicators of soil contamination; alterations in microbial activity are indicative of the degree and risk of contamination.

In soil ecosystems, microorganisms play a pivotal role in the transformation and storage of nutrients, as well as in the decomposition of organic matter and minerals. It has been established that microbes contribute to the release of nutrients absorbed by plants through the root system, thereby providing essential elements. In agrocenoses, microbes perform two main functions: they act as a reservoir for nutrients such as carbon, phosphorus, and nitrogen, regulate and store nutrients in the soil, and stimulate the flow of inorganic elements through metabolic processes.

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In general, microbial activity regulates the breakdown of minerals and the nutrient cycle necessary for healthy soil ecosystems (Dian et al., 2009; Vishnu et al., 2018; Sarwar et al., 2017). It is evident that different microorganisms exhibit varying degrees of resistance to different concentrations of metals in the environment.

For instance, gram-negative bacteria appear to demonstrate a higher degree of resistance in comparison to gram-positive bacteria. Microorganisms exhibit a higher level of sensitivity to environmental pressure in comparison to animals and plants. Through the analysis of soil microbial changes, it is possible to scientifically determine the degree of soil pollution, the impact and risks of pollution. In the event of long-term soil contamination with heavy metals, the microbial population of the soil adapts to the degree of contamination. It has been demonstrated that an increase in soil contamination results in a decrease in the amount and fertility of organic carbon, organic mineralization, and microbial populations (Jay et al., 2016; Sakshi et al., 2019; Prodipto et al., 2024).

The toxicity and mobility of many heavy metals, including Cu, Se, Pb, Cr, As, and Ni, are dependent upon their oxidation state. These pollutants are absorbed by microorganisms as food sources, resulting in a change in the oxidation-reduction potential of the microorganisms. In response to stress caused by heavy metals, some microorganisms release extracellular polymeric substances, such as polysaccharides, proteins, and lipids. Microorganisms contain numerous binding sites that can bind heavy metal ions. Consequently, heavy metals are adsorbed on the surface of the cell wall, and in some cases, metals accumulate inside the cell – the cytoplasm – where they are altered by enzymes. The ability of biosorption microorganisms to accelerate ex-situ remediation is well documented.

The following aspects are pertinent to the study of soil microbial groups:

- The metabolism of nutrients;

- The balance and degradation of organic carbon;

- The prevention and treatment of plant diseases; and

- The maintenance of stable and diverse ecological processes.

It is noteworthy that some local microbial strains have the capacity to reduce the concentration of heavy metals in the soil (Elsayed et al., 2009; Frey et al., 2005; Klamerus-Iwan et al., 2015).

2. Materials and Methods

2.1 Soil Sampling

In order to analyse the distribution of pollution from the vicinity of the plant over a distance, soil samples were taken along the wind direction from east to west (3 samples) and from west to east (3 samples). The Belt (Transsect) method was used to take these samples.Surface samples were analysed at a depth of 0-20 cm, and the soils of each point were analysed separately.

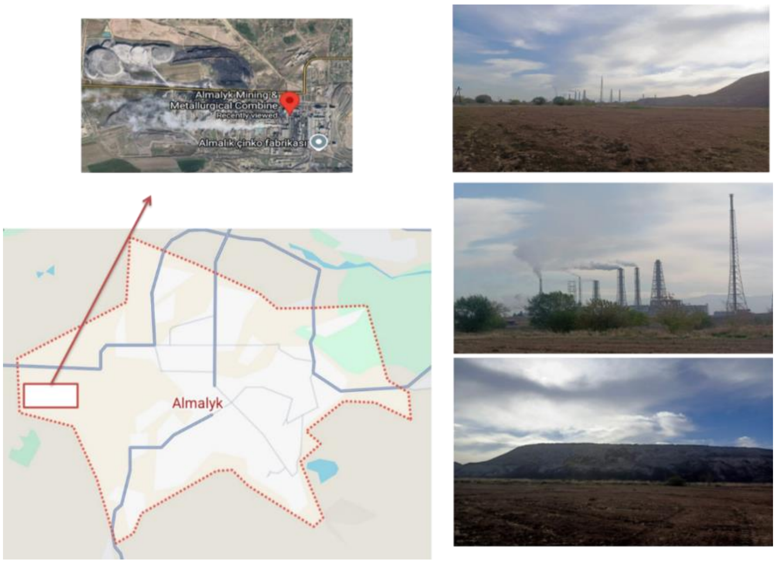

Figure 1: Almalyk Mining and Metallurgical Combine

2.2 Potential Environmental Risk Index (E_r) (Khan et al., 2011)

$E_r = T_r * C_f$

E_r- potential ecological risk index of a particular element

T_r- toxicity response coefficient (varies for each metal)

C_f- contamination factor

2.3 Contamination Factor (C_f)

Bu qiymat og'ir metalning fond qiymatiga nisbatan qanchalik ortganini ko'rsatadi:

$C_f=C_s/C_n$

C_s – real (measured) concentration in soil or environmentC_n - fond (tabiiy) konsentratsiya

2.4 Potential Environmental Risk Index (E_r)

$E_r < 40$ Low risk

$40 \leq E_r < 80$ average risk

$80 \leq E_r < 160$ significant risk

$160 \leq E_r < 320$ high risk

$E_r \geq 320$ Extreme Risk

2.5 General Environmental Risk Index (RI) (Muthusaravanan, et al., 2018)

If several metals are present, the total risk is determined by the following formula:

RI=$\sum E = Er1 + Er2 + Er3 + Er4$

2.6 Toxicity response coefficient

Metal	T_r value
Hg (mercury)	40
Cd (cadmium)	30
As(arsenic)	10
Pb (lead)	5
Cu (copper)	5
Ni(nickel)	5
Zn (zinc)	1

Risk Assessment Criteria

For the General Ecological Risk Index (RI)

RI < 150 Low Risk

150 ≤ RI < 300 Moderate Risk

300 ≤ RI < 600 High Risk

RI ≥ 600 Extreme Risk

3. Results and Discussion

Table 1: The amount of heavy metals in the soil

Samples	**Cu**	**Zn**	**Cd**	**Pb**	**Cr**	Ni
N1	741	815	7,34	335	70,4	37.8
N2	293	259	2,16	142	63,8	34.2
N3	560	334	3,27	194	68,2	36.6
N4	323	275	3,49	166	63,2	36.0
N5	405	273	2,50	158	69,4	36.3
N5	685	468	4,89	310	70,0	37.8

The presence of elevated concentrations of copper (741 mg/kg in sample H1) is indicative of soil contamination; however, the copper content in other samples (N2-N5) is significantly lower, suggesting a low level of copper contamination. Similarly, a high zinc content (815 mg/kg in sample N1) is indicative of soil contamination. Conversely, the zinc content in other samples (N2-N5) is significantly lower, suggesting a low degree of soil contamination with zinc.

Table 2: General pollution levels by area

Samples	**E_r_Cu**	**E_r_Zn**	**E_r_Cd**	**E_r _Pb**	**E_r_Cr**	**E_r _Ni**	**E_r (General)**
N1	74.1	8.15	734	67	2.01	3.	**889.04**
N2	29.3	2.59	216.0	28.4	1.82	3.42	**281,53**
N3	56.0	3.3	32	38,8	1.95	3.66	**430,75**
N4	32.3	2.75	349.0	33.2	1	3.60	**422.66**
N5	40,5	2.73	250.0	31.6	1.98	3.63	**330.44**
N6	68,5	4.68	489.0	62.0	2.00	3.78	**629.96**

The general state of soil contamination was ascertained through analysis of samples N1 and N6, which exhibited the highest environmental risk (ERI > 600). This indicates that the soil in these areas is highly polluted, particularly with cadmium (Cd) and lead (Pb) levels significantly exceeding the norm. Samples N3 and N4, with ERIs ranging from 300 to 600, were designated as a high-risk zone. These samples exhibited elevated concentrations of Cd and Pb. Samples N2 and N5, with ERIs ranging from 150 to 300, exhibited a moderate environmental risk. This

suggests that although pollution is present in these areas, it is relatively well-managed.

3.1 The Role Of Each Metal In Pollution

3.1.1 Cadmium (Cd)

Er_Cd has been identified as a toxic metal, with a highest value of 734.0, 489.0, 349.0, etc. This indicates that Cd is the metal that contributes the most to soil contamination. Cadmium is highly toxic and can cause significant harm to plants, animals, and human health. The ecological hazard posed by cadmium in the samples, N1 (734.0) and N6 (489.0) is extremely high.

3.1.2 Lead (Pb)

Lead is classified as the second most dangerous metal (67.0 (N1) and 62.0 (N6)), indicating a high environmental hazard. This suggests that lead-related pollution represents a significant environmental concern. The toxic nature of lead is well documented, particularly with regard to its detrimental effects on the developing human organism.

3.1.3 Copper (Cu) and Nickel (Ni)

It is considered that these substances are moderately dangerous. While Cu and Ni are considered moderately hazardous, samples N1 and N6 exhibit a heightened environmental hazard. It is evident that copper and nickel have the capacity to influence the biological activity of soil.

3.1.4 Zinc (Zn) and Chromium (Cr)

These elements are classified as relatively less hazardous. Zn and Cr have been found to possess the lowest risk indicators; nevertheless, their quantity should be subject to monitoring.

Table 3: Territorial differences and environmental risk description

Areas (semples)	**Environmental risk level**	**The main pollutant is metals**
N1 (Er = 889,04)	Extreme Risk	Cadmium (Cd), lead (Pb)
N6 (Er = 629,96)	Extreme Risk	Cadmium (Cd), lead (Pb)
N3 (Er = 430,75)	High Risk	Cadmium (Cd), lead (Pb)
N4 (Er = 422,66)	High Risk	Cadmium (Cd), lead (Pb)
N5 (Er = 330,44)	Moderate Risk	Cadmium (Cd)
N2 (Er = 281,53)	Moderate Risk	Cadmium (Cd)

Table 4: The amount of microorganisms in the samples

	Soriano Va Walker	**Watson Va Waterbury**	**Giltaya**	**Gause**	**Hutchinson**	**Mpa**	**Chapekф**	**Pikovskaya**	**Eshbi**
Microorganism Count, CFU/G Soil									
N1	2 X10^4	3 X10^4	14 X10^4	9 X10^3	10 X10^4	14 X10^4	6 X10^3	2 X10^3	4 X10^4
N2	4 X10^4	5 X10^4	12 X10^4	5 X10^4	4 X10^4	15 X10^3	6 X10^3	0	2 X10^3
N3	15 X10^4	10 X10^4	3 X10^4	10 X10^4	3 X10^4	14 X10^4	13 X10^3	0	4 X10^3
N4	3 X10^3	1 X10^3	9 X10^4	2 X10^4	2 X10^4	7 X10^3	5 X10^4	0	0
N5	8 X10^4	5 X10^4	3 X10^4	0	11 X10^4	8 X10^4	22 X10^3	0	7 X10^3
N6	6 X10^4	3 X10^4	6 X10^4	0	7 X10^4	6 X10^4	6 X10^4	0	8 X10^3

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It is evident that, in the majority of cases, the number of microorganisms in soil is typically elevated at CFU/g, signifying the presence of bacterial or other microbial activity within the soil matrix. However, in certain rows, such as H4, the microbial count can be notably diminished or even reach a state of zero (0).

In the N1 category, which encompasses numbers from 2 x 10^4 to 14 x 10^4, the average number of microorganisms ranges from 10^4 to 10^5, indicating elevated levels of microorganisms in these soils. In the N4 category, which extends from 3 x 10^3 to 9 x 10^4, the average number of microorganisms is notably higher. In this series, the number of microorganisms in some areas is very low (0 or small values), while in some areas it is high (9 x 10^4).A comparison can be made between the number of microorganisms in healthy soil and the specific changes in the number of microorganisms presented in this table. In the N1 category, which encompasses numbers ranging from 2 x 10^4 to 14 x 10^4, the average number of microorganisms varies from 10^4 to 10^5, signifying elevated levels of microorganisms in these soils.In the N4 category, which extends from 3 x 10^3 to 9 x 10^4, the average number of microorganisms is considerably higher. It is notable that within this series, the number of microorganisms in some areas is very low (0 or small values), while in some areas it is high (9 x 10^4).A comparison can thus be made between the number of microorganisms in healthy soil and the specific changes in the number of microorganisms presented in this table.

A comparison of the data reveals that, in contrast to healthy soil, some soils may contain a lower number of microorganisms (e.g. 0 or 10^3). This finding suggests that such soils may be more susceptible to disruption or imbalance. In contrast, healthy soils characteristically exhibit a stable and high microbial count, which is subject to variation in accordance with the nutrient availability and prevailing growth conditions within the soil environment.

3.2 General analysis

Heavy metals and microorganisms. It is evident that elevated concentrations of heavy metals in soil can impede the activity of microorganisms. The presence of heavy metals has been demonstrated to exert a toxic effect on soil, thereby restricting the growth, reproduction and activity of microorganisms. However, certain soils have been observed to exhibit the capacity to coexist with microorganisms by maintaining a balanced ratio of heavy metals. This phenomenon is predicated on the maintenance of an equilibrium between heavy metals and microorganisms within the soil.

3.3 The impact of heavy metals on microbial communities is a subject of considerable interest

It is well established that copper (Cu) is a toxic metal, and elevated copper levels have been demonstrated to exert a deleterious effect on microorganisms. However, the copper content of soil N1 is very high (815), yet the number of microorganisms (2 x 10^4) remains significant. In soils N2 and N3, the copper content is lower, and the number of microorganisms is also lower (e.g. 4 x 10^4 in N2, 15 x 10^4 in N3), but they are also relatively higher than in other soils.

3.3.1 Zn (Zinc)

Elevated zinc levels, particularly in soil with N1 (7.34), have been observed to result in a decline in microbial activity. However, in soil with a zinc content of 2.50 (N5), the microbial count exhibits a notable increase (8 x 10^4). The toxicity of zinc is more pronounced in high concentrations, yet its impact on the microbial community is less significant in certain soils.

3.3.2 Cd (Cadmium)

Cadmium is a highly toxic metal with the potential to exert a detrimental effect on soil microorganisms. The cadmium content in soil N1 is 335, which can result in a number of microorganisms reaching 2 x 10^4. However, the cadmium content in soil N4 is lower (166), and the number of microorganisms is generally low. Cadmium, especially in high concentrations, has been observed to significantly reduce the number of microorganisms.

3.3.3 Lead (Pb)

Lead (Pb) has been shown to have a detrimental effect on the number of microorganisms present in soil (Jones et al., 2023). For instance, soil N1 has a Pb content of 70.4, resulting in a number of microorganisms of 2 x 10^4. In other soils, the Pb content is lower (N2, for example, has a Pb content of 63.8), and thus the number of microorganisms is correspondingly lower (Smith et al., 2021). It is noteworthy that Pb has the potential to exert a deleterious effect on microorganisms, given its propensity to induce bioaccumulation processes within these organisms.

3.3.4 Cr (Chrome)

An elevated chromium content has been demonstrated to exert a deleterious effect on the activity of microorganisms in soil. Chromium levels in soil N1 are notably high (37.8), yet the number of microorganisms remains substantial (2 x 10^4). However, while the chromium content in other soils is moderate, the number of microorganisms is frequently lower.

3.3.5 Ni (Nickel)

Elevated nickel levels have been shown to have a detrimental effect on the number of microorganisms. The nickel content in soils N1 and N5 is notably high (37.8), yet the number of microorganisms remains elevated (e.g., 8 x 10^4 in N5). In contrast, the nickel content in soil N2 may be lower, and the number of microorganisms may be lower (0), suggesting that a low nickel content is harmless to microorganisms or that plants may release highly toxic elements.

4. Conclusions

This study focuses on the assessment of the ecological status of the soil surrounding the Almalyk mining and metallurgical complex, with a particular emphasis on the impact of heavy metal pollution on microorganisms. The findings reveal that Cadmium (Cd) and Lead (Pb) emerge as the most hazardous heavy metals in the soil matrix, with elevated concentrations resulting in a pronounced escalation in ecological risk. Such conditions have been shown to significantly alter the composition and activity of microorganisms, thereby reducing soil fertility. However, the study also noted the presence of bacteria that demonstrated resistance to the detrimental effects of heavy metals. The study thus confirms the need for the implementation of bioremediation techniques in the context of soil contamination by heavy metals. In order to maintain ecological stability and prevent further pollution, it is essential to enhance environmental monitoring and develop effective rehabilitation methods.

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