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Scientific article

ASSESSMENT OF THE ECOLOGICAL CONDITION OF THE SOIL COVER OF THE INDUSTRIAL AREA CONTAMINATED WITH HEAVY METALS (IN THE EXAMPLE OF THE KARAGANDY METALLURGICAL COMBINE)

Aizhan Rakhisheva*, Zhanar Rakhymzhan PhD, associate professor, Raikhan Beisenova Candidate of Biological Sciences, professor, Rumiya Tazitdinova PhD, associate professor

L.N. Gumilyov Eurasian National University, Astana, Kazakhstan; Aizhan_enu@mail.ru (AR), raihan_b_r@mail.ru (RB), r.zhanar80@mail.ru (ZhR), irm85@mail.ru (RT)
Corresponding author: Aizhan Rakhisheva, Aizhan_enu@mail.ru

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ABSTRACT

Contamination of the soil of the industrial area with heavy metals is a serious environmental problem. In research soil samples were taken from the territory of the steel and mining company, which owns the largest metallurgical plant in Kazakhstan, "Karagandy Metallurgical Plant", located in the city of Temirtau, Karaganda region, Qarmet JSC, a metallurgical enterprise of Central Kazakhstan, and the content of heavy metals was determined using atomic absorption spectrophotometer (AAS) and X-ray fluorescence spectroscopy. Was determined. Eleven heavy metals were detected in the soil samples and the following heavy metals were found in the dissolved state: TiO_2, MnO, and Fe_2O_3. It is known that the concentration of heavy metals Sr, Zn, Cr, and Cu in the soil samples is much higher. According to the research results, it was determined that the concentration of heavy metals increases in the order of Sr>Zn>Cr>Cu>V>Ni>Pb>As>Co>Cd>Hg. As a result of the comparison of the three samples №1, №2, №5 with the highest contamination level, the highest concentration of Strontium in the first sample is 287,1±0,05 mg/kg ($p<0,05$), the highest concentration of Zinc in the second sample is 132,2±0,05 mg/kg ($p<0,05$), high concentration of Chromium in the first sample is 137,2±0,05 mg/kg ($p<0,05$), Copper concentration was highest at the second point, amounting to 87,6±0,05 mg/kg ($p<0,05$). According to the results of the soil samples, it was found that the soil near the metallurgical plant is contaminated with strontium, zinc, chromium and copper.

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1. INTRODUCTION

Chromium (Cr) is one of the pollutant heavy metal elements that threaten human health, and animal and plant growth. Human consumption of hexavalent chromium [Cr(VI)] can cause symptoms such as asthma, cardiovascular disease, and organ failure, and is known to pose a risk to plants and animals [1]. In addition, Cr(VI), known as an extremely toxic highly mobile oxyanion species, poses a major carcinogenic risk to ecosystems and human health [2…3]. Therefore, it is essential to remediate Cr(VI)-contaminated soils to reduce their ecological risk and subsequent environmental impact. Scientific assessment of the environmental risk of soil chromium (Cr) and the formulation of ecological standards for it may be of great importance in controlling its toxicity, as Cr is listed as one of the 20 most dangerous substances by the Agency for Toxic Substances and Disease Registry [4].

Strontium (Sr), an alkaline earth metal, is a common element in nature [5]. Elevated concentrations of persistent and radioactive strontium in soil and water are considered a major public health and environmental concern. Strontium is absorbed by the human body in the same way as calcium, because these two elements are chemically very similar and accumulate mainly in human bones and teeth, and also impairs bone growth in children [6]. When strontium enters our bodies, it can displace calcium from bones or inhibit the production of vitamins and cause leukemia, rickets, and kidney disease [7].

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Soil contamination with zinc leads to significant environmental problems, including reduced soil fertility and potential toxicity to plants and microorganisms. Effective recovery strategies are

needed to reduce its adverse effects [8]. High levels of Zn disrupt nutrient cycling and alter soil microbial communities, affecting ecosystem stability [9]. This pollution can have a significant impact on the environment, disrupting nutrient cycling, altering microbial communities, and affecting the overall balance and stability of ecosystems. The effects of zinc on soil microbial processes and the sensitivity of earthworms to zinc further highlight the potential ecological consequences of zinc pollution [10]. Zn to soil is mainly from metallurgy (mining, smelting), agriculture (fertilizers, pesticides, manure), energy use (electricity generation, gasoline), sewage sludge, surface runoff, etc. enters through [11].

Vanadium is a strategic metal element widely used in modern industries such as metallurgy, manufacturing and oil refining [12]. Vanadium is widely used in a variety of industries, including steelmaking, aerospace and renewable energy technologies [13]. Vanadium is highly toxic to living organisms when exposed to excess, causing damage to the respiratory system and metabolic disturbances [14]. The United Nations Environment Program (UNEP) recommends placing vanadium on the priority list of environmental threats [15].

Soil is a constantly developing natural organism important for life on earth. It is the main medium for plant growth and habitat creation. Soil is a limited resource that provides a variety of microorganisms for micro- and macro-organisms, and is fundamentally involved in carbon accumulation and the hydrological cycle (storage, replenishment of aquifers) [16]. The land is an important resource for human production and livelihood, and with the development of agricultural and industrial technology, soil contamination with heavy metals is becoming an increasingly important problem [17]. Excessive and unstable industrialization, intensive agricultural activities, improper mining, production and use of synthetic products (pesticides, paints, batteries), combustion products of coal, oil spills and precipitation, metal waste, and fuel residues have made the restoration of soil ecosystems contaminated with heavy metals and metalloids, damaged by high sediment levels of toxic metals, an important issue for humanity [18].

Today, environmental pollution with heavy metals is the most serious problem on a global scale, causing damage to plants, animals and humans through chronic or acute exposure [19].

Heavy metals are the inorganic pollutants of greatest concern due to their toxicity and persistence in the environment [20]. Heavy metals are non-biodegradable by nature, some of them combine with other components to form stable but toxic compounds [21]. Heavy metals are not biodegradable due to their chemical complexity and stable nature [22]. Heavy metals are known to be very toxic even in small amounts [23], are particularly dangerous pollutants of the natural environment, and even at low concentrations can cause various pathologies in the development of living organisms. The increase in heavy metals leads to many physical, chemical and biological changes in the environment. The nature and extent of such changes depend on the composition and form of heavy metals in natural objects [24]. The group of heavy metals mainly includes 19 chemical elements: Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, Mo, Cd, Sn, Sb, Te, W, Hg, Tl, Pb, Bi. The most typical heavy metal contaminants are: Pb, Cd, Hg, Zn, Mo, Ni, Co, Sn, Cu, V, Sb, As [25].

Regarding their role in biological systems, heavy metals are classified as essential and non-essential. Essential heavy metals are those that living organisms need in small amounts for vital physiological and biochemical functions. Important heavy metals include Fe, Mn, Cu, Zn, and Ni [26]. Nonessential heavy metals are those that living organisms do not need for physiological or biochemical functions. Non-essential heavy metals: Cd, Pb, As, Hg and Cr [27].

A serious global environmental problem is environmental pollution with heavy metals, namely cadmium, lead, arsenic, mercury and nickel [28]. Metals play an important role in our society, and the metallurgical industry includes activities as diverse as mineral exploration, mining, screening, smelting and rolling. Ferrous and non-ferrous metallurgy is primarily responsible for the production and refining of metals [29].

Anthropogenic sources of environmental pollution with heavy metals include metal production, smelting, production of fertilizers and pesticides, metal leaching from landfills, and industrial wastewater [30...31]. With the rapid development of the metallurgical industry, a large

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amount of metallurgical sludge was produced. The composition of industrial sludge consists of various sources, mainly heavy metals, organic pollutants, viruses and microorganisms [32]. Owing to backward production and processing technologies, a huge amount of mining wastes (metallurgical slags, tailings, tailings, etc.) are generated during mining, smelting, etc. The smelting of metal ores caused severe environmental pollution and damage to the environment [33].

Unprocessed waste takes up land resources, and very high concentrations of metals and metalloids are transferred to the atmosphere, water, soil and groundwater, which pose a threat to human health through food intake [34].

All heavy metals emitted by different types of industrial activities are toxic above a certain concentration level, and As, Cd, Hg and Pb are the most toxic elements even at low concentration levels [35]. The increased level of toxic metals in the environment poses a potential threat to human and environmental health, so it has attracted the attention of scientists around the world [36]. They are typically found in submicron-size fractions (<1 μm) with different physical and chemical properties related to their appearance, size, solubility, and toxicity [37]. Heavy metals such as Cd, Cu, Pb, and Zn, known for their higher toxicity, are also recognized as potentially toxic elements, and are associated with the metallurgy industry, mining, waste incineration, road infrastructure, smelting plants, and the burning of fossil fuels [38]. Their concentration is significantly higher in urban/transport and industrial areas [39].

Humans are harmed by inhaling, swallowing and skin contact with toxic fine dust particles of heavy metals. This effect leads to serious human health problems such as depression and anxiety, immune, endocrine, respiratory and other diseases [40].

Arsenic (As) is a common constituent of many ores and appears as a major, minor, or trace element in sulfides associated with mine tailings. It is a redox element, usually found in soil in two oxidation states +3 and +5. Arsenate (As(V)) is generally considered to be less toxic than arsenite (As(III)) [41]. Cadmium (Cd) is highly toxic because it is easily absorbed by plant roots and transported to above-ground parts. Itai-Itai disease caused by Cd residue deposition is a well-documented phenomenon [42]. Lead (Pb), the most toxic heavy metal pollutant found in many fertilizers, is readily absorbed and eventually accumulates in the edible parts of medicinal plants [43].

Heavy metals adversely affect the circulatory system, endocrine system, and central nervous system, leading to stunted growth, kidney disease, and various types of cancer [44].

The use of pesticides and fertilizers, as well as the growth of industrial production in the surrounding area, has led to the accumulation of heavy metals in the soil in recent years. A national soil contamination study conducted in 2021 [45] found that the concentration of heavy metal elements exceeded the threshold by more than 20 % in agricultural lands. The toxicity of these metals represents a complex environmental issue that bioaccumulates and is non-biodegradable in the environment [46]. Toxicity and the predicted persistence of environmental contamination with heavy metals are of concern [47]. Heavy metals have carcinogenic, teratogenic and mutagenic properties that can adversely affect human health [48].

Industrial areas are generally exposed to high levels of air pollution due to the predominance of local industrial emissions [49].

Crops rich in these heavy metals can enter the human body in various ways, such as hand-to-mouth contact, which can have harmful effects on human health [50]. As a result of all these activities, heavy metals accumulate in the soil and become polluted. Contaminated soil poses a significant threat to ecosystems and humans [51]. Removing these heavy metals from the polluted environment through natural and human intervention and converting them into useful niches for life is a priority [52]. The purpose of the work is to evaluate the characteristics of the distribution of heavy metals in the soil cover in the territory of metallurgical enterprises.

2. MATERIALS AND METHODS

The soil was chosen as the main object of study due to the long-term impact of anthropogenic sources of pollution, as soils are integral components of technogenic landscapes and are directly influenced by human activities. Soil absorbs toxicants from the air and water environment and acts as a filter. In this regard, the amount of toxic elements in soil and plants can be considered as a diagnostic sign that determines the impact of transport and industrial enterprises [53].

Study area The soil cover in the territory of Qarmet Joint Stock Company Complex «Karagandy Metallurgical Plant» located in the city of Temirtau, Karaganda Region, Central Kazakhstan, Republic of Kazakhstan is shown in Figure 1. The presented maps were created using ArcGIS 10.6.

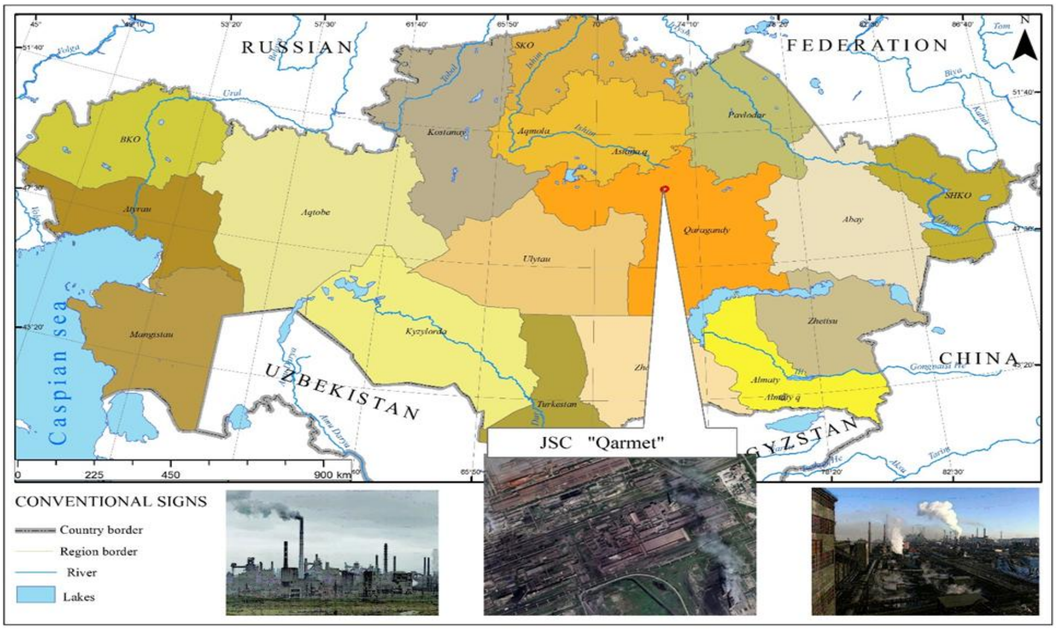

Figure 1. *Map of the territory of Qarmet JSC.*

Note: created based on the author

The geolocation of soil sampling points is shown in Figure 2. The coordinates of the soil sampling points are: 50.04'47"09N and 73.04'13"95E. At the end of September 2023, soil samples were taken from the production areas of Central Kazakhstan at a depth of 25...30 cm of the root layer using the "envelope method". The soil sampling process was carried out according to GOST 17.4.4.02-2017 [54].

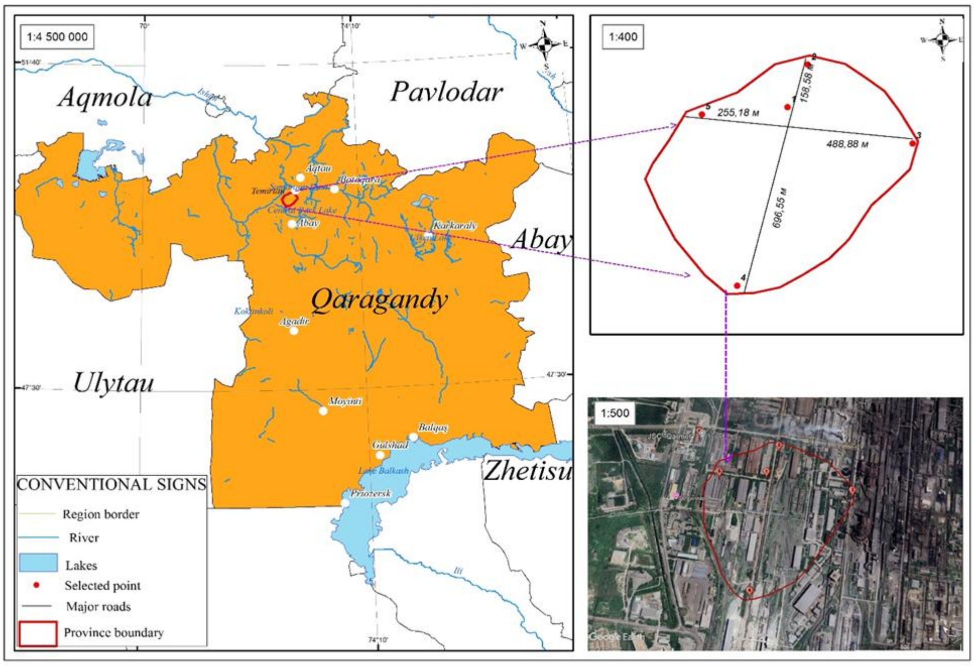

Figure 2. *Location map of the study area with sampling points.*

Note: created based on the author

Soil samples were taken from five points on the territory of the Qarmet Joint Stock Company complex «Karagandy Metallurgical Plant» from different distances. Four points were marked in the corners of the test areas and one in the middle. From the point in the middle of the first sample and this first point, the second point sample is ±158,58m, the third point sample is ±488,88m, the fourth point sample is ±696,55m, the fifth point sample is ±255,18m (total five samples). The sixth soil sample was taken from the clean area for control purposes. Samples were collected in clean plastic bags weighing approximately 1 kg. The collected samples were sequentially numbered and delivered to the laboratory. Laboratory analysis of soil samples was carried out to determine heavy metals. Atomic absorption and X-ray fluorescence spectroscopy methods were used in the work.

3. RESULTS AND DISCUSSION

As a result of experimental studies, the concentrations of heavy metals in soil samples taken near this production area are presented in Figures 3…8. The distribution of the concentration of heavy metals in soil samples is described in the histogram. The vertical axis shows heavy metals, and the horizontal axis shows the concentration of metals in mg/kg. The blue columns represent the soil samples taken from five points on the territory of the Qarmet Joint Stock Company complex «Karagandy Metallurgical Plant», the orange is the soil sample taken for control purposes from the clean area.

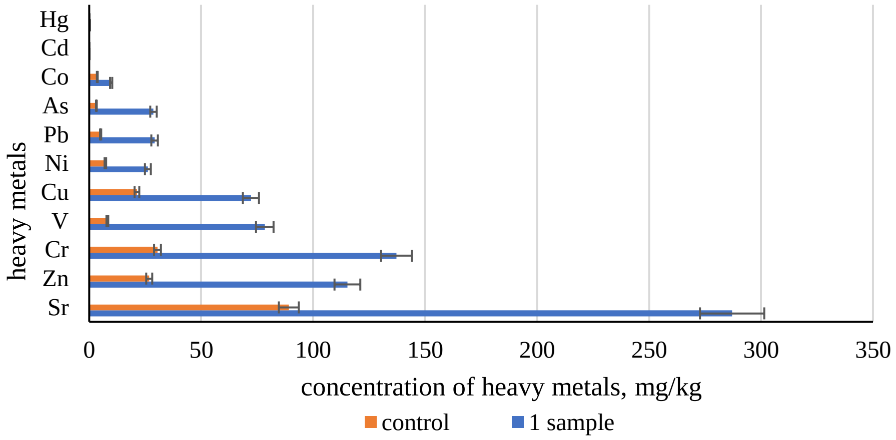

Figure 3. *Amount of heavy metals (mg/kg) in the soil taken from the first point*

The soil sample taken from the first point (sample) in Figure 3 showed the highest values of Sr, Cr, Zn and V. They are, respectively, Sr – 287,1±0,05 mg/kg ($p<0,05$), which is about three times more than the amount of strontium in the soil sample taken from the clean area (control). Cr is 137,2±0,05 mg/kg ($p<0,05$), which is about five times higher than the amount of chromium in the sample taken from the clean area. Zn is 115,3±0,05 mg/kg ($p<0,05$), which is four times higher than the amount of zinc in the soil sample taken from the control area. V – 78,4±0,05 mg/kg ($p<0,05$), about ten times more than the amount of vanadium in the soil from the control area.

As shown in Figure 4, the maximum accumulation of heavy metals Sr, Zn, Cr, and Cu (mg/kg) was observed in the soil sample taken from the second point (sample). Strontium is 281,6±0,05 mg/kg ($p<0,05$), about three times more than strontium in the soil sample from the clean area. Zinc is 132,2±0,05 mg/kg ($p<0,05$), which is about five times more than the amount of zinc in the sample from the clean area compared to the soil in the control sample. Chromium is 98,5±0,05 mg/kg ($p<0,05$), which is three times higher than the amount of chromium in the soil sample taken from the control area. Copper is 87,6±0,05 mg/kg ($p<0,05$), which is about four times more than the amount of copper in soil from the control area.

Figure 5 shows that at the third point (sample), the highest index of heavy metals increased in the order Sr>Zn>Cr>V. Strontium is 490,1±0,05 mg/kg ($p<0,05$), which is about 5,5 times higher than the amount of strontium in soil from the control area. Zinc is 91,4±0,05 mg/kg ($p<0,05$), which is three times higher than the zinc concentration in the soil sample from the clean area. Chromium is 84,5±0,05 mg/kg ($p<0,05$), which is three times higher than chromium in soil from the control area. Vanadium is 76,5±0,05 mg/kg ($p<0,05$), the amount of vanadium in the soil is about ten times higher than in the control area.

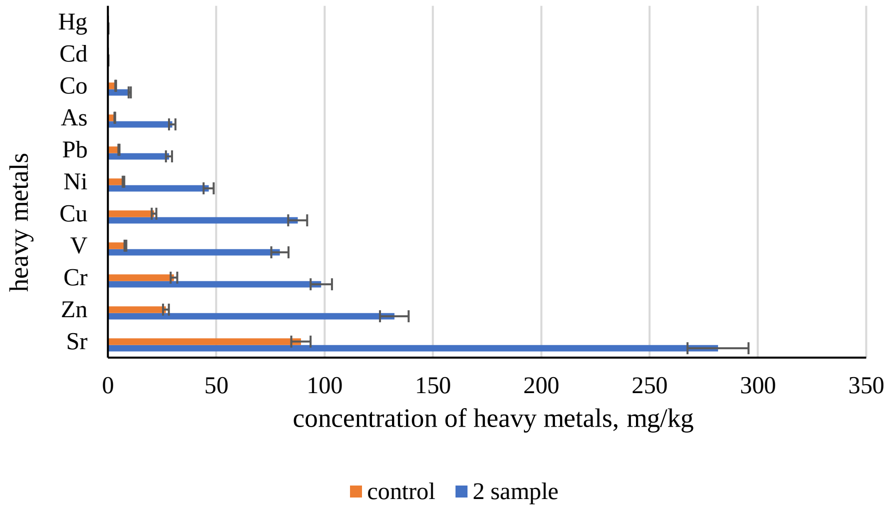

Figure 4. *Amount of heavy metals (mg/kg) in the soil taken from the second point*

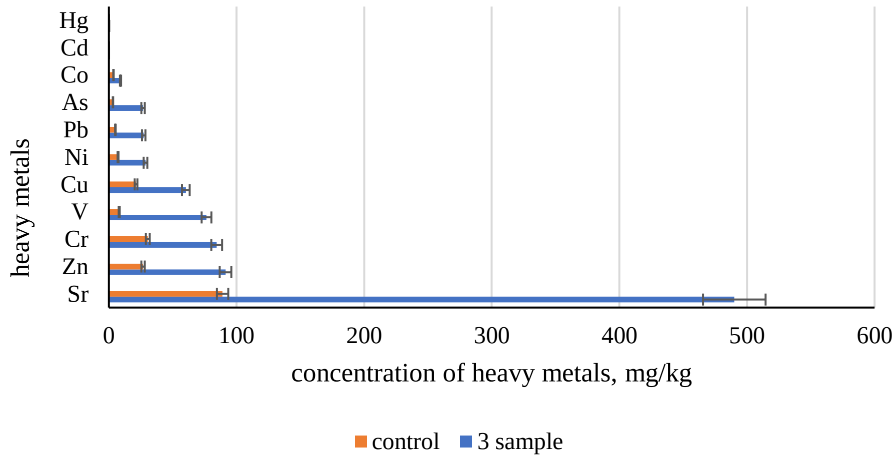

Figure 5. *Amount of heavy metals (mg/kg) in the soil taken from the third point*

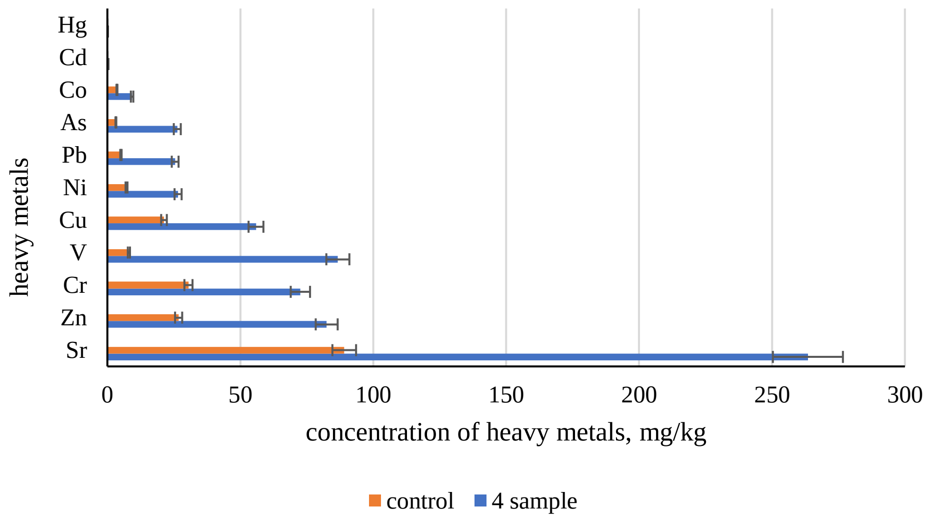

Figure 6. *Amount of heavy metals (mg/kg) in the soil from the fourth point*

Figure 6 shows that in the soil sample taken from the fourth point, heavy metals are increasing in the order Sr>V>Zn>Cr. Strontium is 263,5±0.,5 mg/kg (p<0,05), which is about three times higher than the amount of strontium in soil from the control area. Vanadium is 86,7±0,05 mg/kg (p<0,05), which is about ten times higher than the concentration of vanadium in a soil sample taken from a clean area. Zinc is 82,5±0,05 mg/kg (p<0,05), which is about three times higher than soil zinc from the control area. Chromium is 72,6±0,05 mg/kg ($p<0,05$), which is about twice as high as chromium in the soil from the control area.

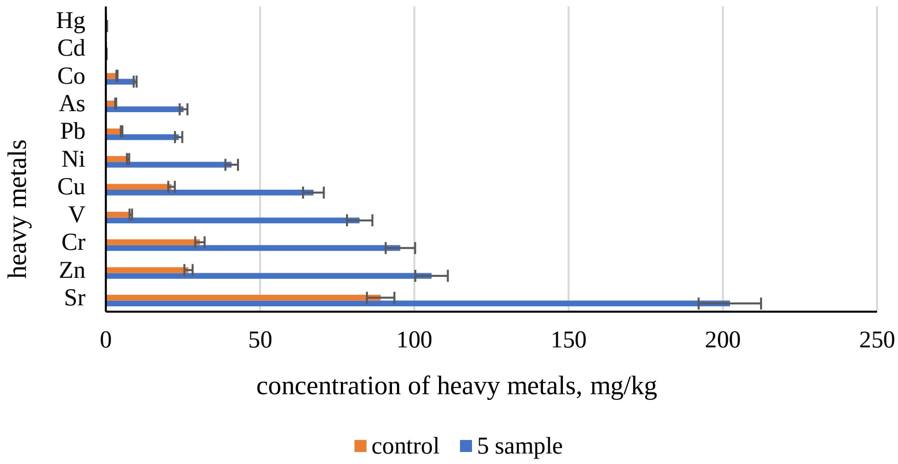

Figure 7. *Amount of heavy metals (mg/kg) in the soil from the fifth point*

Figure 7 shows that heavy metals increased in the order Sr>Zn>Cr>V in the soil sample taken from the fifth point. Strontium is 202,3±0,05 mg/kg ($p<0,05$), which is about 2,2 times higher than the strontium level in the soil sample from the control area. Zinc is 105,6±0,05 mg/kg ($p<0,05$), which is about four times higher than the zinc level in the soil sample from the control area. Chromium was 95,5±0,05 mg/kg ($p<0,05$), about three times higher than chromium in the soil sample from the control area. Vanadium is 82,3±0,05 mg/kg ($p<0,05$), which is about four times higher than the zinc level in the soil sample from the control area.

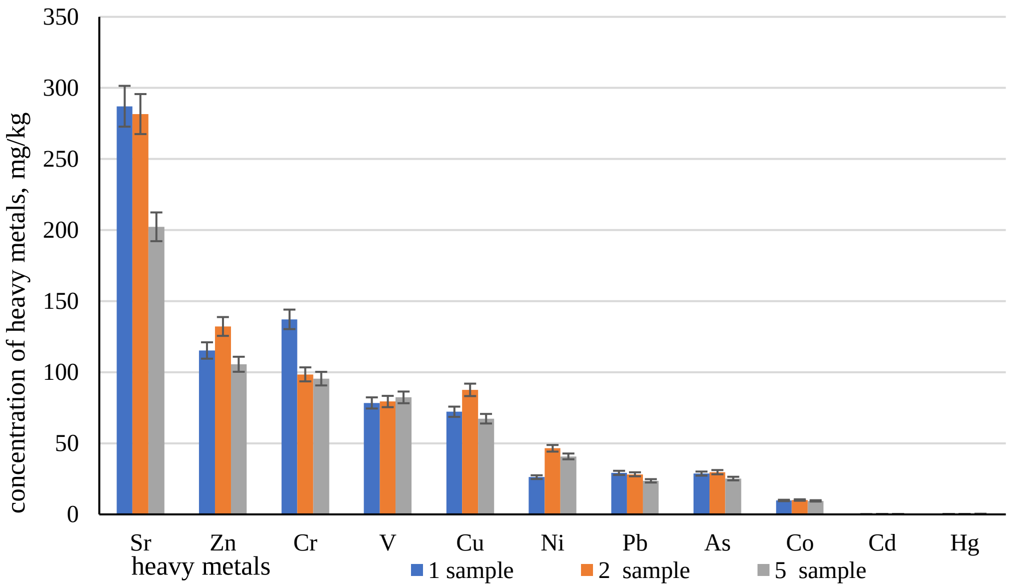

Figure 8. *Amount of heavy metals (mg/kg) in the soil obtained from points №1, №2, and №5*

The results of the comparison of the three points (samples) with the highest contamination levels are shown below. The highest concentrations of strontium are observed at the first point: 287,1±0,05 mg/kg ($p<0,05$), at the second point: 281,6±0,05 mg/kg ($p<0,05$), and at the fifth point: 202,3±0,05 mg/kg ($p<0,05$). The highest concentrations of zinc are observed at the second point: 132,2±0,05 mg/kg ($p<0,05$), at the first point: 115,3±0,05 mg/kg ($p<0,05$), and at the fifth point: 105,6±0,05 mg/kg ($p<0,05$). High concentrations of chromium were observed at the first point: 137,2±0,05 mg/kg ($p<0,05$), at the second point: 98,5±0,05 mg/kg ($p<0,05$), and at the fifth point: 95,5±0,05 mg/kg ($p<0,05$), while high concentrations of copper were observed at the second point: 87,6±0,05 mg/kg ($p<0,05$), at the first point: 72,2±0,05 mg/kg ($p<0,05$), and at the fifth point: 67,3±0,05 mg/kg ($p<0,05$). The following order of increasing elements in the soil was determined: Sr>Zn>Cr>Cu

4. CONCLUSION

The results of the study showed that, according to the Environmental Code of the Republic of Kazakhstan [55], the level of heavy metals in the soil in industrial areas, regardless of distance, exceeded the maximum permissible concentration (MPC). A mosaic pattern of heavy metal content was observed, depending on the sources of emissions. It was found that soil samples taken from industrial areas contained higher levels of Sr, Zn, Cr, and Cu compared to samples taken from clean areas. Mercury (Hg) and cobalt (Co) were found to be uniformly distributed at very low concentrations in all soil samples.

The highest level of contamination was detected: the maximum concentration of strontium was found at the first point, amounting to 287,1±0,05 mg/kg ($p<0,05$), which is approximately three times the MPC value. The highest level of zinc was found at the second point, amounting to 132,2±0,05 mg/kg ($p<0,05$), exceeding the MPC by approximately six times. The maximum concentration of chromium at the first point was 137,2±0,05 mg/kg ($p<0,05$), which is about twenty-three times higher than the MPC value. Copper concentration was highest at the second point, amounting to 87,6±0,05 mg/kg ($p<0,05$), which exceeds the MPC by approximately twenty-nine times.

According to the study's conclusions, the territory near the metallurgical enterprise «Karaganda Metallurgical Plant» of Qarmet Joint Stock Company in Central Kazakhstan showed the highest levels of contamination with heavy metals such as Sr, Zn, Cr, and Cu. A comparative analysis of the indicators of the four most contaminated points revealed the following results: for Sr, №1>№2>№5, for Zn, №2>№1>№5, for Cr, №1>№2>№5, and for Cu, №1>№2>№5. Based on these results, it was determined that the soil in areas closest to the «Karaganda Metallurgical Plant» of Qarmet JSC is heavily contaminated with heavy metals, posing significant ecological risks.

This issue impacts not only local ecosystems but also the overall environmental condition of the region. To reduce contamination, it is necessary to conduct periodic monitoring of heavy metal accumulation, apply cleaning technologies in accordance with the requirements of the Environmental Code, and implement soil remediation methods. These recommendations include effective measures to improve soil quality and ensure the sustainability of local ecosystems.

DATA AVAILABILITY

The data used in this study were obtained as a result of laboratory analysis of soil samples.

AUTHORS' CONTRIBUTION

Conceptualization – RB, ZhR, AR; resources - AR; formal analysis – AR, ZhR; methodology - AR, ZhR; software - AR; supervision -RR, ZhR; visualization –AR; writing—original draft preparation – AR; writing—review and editing - ZhR, RT.

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АУЫР МЕТАЛДАРМЕН ЛАСТАНҒАН ӨНДІРІС АУМАҒЫНЫҢ ТОПЫРАҚ ЖАМЫЛҒЫСЫНЫҢ ЭКОЛОГИЯЛЫҚ ЖАҒДАЙЫН БАҒАЛАУ (ҚАРАҒАНДЫ МЕТАЛЛУРГИЯЛЫҚ КОМБИНАТЫ МЫСАЛЫНДА)

Айжан Д. Рахишева*, Жанар Рахымжан PhD, доцент, Райхан Р. Бейсенова б.ғ.к., профессор,
Румия М. Тазитдинова PhD, доцент

Л.Н. Гумилев атындағы Еуразия ұлттық университеті, Астана, Қазақстан; Aizhan_enu@mail.ru, raihan_b_r@mail.ru, r.zhanar80@mail.ru, irm85@mail.ru
Автор корреспондент: Айжан Д. Рахишева, Aizhan_enu@mail.ru

ТҮЙІН СӨЗДЕР

АБСТРАКТ

лastany
ауыр металдар
топырақ жамылғысы
қара және түсті металлургия
рентгендік флуоресцентті спектроскопия
атомдық-адсорбциялық әдіс
экожүйе

Өндірістік аумақтың топырағының ауыр металдармен ластануы күрделі экологиялық проблема болып табылады. Зерттеуде Орталық Қазақстанның металлургиялық кәсіпорыны Qarmet АҚ — Қарағанды облысы Теміртау қаласында орналасқан Қазақстандағы ең ірі металлургиялық зауыт "Қарағанды металлургиялық зауытына" иелік ететін болат және тау-кен өндіруші компания аумағынан топырақ үлгілері алынды және ауыр металдардың құрамы атомдық абсорбциялық спектрофотометр (AAS) және рентгендік флуоресцентті спектроскопия көмегімен анықталды. Алынған топырақ сынамаларында он бір ауыр металдар анықталды және еріген күйінде мына ауыр металдар кездесті TiO_2, MnO, Fe_2O_3. Топырақ сынамаларындағы Sr, Zn, Cr және Cu ауыр металдардың концентрациясының анағұрлым жоғары екендігі белгілі болды. Зерттеу нәтижелері көрсеткендей ауыр металдардың концентрациясының өсуі Sr>Zn>Cr>Cu>V>Ni>Pb>As>Co>Cd>Hg ретпен болатындығы айқындалды. Ластану деңгейі ең жоғары болған үш үлгіні №1, №2, №5 өзара салыстыру нәтижесінде Стронций ең жоғары концентрациясы бірінші үлгіде 287,1±0,05 мг/кг ($p<0,05$), Мырыштың ең жоғары концентрациясы екінші үлгіде 132,2±0,05 мг/кг ($p<0,05$), Хромның жоғары концентрациясы бірінші үлгіде 137,2±0,05 мг/кг ($p<0,05$), Мыстың жоғары концентрациясы екінші үлгіде 87,6±0,05 мг/кг ($p<0,05$) болғандығы анықталды. Алынған топырақ сынамаларының көрсеткішіне сай металлургиялық комбинат маңындағы топырақ жамылғысының стронций, мырыш, хром және мыспен ластанғаны анықталды.

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ОЦЕНКА ЭКОЛОГИЧЕСКОГО СОСТОЯНИЯ ПОЧВЕННОГО ПОКРОВА ПРОМЗОНЫ, ЗАГРЯЗНЕННОГО ТЯЖЕЛЫМИ МЕТАЛЛАМИ (НА ПРИМЕРЕ КАРАГАНДИНСКОГО МЕТАЛЛУРГИЧЕСКОГО КОМБИНАТА)

Айжан Д. Рахишева*, Жанар Рахымжан PhD, доцент, Райхан Р. Бейсенова к.б.н., профессор, Румия М. Тазитдинова PhD, доцент

Евразийский национальный университет имени Л.Н. Гумилева, Астана, Казахстан; Aizhan_enu@mail.ru, r.zhanar80@mail.ru, raihan_b_r@mail.ru, , irm85@mail.ru
Автор корреспондент: Айжан Д. Рахишева, Aizhan_enu@mail.ru

КЛЮЧЕВЫЕ СЛОВА

загрязнение
тяжелые металлы
почвенный покров
черная и цветная металлургия
рентгенофлуоресцентная спектроскопия
атомно-адсорбционный метод
экосистема

АБСТРАКТ

Загрязнение почвы в производственной зоне тяжёлыми металлами является сложной экологической проблемой. В исследовании были взяты образцы почвы с территории металлургического предприятия Центрального Казахстана Qarmet АО — крупнейшего металлургического завода Казахстана «Карагандинский металлургический завод», расположенного в городе Темиртау, Карагандинская область, и состав тяжёлых металлов был определён с помощью атомно-абсорбционного спектрофотометра (AAS) и рентгеновской флуоресцентной спектроскопии. В пробах почвы обнаружено 11 тяжелых металлов, а в растворенном состоянии обнаружены следующие тяжелые металлы: TiO_2, MnO, Fe_2O_3. Известно, что концентрация тяжелых металлов Sr, Zn, Cr и Cu в пробах почвы значительно выше. По результатам исследований установлено, что концентрация тяжелых металлов возрастает в ряду Sr>Zn>Cr>Cu>V>Ni>Pb>As>Co>Cd>Hg. В результате сравнения трех проб №1, №2, №5 с наибольшим уровнем загрязнения наиболее высокая концентрация стронция в первой пробе составляет 287,1±0,05 мг/кг ($p<0,05$), наибольшая концентрация цинк во второй пробе составляет 132,2±0,05 мг/кг ($p<0,05$), высокая концентрация хрома в первой пробе 137,2±0,05 мг/кг ($p<0,05$), установлено, что наибольшая концентрация меди составила 87,6±0,05 мг/кг ($p<0,05$) в втором образце. По результатам анализа проб почвы установлено, что почва возле металлургического завода загрязнена стронцием, цинком, хромом и медью.

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