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Assessing the Ecological Risks and Spatial Distribution of Heavy Metal Contamination at Solid Waste Dumpsites

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Abstract—Soil samples from wild solid waste dumpsites were collected in the Bijeljina-Zvornik region (Republic of Srpska, Bosnia and Herzegovina), and the concentrations potentionally toxic metals (Ni, Cr, Mn, Zn, Cu, Pb, Cd, Fe and Al). The disposal of waste at wild dumpsites has emerged as a serious environmental challenge affecting both developed and developing countries. This paper aims to provide an in-depth analysis of the complex issue of wild dumpsites, focusing on the contamination of the environment with toxic metals. The improper disposal of solid waste has become a global concern, with wild dumpsites being a significant component of the problem. In accordance with national legislation, the mean values for Cd and Ni exceeded the limit values. Very strong positive correlations are observed between Zn and Cu, between Cd and Pb and between Ni and Cr. The ecological risk assessments for Mn are extremely high; for Ni and Pb, they are high; for Zn, Cu and Cr, they are appreciable; and for Cd, they are moderate. The Pollution Load Index (PLI) and Contamination Factor were used to evaluate metal pollution in soil samples. PLI values exceeding 1.0 in five samples signify soil pollution, supported by mean values indicating contamination. Research findings reveal different contamination levels, with Pb, Cr, Cu, and Zn at low levels, and Ni and Cd at moderate levels. The visualized results of ecological risk assessments for heavy metals in the soil underscore the critical importance of continuous monitoring and effective management of heavy metals at illegal dumpsites to preserve and protect surrounding ecosystems. The use of Surfer 12 software and the kriging method has proven to be an invaluable tool for exploring the spatial distribution of toxic metals in the study area.

Keywords: pollution, environmental hazards, contamination assessment, ecological impact, geographic dispersion

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INTRODUCTION

The indiscriminate disposal of waste at wild dumpsites has emerged as a critical environmental and public health challenge in both developed and developing countries [20, 96, 110]. These unregulated dumpsites, also known as illegal or informal dumpsites, are unregulated dumping grounds where various types of waste materials are discarded without proper waste management practices and pose multiple challenges for ecosystems and public health [8, 19, 39, 71]. The absence of adequate waste infrastructure, weak regulatory frameworks, and limited enforcement of waste disposal laws contribute to the persistent emergence of new wild dumpsites, exacerbating this problem [27]. Solid waste constitutes a major concern and unresolved problem in most parts of the world, particularly in developing countries, where solid waste is frequently disposed of at unregulated dumpsites [12, 88]. Unregulated dumping grounds devoid of proper waste management practices have become prevalent in various regions worldwide, adversely impacting ecosystems and human health [39, 48, 87, 96].

One of the most significant concerns associated with wild dumpsites is contamination of the environment with toxic metals [87, 90]. These dumpsites often contain a diverse range of waste, including electronic waste, household chemicals, batteries, and industrial residues [96]. Within this waste stream, toxic heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), zinc (Zn), and copper (Cu) are commonly found. The degradation of waste at these sites releases these metals and organic pollutants [40, 45, 46, 107, 122] into the surrounding environment, posing potential ecological and health risks for both ecosystems and human populations [11, 87, 106, 112].

Metal pollution stemming from wild dumpsites can significantly impact the environment [10, 39, 59, 61, 64, 114]. The leaching of toxic metals into soil and water leads to soil degradation, altered soil pH, and reduced biodiversity [28, 39]. Contaminated water bodies can disrupt aquatic ecosystems, harming aquatic life and resulting in bioaccumulation and biomagnification of metals in the food chain [5, 23, 55, 115].

The processes of waste degradation and decomposition at wild dumpsites release toxic metals into the surrounding environment. These metals can accumulate in soil and water, exerting long-term impacts on the environment and ecosystems [12, 39, 90, 96, 112]. Metal pollution can adversely affect biodiversity, endangering habitats and endemic species. Airborne particles carrying metal contaminants can be inhaled, leading to respiratory issues [39]. Moreover, metals can enter the food chain, be transferred from plants to animals and eventually reach humans, resulting in health issues such as metal poisoning, neurotoxic effects, and potential carcinogenicity [73]. Metal pollution poses health risks for nearby communities and waste workers and can cause air pollution [22, 41, 43, 50, 51, 49, 100].

A significant quantity and variety of trace elements and other pollutants, some of which are potentially harmful, are transferred to the surrounding environment through different pathways [2, 3, 29, 30, 40, 42, 46, 113, 120, 125]. Through the extraction of resources and anthropogenic activities, heavy metals or potentially toxic elements (PTEs), such as Cd, arsenic (As), Ni, Cr, Pb, and mercury (Hg), can reach the environment. These compounds are widely present in the environment, particularly in soils [40, 42, 46, 58, 62, 75, 124, 113]. Metal pollution also threatens the overall environmental balance. Contaminated soil and water impact plant growth, disrupt natural ecosystems, and reduce overall biodiversity. This, in turn, affects ecological services such as water purification, soil fertility, and climate regulation [12, 20, 24, 53].

Wild solid waste dumpsites are a pressing environmental issue, particularly in developing countries, where they contribute to the accumulation of toxic metals in soil [28, 96, 110]. This study aimed to assess the presence of toxic metals, including Ni, Cr, manganese (Mn), Zn, Cu, Pb, Cd, iron (Fe), and aluminum (Al), in soil samples obtained from wild solid waste dumpsites in Bosnia and Herzegovina (B&H). The potential ecological risks associated with the accumulation of these metals have also been investigated [39, 47]. By analyzing the data from the soil samples, this research provides crucial insights into the severity of metal contamination and the environmental implications these dumpsites pose [93, 94].

The presence of toxic metals, such as Ni, Cr, Mn, Zn, Cu, Pb, Cd, Fe, and Al, in various wild solid waste dumpsites raises significant environmental and health concerns. These metals, often originating from diverse anthropogenic sources [14], find their way into the soil ecosystem, predominantly through discarded electronic waste, batteries, industrial residues, and other waste materials [1, 9, 6, 17, 25, 26, 69, 93–95, 97]. For instance, studies have shown that soils in the proximity of municipal waste dumpsites, like in Omuooke-Ekiti, Nigeria, exhibit significantly higher concentrations of heavy metals in the topsoil, especially near the center of dumpsites, indicating a strong anthropogenic contribution [1]. Similarly, the type of waste being dumped plays a crucial role in the resultant soil contamination. In urban soils of Bauchi, Nigeria, different sources of waste such as residential, commercial, and industrial significantly affect the heavy metal concentration in the soils, with varying levels of pollution observed across different dumpsite types [26]. Moreover, the migration of heavy metals from waste to soil has been observed to be a site-specific phenomenon, largely influenced by the nature of the waste and the surrounding environment. For example, in Khamees-Mushait, Saudi Arabia, the migration of heavy metals from municipal waste dumpsites has shown significant impacts on both surface and deep soil layers, as well as on native plant leaves, indicating varying levels of metal uptake by plants [6]. Additionally, in Dar es Salaam City, Tanzania, solid waste disposal sites have been identified as serious sources of pollution to soil, groundwater, and surface water, particularly in areas close to water sources [69]. This is further corroborated by findings in Nairobi City County, Kenya, where vegetables grown around dumpsites were found to accumulate high levels of heavy metals, posing health risks to consumers [95].

The specific sources and pathways of these metal contaminations are complex and diverse. In Abeokuta, Nigeria, for instance, the distribution of heavy metals in soils affected by waste deposits from market and auto-mechanic sites showed high levels of Fe, Cr, Pb, Cu, Mn, and Zn, likely due to the formation of metal-organo-complexes [9]. In Osogbo, Nigeria, studies have indicated that heavy metals and naturally occurring radioactive materials in soils around dumpsites pose potential ecological and health risks, with evidence of contamination from various sources including electronic waste and scrap metals [97]. Furthermore, in Peshawar, Pakistan, geophysical and geochemical characterization of a non-engineered open dumpsite revealed the presence of heavy metals in the adjacent agricultural land, demonstrating the extent of contamination and its impact on agriculture [17]. These findings underscore the complexity of heavy metal contamination at solid waste dumpsites and highlight the need for targeted and effective waste management strategies to mitigate potential ecological and health consequences [12, 44, 60, 65].

In the investigated landfill sites in Bosnia and Herzegovina, the primary sources of heavy metal contamination are local waste disposal practices. Residents frequently dispose of electronic waste at these sites, including televisions, computers, and other electronic devices. This type of waste contains various heavy metals such as lead, cadmium, and mercury, which are common in electronics. As these devices degrade or are improperly disposed of in landfills, the heavy metals they contain can be released and accumulate in the soil. Bešta-Gajević et al. [13] found that illegal waste dumps in Bosnia and Herzegovina pose a significant threat to soil and water contamination, with high concentrations of heavy metals like Cd and Pb recorded in soil at particular sites above maximum allowable concentrations. This highlights the impact of improper waste disposal practices on heavy metal pollution in the region. In addition to household waste, significant contributions to soil contamination at these sites also come from commercial and industrial sources [74, 77]. Waste from these sources often contains various heavy metals, including zinc, copper, and nickel, derived from different industrial processes and materials such as paints, batteries, and machine residues. Improper management of these types of waste, including their unsorted disposal at landfills, can lead to soil contamination with heavy metals. Therefore, the combination of improperly discarded electronic waste by citizens and industrial waste from various economic entities constitutes the main source of heavy metal pollution at the studied locations in Bosnia and Herzegovina. This pollution poses a significant ecological and health risk, as heavy metals can affect the quality of soil and water, as well as human health and the environment.

On the municipal/city dumpsite in the Republic of Srpska (entity in B&H), waste is mostly disposed of without any plan or order in an unsanitary way; in most cases, it is not compacted and not covered with inert material on a daily basis, so the waste is exposed to wind, atmospheric precipitation and pests. Since the waste brought to the site of the dumpsite is generally not controlled, there is no control over the waste that is disposed of. In addition to household waste, industrial and other waste are often disposed of at municipal dumpsites. Most municipal dumpsites do not have the necessary operating permits. Such uncontrolled dumpsites are a great risk to human health, especially for those living near these dumpsites. As mentioned above, most dumpsites do not meet the standards for sanitary waste disposal [54, 93, 94].

In addition to municipal dumpsites, waste is disposed of in "wild" dumpsites where various types of waste are disposed from household waste through bulky waste to organic and medical waste. "Wild" dumps are uncontrollable and dangerous to human health and the environment. Local government units occasionally or regularly rehabilitate illegal dumpsites; however, due to insufficient education of the population, these places are inundated with waste, or new "illegal" dumpsites are formed again as places of pollution. Illegal dumpsites are a potential risk factor for environmental pollution through one or more spreading mechanisms of pollutants from dumpsites. Regarding the territory of the analyzed area of the regions of Bijeljina and Zvornik, 79 dumpsites were registered in the Bijeljina-Zvornik region [54].

This research paper aims to comprehensively examine the issues of wild dumpsites (municipal/city and "wild") and the metal pollution region Bijeljina-Zvornik (Republic of Srpska, B&H). Through a systematic analysis of relevant literature and original data, this paper seeks to identify the sources of metal contamination and evaluate the ecological risk from these contaminated areas.

OBJECTS AND METHODS

Study region. The Bijeljina-Zvornik region (Fig. 1) is one of the nodal-functional regions of the Republic of Srpska, B&H. This region is defined as a mesoregion and encompasses the following municipalities: Bijeljina, Ugljevik, Lopare, Donji Žabar, Pelagićevo, Zvornik, Osmaci, Šekovići, Vlasenica, Milići, Bratunac, and Srebrenica.

Geographical and geological characteristics of the Bijeljina-Zvornik region. The Bijeljina-Zvornik area, situated in the northeastern sector of Bosnia and Herzegovina, showcases a vast array of geological and pedological traits essential for assessing the environmental repercussions associated with wild solid waste disposal sites. This area is distinguished by its varied geological makeup, which plays a pivotal role in shaping the soil's properties and the broader ecological landscape. Predominantly, the region of Bijeljina (Semberija) is recognized in numerous physical-geo-

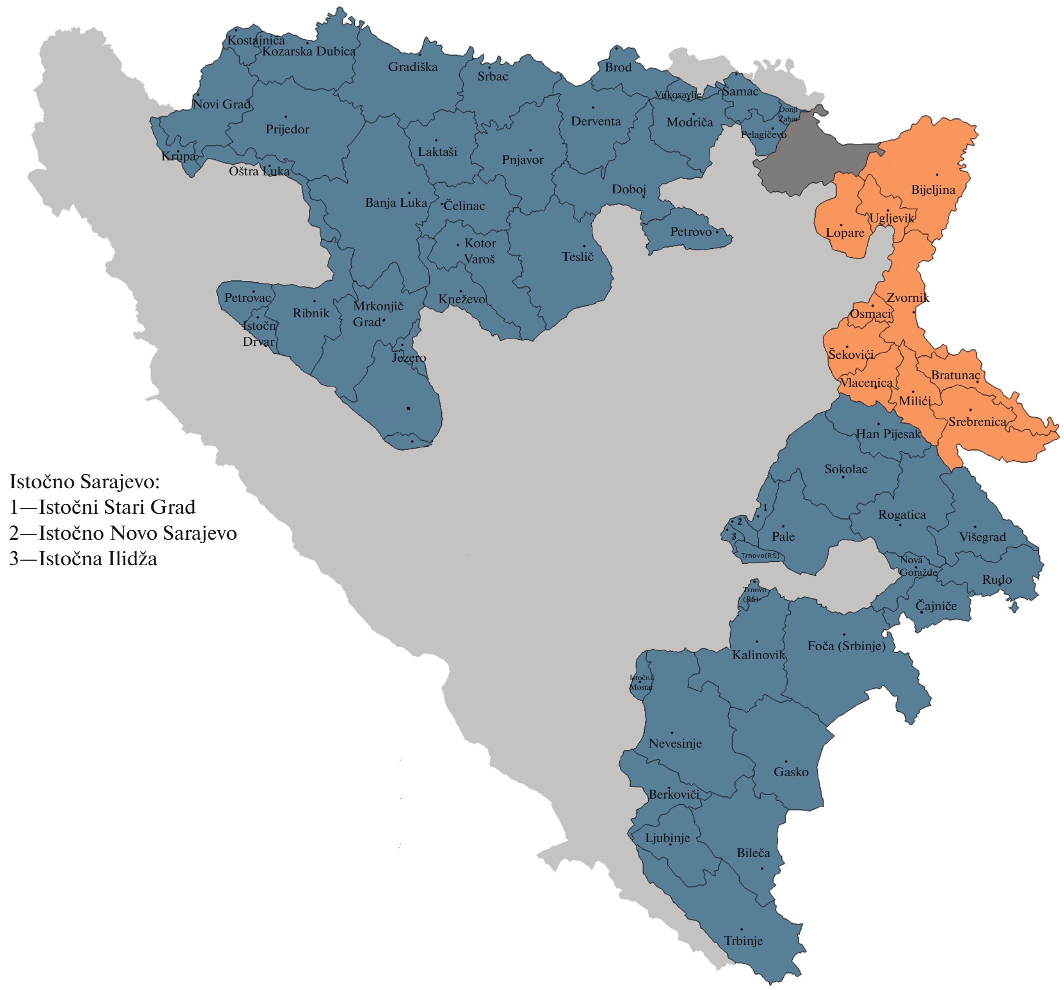

Fig. 1. The Bijeljina-Zvornik—region [102].

graphical and geomorphological studies as an integral component of the Pannonian or Peripannonian domain. Geotectonically, the terrain of this lowland mesoregion was developed within the Sava zone, marking the most recent structural division of the Inner Dinarides, characterized by a landscape of uplifts and depressions. This zone encompasses sections of the Pannonian structural complex as well as the Inner Dinarides (Supradinaric) [78]. The region's relief varies significantly, ranging from mountainous areas to lowland plains. This variability in relief plays a critical role in the distribution and accumulation of pollutants from the dumpsites. The dominant soil types are pseudogley, humofluvisol and Fluvisol (Bijeljina area) in combination with Cambisol (Zvornik area), in combination with Vertisol, Eutric Cambisol and other types of soil [57]. The hydrological characteristics of the region, such as the Drina and Sava rivers, affect the distribution and accumulation of pollutants in the soil. These rivers not only shape the local landscape but also contribute to the transport and deposition of sediments that may contain heavy metals. The interaction of topography with the prevalent soil types, predominantly alluvial in the river valleys and higher terrains, influences the movement and sequestration of heavy metals and other contaminants. In addition to the natural geological features, the region's history and demographic changes, including migration patterns and urbanization, have significantly influenced the land use and environmental conditions. These human activities have further complicated the ecological dynamics of the region, impacting the effectiveness of waste management practices [92].

Sampling and analysis. Soil sampling and analysis were performed at 45 locations in the Bijeljina-Zvornik region. Sampling was performed in June and on Jule 2022.

The sample was prepared by acid digestion in accordance with the standard ISO 11466, Soil quality—Extraction of trace elements soluble in aqua regia [56].

The analysis device used was an Agilent 4210 MP-AES microwave plasma atomic emission spectrometer. The

Table 1. LODs and LOQs for metals

Metals	LOD	LOQ
Ni	0.1	0.3
Cr	0.3	1.1
Mn	0.5	1.5
Zn	0.4	1.3
Cu	0.6	1.9
Pb	0.5	1.8
Cd	0.0	0.1
Fe	0.5	1.8
Al	0.6	1.9

analysis of the samples was conducted in accordance with the Aplication Note Determination of metals in soils using the 4100 MP AES (Agilent Technologies, Melbourne, Australia) [37]. This analytical method for the determination of metals in soils was developed using a new, simple, and relatively inexpensive microwave plasma atomic emission spectrometer (MP-AES). An Agilent 4100 MP-AES instrument generates a self-sustained atmospheric pressure microwave plasma (MP) using nitrogen gas and a torch specifically designed for the MP-AES. The samples were introduced to the MP via pneumatic mixing using a concentric nebulizer and a cyclonic spray chamber. Emission line isolation and detection are sequential using a Czerny-Turner monochromator and charge-coupled device detector. This MP-AES allows easy entrainment of sample aerosols, both aqueous and organic. The tolerance of aqueous and organic solvent loads as well as ambient air is significantly greater than that of other analytical plasmas.

The principle of sample preparation and analysis is based on sample preparation through acid digestion. The sample extract was injected into the MP-AES system for analysis.

The equation used to calculate the results obtained from the analysis of the MP-AES data is:

$$(cV)/mu, \tag{1}$$

where *C*—metal concentration in the samples (mg/kg), *c*—metal concentration in the vial (mg/L), *V*—volume to which the extract was concentrated (mL), *mu*—mass of the sample used for extraction (g).

The metal content in the soil samples is expressed in mg/kg. The limit of detection (LOD) was defined as the concentration corresponding to three times the standard deviation for ten reagent blank determinations, while the limit of quantitation (LOQ) was defined as the lowest concentration of analyte in a calibration curve with a signal-to-noise ratio of at least 5 : 1 [15]. The LODs and LOQs obtained for individual heavy metals are presented in Table 1.

Ecological risk assessment. For the ecological risk assessment, the following criteria were used: the ecological risk assessment (ERI) and potential ecological risk index (RI).

The method for determining the RI was proposed by Hakanson [35]. This method was used to evaluate the potential ecological risk from a sedimentology perspective to assess the characteristics and environmental behavior of heavy metal contaminants [35, 63, 81, 113]. The ecological risk of toxic metals in the soil can also be assessed by the ERI:

$$\mathrm{ERI} = \mathrm{Tr}\,\mathrm{CF}, \tag{2}$$

where Tr represents the toxic response factor and CF is the concentration factor. The Tr values for the metals are As = 1, Cd = 30, Cr = 2, Mn = 1, Pb = 5, Zn = 1, Cu = 5, and Ni = 5.

The ecological risk was classified into five classes [35, 38, 42, 52, 63, 82, 119, 156]. The RI is given by RI = ∑ERI. The degree of contamination for particular heavy metals according to the RI is shown in Table 2 [63].

Contamination factor (CF): The concept of the Contamination Factor (CF) is based on the Tomlinson model [118], where CF is determined by the ratio of metal concentration in soil to the set limit concentration for each metal. The established limit values for various metals are specified in national regulations: Ni at 35 mg/kg, Cr at 100 mg/kg, Zn at 140 mg/kg, Cu at 36 mg/kg, Pb at 85 mg/kg, and Cd at 0.8 mg/kg [104]. Notably, no limit values are defined for Manganese (Mn), Iron (Fe), and Aluminum (Al), with Fe and Mn not included in the toxic metal category.

Since these limit values may vary internationally, CF values could differ across countries even with identical metal concentrations [99]. CF is a vital indicator for gauging metal pollution in soil, calculated as per equation (3):

$$\mathrm{CF} = \frac{\text{Potential toxic element conc. in study area}}{\text{Potential toxic element conc. (limit values)}}, \tag{3}$$

Table 2. Classification of ecological risk and potential ecological risk for metals

Ecological risk	Low	Moderate	Appreciable	High	Extremely high
Eri	<40	40–80	80–160	160–320	>320
Potential ecological risk	Low	Moderate	Strong		Very strong
RI	<150	150–300	300–600		≥600

Table 3. Statistical analysis of the toxic metals detected in soil samples from wild solid waste dumpsites

Parameter	Zn	Cd	Fe	Cu	Ni	Pb	Mn	Cr	Al
Mode	4.04	1.07	0.00	7.87	5.89	6.10	76.58	12.38	0.00
Median	61.66	1.35	9853.20	13.13	37.95	7.90	346.98	44.07	0.00
Mean	109.760	1.495	9211.961	21.831	43.816	37.980	380.809	47.118	1709.858
Std. Deviation	179.541	0.654	7123.371	31.650	46.513	100.077	195.228	24.385	3512.222
Coefficient of variation	1.636	0.437	0.773	1.450	1.062	2.635	0.513	0.518	2.054
Variance	32234.819	0.427	$5.074 \times 10^{+7}$	1001.751	2163.441	10015.398	38114.026	594.652	$1.234 \times 10^{+7}$
Skewness	4.115	2.389	0.829	4.407	4.934	4.806	1.628	1.897	1.943
Kurtosis	18.819	9.228	1.998	21.098	28.633	25.698	3.282	5.135	2.732
Shapiro–Wilk	0.467	0.803	0.893	0.423	0.498	0.370	0.855	0.836	0.554
P value of Shapiro–Wilk	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0001
Minimum	4.04	0.69	0.00	5.40	5.89	0.00	76.58	12.38	0.00
Maximum	1054.24	4.51	33.27516	192.97	318.39	611.74	1044.61	135.48	13083.91
Limit value	140	0.8	–	36	35	85	–	100	–
Remediation values	720	12	–	190	210	530	–	380	–

CF categorizes soil contamination levels into four: CF < 1 for low, 1 ≤ CF < 3 for moderate, 3 ≤ CF < 6 for considerable, and CF ≥ 6 for very high degree of contamination [116].

Pollution load index (PLI). PLI is a comprehensive measure of metal contamination for a specific site or area [35]. PLI, derived from CF values, evaluates toxic metal pollution, soil condition, and necessary remediation actions [99]. It is calculated using the eq. (4) [35]:

$$PLI = \sqrt[n]{CF1\,CF2\,CF3\ldots CFn}, \quad (4)$$

where CF to CFn represents the contamination factor and n is the number of metals. PLI > 1 indicates the presence of soil pollution [99].

Statistical analysis. In Excel 2016, JASP 0.16.0.0 software was used for statistical data processing. Descriptive statistics (mode, median, mean, standard deviation (SD) with coefficient of variation (CV), skewness, kurtosis, Shapiro–Wilk test, minimum, maximum) and factor analysis (FA) were applied for the analysis of the collected data. Correlations (Pearson's) between parameters in soil were calculated to obtain qualitative information about the possible sources of the toxic metals. A $p_{\text{value}} < 0.05$, < 0.01, and 0.001 were used as the significance levels.

Spatial distribution. Spatial distribution analysis of toxic metal (Ni, Cr, Mn, Zn, Cu, Pb, Cd, Fe and Al) concentrations was conducted using Surfer 12 software. Surfer employs the kriging method, a geostatistical interpolation technique, to generate an interpolated grid.

RESULTS AND DISCUSSION

Toxic metal concentrations in the soil. The present study explored the toxicity of metals originating from human activity in soil samples collected from wild solid waste dumpsites. The current investigation delves into the toxicity of metals that have their origins in anthropogenic activities, analyzing soil samples gathered from wild solid waste dumpsites. A notable finding presented in Table 3 is the significantly high Zn content recorded, with the maximum concentration reaching an exceptional level of 1054.24 mg/kg, contrasting starkly with a minimum value of just 4.04 mg/kg. This stark contrast in Zn concentrations underscores a pronounced heterogeneity in the types of waste deposited at these sites. Such variability is not merely indicative of the diverse nature of waste materials but also underscores the critical need for implementing more rigorous waste management practices at these unregulated dumpsites. The exceptionally high levels of Zn detected can be attributed to various sources, including but not limited to, industrial discharges, electronic waste, and galvanized materials, which often find their way into solid waste streams. The presence of Zn at such elevated levels poses potential risks not only to soil health but also to the broader ecosystem, affecting plant growth and potentially entering the food chain, thereby impacting human health [7]. The observed heterogeneity in metal concentrations across the sampled sites highlights a crucial aspect of environmental pollution studies. As noted by Kumar et al. [76], analyzing the spatial distribution of heavy metals in soils near dumpsites can provide valuable insights into pollution sources and pathways.

Cd exhibited significant variability in soil concentrations, with a minimum value of 0.69 mg/kg and a maximum of 4.51 mg/kg. This variability could be linked to various sources of pollution, including industrial and agricultural activities. The study by Zhao et al. shows that variations in soil heavy metal concentrations are often the result of anthropogenic influences, such as industrial production [115]. Variations were also observed among the samples for Cu, Ni, Pb, and Cr, with average values of 21.831, 43.816, 37.980, and 47.118 mg/kg, respectively. These variations could be due to different anthropogenic and geological sources, as indicated in the research by Meng et al. [89], where various pollution sources, including industrial activity and urban development, were identified as major contributors to the variability of heavy metals in the soil.

The soil samples exhibited elevated Fe contents, with an average value of 9211.961 mg/kg and a maximum value as high as 33 275.16 mg/kg. Such excessive iron content in the soil can lead to adverse effects on plant and animal life and can influence soil quality for agricultural purposes. High levels of iron in the soil can interfere with the availability of other essential micronutrients, potentially leading to deficiencies and affecting plant growth and development [16]. Excessive iron can also affect soil microbial communities [98], influencing key soil processes such as nutrient cycling and organic matter decomposition [66].

Cu, while essential for plant metabolism, in excess can inhibit root growth and affect soil microbial communities, potentially leading to reduced soil fertility and plant productivity [7]. Ni, beyond certain concentrations, is toxic to plants, causing chlorosis, necrosis, and reduced growth, impacting food quality and safety [4]. Pb contamination is of particular concern due to its well-documented adverse effects on human health, including neurotoxicity, especially in children, and its ability to be taken up by crops growing in contaminated soils, entering the food chain [91, 117]. Cr, in its hexavalent form, is highly toxic and carcinogenic, posing risks to both ecosystem health and human safety through water contamination and accumulation in food crops [109]. The presence of these metals in soils near wild dumpsites can be attributed to various sources, including industrial waste, electronic waste, and vehicular emissions. The leaching of these metals into groundwater and surface water can exacerbate the risk of water contamination, affecting both aquatic life and human populations reliant on these water sources for drinking and irrigation [76]. Moreover, the accumulation of these metals in agricultural soils can lead to their uptake by food crops, posing direct health risks to consumers through food contamination [111]. Its presence in the soil can have serious implications for the environment and human health, particularly in cases of water and food contamination.

Al, commonly found in soils, especially those affected by acidification and anthropogenic pollution, can significantly impact soil chemistry and plant health. An average Al concentration of 1709.858 mg/kg, as observed in the soils of wild dumpsites, suggests a substantial deviation from typical background levels, which can lead to several detrimental effects. Excessive Al concentrations in soil can lead to acidification, reducing soil pH and causing nutrient imbalances. This acidification can hinder plant growth by affecting root development and limiting the absorption of essential nutrients [72]. The toxic effects of Al on plants are primarily observed in the inhibition of root elongation, which limits water and nutrient uptake, affecting overall plant health and yield [85].

The results indicate the impact of the deposited waste on the soil, especially regarding the presence of Cd and Ni in almost all locations but also the presence of other pollutants in certain locations. These results indicate significant variations in the concentrations of toxic metals in soils from wild dumpsites. Elevated levels of Zn, Cd, Fe, and other metals demand attention and prompt action to mitigate adverse effects on the environment and human health. This study emphasizes the need for improved waste management and the establishment of sustainable waste treatment systems to safeguard nature and human health from potential risks posed by wild dumpsites. The Shapiro–Wilk test was applied to test the normality of the data [108] because the sample size was small (<50) [36]. For data normality testing, the usual significance threshold of $\alpha = 0.05$ was applied. In the present study, there was no metal with a value higher than 0.05. The Shapiro–Wilk test results demonstrated that the data were not normally distributed for all metals, further confirming the necessity of careful monitoring and management of wild dumpsites to reduce potential risks to the environment and public health.

For small samples, skewness test values greater than 1.96 or less than –1.96 are sufficient to establish normality of the data (except for Fe, Mn and Cr) [33]. Similarly, the Kurtosis test was used. CV, an index reflecting the extent of variability in relation to the mean of the samples for pollutants, can be used to determine the degree of anthropogenic contribution to pollution in environmental studies. CV < 0.10 and >0.90 indicate low and high anthropogenic contributions, respectively [18]. CVs > 0.90 are for Zn, Cu, Ni, Pb and Al.

In accordance with national legislation, limit and remediation values were applied [103]. The mean values for Cd and Ni exceeded the limit values, while the remediation values were not exceeded for any of the analyzed parameters. The measured values for Cd and Ni indicate the need for additional caution and continuous monitoring of pollution at these locations, particularly if agricultural areas are in close proximity.

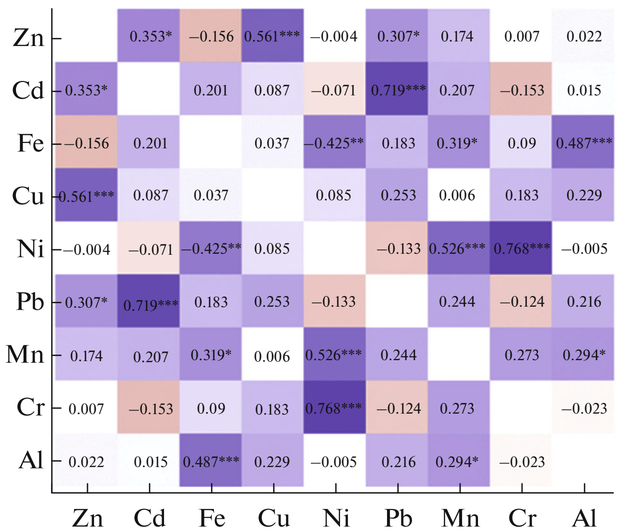

Fig. 2. Correlation analysis for several analyzed parameters in the soil.

Correlation analysis. The results of the correlation analysis are shown in Table S1 and Fig. 2. The correlation findings provide insight into the relationships between concentrations of toxic metals in soil from wild dumpsites. A positive correlation indicates situations where the values of two variables increase together, which may suggest similar sources or contamination processes in the vicinity of wild dumpsites.

Significant positive correlations were observed between Zn and Cu ($r = 0.561$, $p < 0.001$). These metals exhibit a strong positive correlation, implying potential similarity in their sources or contamination mechanisms. It can be assumed that there is a common pollution source or similar geochemical processes contributing to their presence in the soil.

Similarly, there was a strong positive correlation between Cd and Pb. These results suggest the frequent co-occurrence of these metals in the soil samples from wild dumpsites. The possible sources of these metals may be similar, and their presence could pose a potential threat to the environment and human health in the vicinity of these dumpsites.

Ni and Cr ($r = 0.768$, $p < 0.001$) also exhibited a very strong positive correlation. This exceptionally strong association indicates the frequent co-occurrence of these metals in the soil of wild dumpsites. Their close connection may indicate common contamination sources or geochemical processes contributing to their accumulation in the soil.

We also observe weaker positive correlations, such as between Fe and Al ($r = 0.487$, $p < 0.001$). The concentrations of these metals exhibited a moderate positive correlation, possibly due to their similar geochemical characteristics, which contributed to their association in the soil from wild dumpsites. There is a moderate positive correlation between Fe and Ni ($r = 0.425$, $p = 0.004$). The possible sources of these metals may be similar, or they may share similar physical and chemical properties, contributing to their accumulation in the soil.

On the other hand, several metal pairs show very small or insignificant correlations, implying that their concentrations are not related or that the relationship is very weak. These metal pairs included Zn and Fe, Zn and Ni, Zn and Cr, Zn and Al, Cd and Fe, Cd and Cu, Cd and Ni, Cd and Cr, Cd and Al, Fe and Cu, Fe and Pb, Fe and Mn, Fe and Cr, Cu and Ni, Cu and Pb, Cu and Mn, Cu and Cr, Cu and Al, Ni and Mn, Ni and Al, Pb and Mn, Pb and Cr, Pb and Al, Mn and Cr, and Mn and Al, Cr and Al. These correlations suggest different sources or mechanisms of metal accumulation in the soil from wild dumpsites, highlighting the complexity of metal interactions in the environment. However, further research is needed to better understand the exact nature of these relationships and their impact on the environment and human health.

Ecological risk assessment. This study conducted an ecological risk assessment of heavy metals in the soil at various locations, specifically focusing on illegal dumpsites. The assessment was carried out using the Hakanson method [35], and the results provide crucial insights into the environmental risks associated with these sites (Table S2).

The analysis revealed substantial ecological risks linked to the presence of heavy metals, with notable variations among the different metals (Fig. 3). Mn stands out as having an extremely high ecological risk, indicating a severe potential impact on the environment. Additionally, Ni and Pb were identified as metals with high ecological risk, further underscoring environmental concerns.

Zn, Cu and Cr were rated as having "appreciable" ecological risks, indicating the need for careful monitoring and management to mitigate potential adverse effects on the environment.

Cd, on the other hand, was assessed as having a 'moderate' ecological risk, suggesting a comparatively lower impact on the environment when present in the soil.

Notably, the calculated ecological risk indices (RIs) for all 45 locations consistently fall into the "very strong" category, signifying an urgent need for remediation [79] and management measures at these illegal dumpsites. The overall average RI for all locations reinforced the high ecological risk posed by heavy metal contamination. Additional factors that should be investigated are the degree of technogenic soil degradation, the loss of soil organic matter [67] and competitive relationships between the elements, which can affect the soil contamination level [68].

Contamination factor and Pollution load index: As part of the research on the impact of landfills on soil quality, the Contamination Factor (CF) and Pollution Load Index (PLI) were analyzed to assess the level of

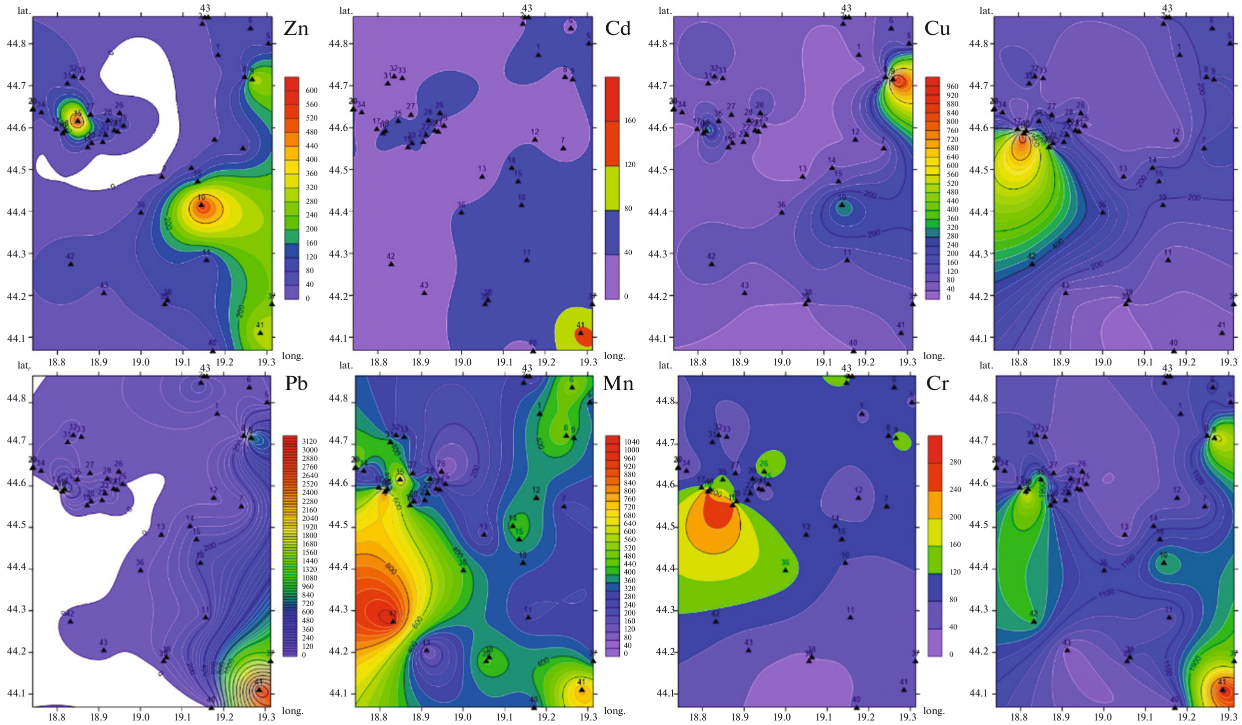

Fig. 3. ERIs for Zn, Cd, Cu, Ni, Pb, Mn and Cr and RIs of toxic metals.

heavy metal contamination in the soil. CF was determined as the ratio of the metal concentration in the analyzed soil [42]. Pb, Cr, Cu, and Zn showed low contamination levels (respectively 0.45, 0.47, 0.61, and 0.78). PLI values ≤1 indicate a low degree of contamination. The values for Ni and Cd indicate a moderate degree of contamination (1 ≤ CF < 3) with values 1.25 and 1.87, respectively. The results of this research showed variable levels of contamination, with low levels for Pb, Cr, Cu, and Zn, and moderate levels for Ni and Cd. These findings are in line with the results of the research conducted by Bešta-Gajević et al. [13], which also identified significant presence of heavy metals in the soil at illegal waste dumps in Bosnia and Herzegovina.

On the other hand, the research carried out by Sadeq and Mohammad [105] in the Kirkuk area of Iraq shows high levels of soil contamination with heavy metals due to the percolation of landfill leachates. Similarly, Fonge et al. [31] in Cameroon discovered medium to high levels of contamination with heavy metals such as Cu, Zn, and Cd in soils around urban landfills. These findings contrast with the results of this study, which indicate lower levels of contamination for some metals. The research conducted in Burkina Faso [83] shows high average concentrations of Cr, Pb, and Zn in landfill soils, exceeding recommended limits, indicating significant soil contamination. These findings further confirm the variability of soil contamination in different geographical contexts and under different waste disposal conditions.

The PLI was derived from the Contamination Factor (CF) values to assess toxic metal pollution. In 5 soil samples, the analyzed PLI values were greater than 1, as shown in Table 4, indicating the presence of soil pollution. The mean values further corroborate the presence of soil pollution. While some areas exhibit moderate levels of contamination, others show serious levels of contamination, highlighting the complexity and diversity of the impact of waste disposal sites on soil quality. The use of CF and PLI has proven to be a valuable tool in assessing and comparing the level of soil contamination in different geographical contexts.

Component analysis. Factor analysis (FA) was applied to determine the effective variable factors. The aim of FA is to create fewer factors by combining two or more variables [32, 47]. These fields may easily hypothesize too many variables, so factor analysis helps to find essentials of a theory [86]. Principal component analysis (PCA) and the rotation method Promax were used. The primary output for a PCA shows the correlation between each variable of a principal component and the variable factors (RC1, RC2 and RC3) (Table 5).

PCA, which attempts to explain the variance of a large dataset of intercorrelated variables with a smaller set of independent variables, is a powerful pattern recognition tool [21]. PCA's approach to data reduction involves creating one or more index variables (components) from a set of measured variables. Figure 2a shows what PCA is doing to combine seven measured

Table 4. Contamination factors (CF) and pollution load index (PLI) of toxic metals in soil per samplers

Samples	Contamination factors (CF)						PLI
	Zn	Cd	Cu	Ni	Pb	Cr	
1	0.36	2.73	0.30	1.08	0.09	0.40	0.11
2	0.33	1.78	0.29	0.89	0.13	0.36	0.08
3	0.19	1.35	0.25	0.81	0.51	0.62	0.13
4	0.51	2.70	0.39	1.19	0.15	0.50	0.22
5	0.30	1.11	0.33	1.13	0.10	0.66	0.09
6	0.45	2.65	0.44	1.20	0.14	0.37	0.18
7	0.46	1.41	0.58	1.36	0.18	0.53	0.22
8	0.35	1.34	0.36	1.46	0.09	0.48	0.10
9	0.51	1.34	0.50	1.21	0.12	0.48	0.16
10	2.25	1.69	5.36	1.38	1.99	0.67	6.11
11	7.53	2.81	3.16	0.91	0.66	0.39	3.97
12	0.66	3.21	0.44	1.18	0.38	0.39	0.41
13	0.58	1.78	0.64	0.53	0.33	0.22	0.16
14	0.27	1.63	0.24	0.45	0.07	0.30	0.03
15	0.03	1.06	0.17	0.81	0.03	0.44	0.01
16	0.40	1.94	0.48	1.14	0.25	0.42	0.21
17	1.14	2.26	0.52	1.43	0.41	0.48	0.62
18	0.51	2.00	0.80	9.10	0.04	1.29	0.66
19	0.25	1.23	0.25	1.52	0.05	0.62	0.06
20	0.90	1.89	2.00	1.36	1.70	0.67	2.30
21	0.29	1.44	0.42	3.31	0.07	1.35	0.24
22	0.23	2.65	0.27	0.84	0.19	0.48	0.11
23	0.23	1.59	0.29	1.39	0.07	0.46	0.07
24	0.71	1.88	0.60	1.68	0.55	0.61	0.67
25	0.22	1.61	0.22	0.86	0.07	0.25	0.04
26	0.44	1.59	0.34	0.85	0.09	0.26	0.07
27	0.47	0.99	0.16	0.38	0.00	0.46	0.00
28	0.17	2.49	0.70	0.94	0.08	0.79	0.13
29	0.22	1.38	0.24	0.73	0.03	0.37	0.02
30	0.55	2.00	0.28	1.10	0.13	0.45	0.14
31	0.72	2.34	0.33	0.56	0.06	0.26	0.07
32	0.40	1.34	0.32	0.84	0.08	0.34	0.06
33	0.38	1.44	0.35	1.09	0.08	0.54	0.10
34	0.68	0.86	0.73	1.21	0.14	0.44	0.18
35	0.07	1.39	0.35	0.47	0.07	0.24	0.02
36	0.25	0.94	0.31	0.98	0.09	0.30	0.04
37	4.56	1.86	0.57	2.03	0.11	0.70	0.87
38	0.42	1.78	0.45	2.03	0.07	0.71	0.19
39	1.79	2.79	0.55	0.54	3.08	0.36	1.28
40	0.74	1.94	0.60	0.68	0.25	0.23	0.18
41	0.45	2.44	0.15	0.17	0.09	0.12	0.02
42	0.33	1.45	0.22	0.28	0.01	0.21	0.01
43	2.28	5.64	0.48	0.29	7.20	0.21	1.64
44	0.49	1.20	0.58	2.34	0.04	0.52	0.13
45	0.24	1.21	0.28	0.61	0.03	0.26	0.02
Mean	0.78	1.87	0.61	1.25	0.45	0.47	0.49

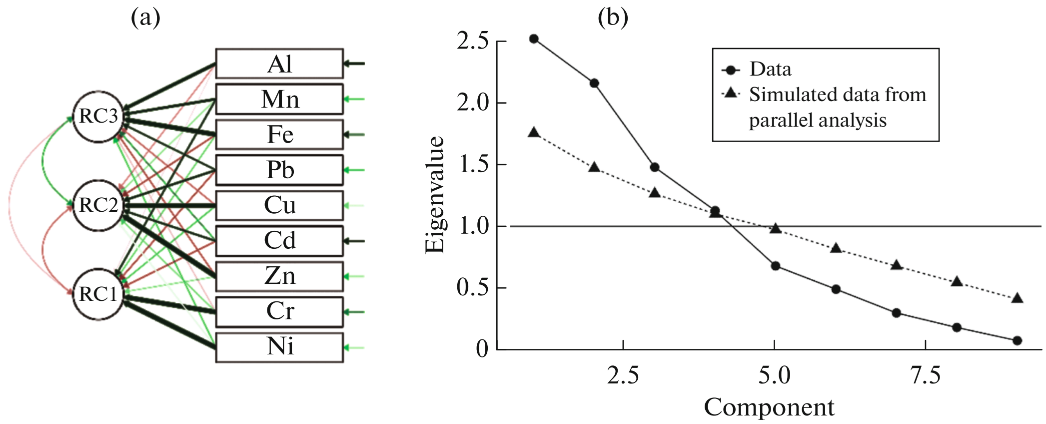

Fig. 4. Path diagram (a) and scree plot (b).

variables into three components, RC1, RC2 and RC3. The arrows indicate that the variables (Ni, Cr, Mn, Zn, Cu, Pb, Cd, Fe and Al) contributed to the variables. Weights to emphasize the Ni, Cr and Mn (for RC1); Zn, Cu, Pb and Cd (for RC2); and Mn, Pb, Fe, and Al (for RC3) variables more than others. This distribution of variance across the factors illustrates the differing degrees of influence each has on the dataset analyzed.

The first factor (RC1) has an eigenvalue of 2.512, accounting for 40.90% of the total variance. RC1 (Factor 1) has high loadings for Ni (0.916) and Cr (0.899) and, to a lesser extent, for Zn (0.940) and Cu (0.790). Ni and Cr were strongly positively loaded (>0.75). Mn was weakly loaded (0.50–0.30) [80] (Table 5). This means that Ni and Cr are strongly associated with this factor, indicating a high correlation between these two variables, which frequently cooccur in soil samples from wild dumps. Zn and Cu also had moderate associations with this factor. Ni, which occurs naturally in the Earth's crust, may enter the environment as a result of natural processes and mostly human activities [21]. Other metals are generated from waste in these locations.

The second factor (RC2) holds an eigenvalue of 2.153, contributing to 35.06% of the total variance. RC2 (Factor 2) had high loadings for Fe (0.878) and, to a lesser extent, for Mn (0.579), Cu (0.424), and Al (0.690) and explained 35.059% of the total variance. Zn and Cu were strongly positively related (>0.75). Pb had a moderate loading (0.75–0.50), and Cd had a weak loading (0.50–0.30). This indicates a strong association of Fe with this factor and moderate associations of Mn, Cu, and Al. This factor may represent a combination of metals that frequently cooccur in soil from wild dumps.

The third factor (RC3) comes with an eigenvalue of 1.476, representing 24.04% of the total variance. RC3 (Factor 3) has high loadings for Mn (0.438) and Zn (0.227) and, to a lesser extent, for Pb (0.446) and Al (0.562). This indicates moderate associations of these metals with this factor. Factor 3 may represent a group of metals sharing similar characteristics in soil from wild dumps. Fe was strongly positively loaded (>0.75). Mn and Al were moderately loaded (0.75–0.50), and Pb was weakly loaded (0.50–0.30).

The uniqueness values represent the proportion of variability in each variable that is not explained by the extracted factors. Higher uniqueness values indicate weaker correlations of that variable with the extracted factors. In this case, higher uniqueness values for Mn, Pb, and Cd suggest that these variables have weaker associations with the factors than other metals.

Figure 4a shows the PCA pathway diagram. Figure 4b shows the PCA scree plot. Eigenvalues higher than one were taken as criteria for evaluating the principal components required to explain the sources of variance in the data.

Spatial distribution. This study utilized Surfer software to visually represent and analyze the results of an ecological risk assessment for heavy metals in the soil at various locations, specifically focusing on illegal dumpsites in the Bijeljina-Zvornik region. The resulting grid provides a visual representation of the distri-

Table 5. Component loading of toxic metals

Metals	RC1	RC2	RC3	Uniqueness
Ni	0.916	–	–	0.105
Cr	0.899	–	–	0.208
Mn	0.456	–	0.579	0.438
Zn	–	0.940	–	0.227
Cu	–	0.790	–	0.424
Pb	–	0.508	0.446	0.259
Cd	–	0.477	–	0.364
Fe	–	–	0.878	0.272
Al	–	–	0.690	0.562

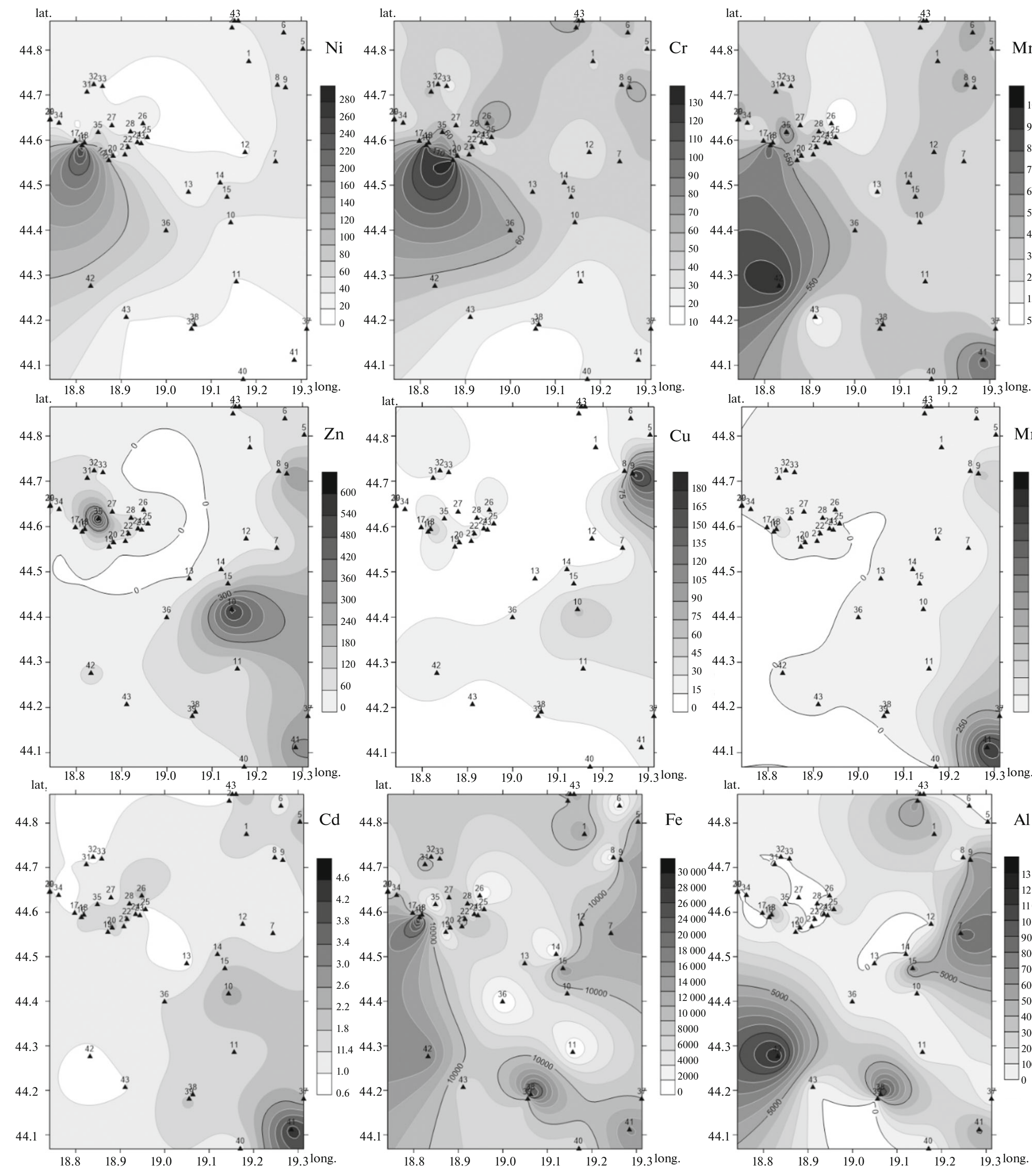

Fig. 5. The distributions of Ni, Cr, Mn, Zn, Cu, Pb, Cd, Fe and Al concentrations.

bution of metal concentrations across the studied region. The spatial distribution of toxic metals is depicted in Fig. 5. The spatial distribution of these results on the map provides a clear and informative overview of the environmental risks associated with these sites. For instance, the distribution and ecological risk assessment of heavy metals in a manganese (Mn) contaminated site revealed that Mn, along with other heavy metals like Pb, Cu, Cd, Zn, and Cr, can significantly exceed the limited standard, demonstrating a similar pattern in our study [84]. The map highlights the significant ecological risks posed by heavy metal contamination, with distinct variations in risk levels among the different metals. For example, Mn appears to be a pronounced hotspot with an extremely high ecological risk, indicating a substantial potential impact on the surrounding environment. This is in line with studies showing that industrial and mining activities are major sources of soil heavy metal contamination, which often lead to uneven distribution and significant ecological risks [34, 123]. Additionally, Ni and Pb prominently feature areas with high ecological risk, emphasizing environmental concerns. The findings from Northeastern Iran on agricultural soils contaminated with heavy metals, including Mn, Cu, and Ni, support our observations, indicating less contamination but still posing low ecological risks [74]. Cd, Cu, and Cr are considered regions with 'appreciable' ecological risk, highlighting the need for precise monitoring and management to mitigate potential adverse effects on the environment. This is corroborated by studies conducted in Southeastern China, where industrial production was a major factor influencing the spatial distribution of heavy metals [121]. Iron (Fe) regions are depicted as having a 'moderate' ecological risk, suggesting comparatively lower environmental impacts in those areas. This finding is consistent with the results from a study in Iran, where heavy metals usually accumulate in soil due to human activities and pose potential ecological and health risks [101]. The spatial visualization reinforces the high ecological risk posed by heavy metal contamination across the entire study area.

This study represents the first attempt to analyze the spatial distribution of toxic metals in the specific area under investigation. The use of Surfer's kriging method allowed for a comprehensive understanding of how these metals are distributed across the selected regions. Such information can play a pivotal role in identifying potential contamination hotspots and assessing environmental risks associated with toxic metal exposure. The interpolated grid provided by Surfer facilitates the visualization of metal concentration patterns, highlighting areas with higher or lower concentrations. This valuable insight can aid in the development of targeted remediation strategies, particularly for regions with elevated concentrations of toxic metals. Moreover, this spatial analysis enables researchers and policymakers to make informed decisions about the implementation of proper waste management practices and pollution control measures.

CONCLUSIONS

Wild dumpsites are critical sources of pollutants in soil and water and have significant ecological and health impacts. The indiscriminate disposal of solid waste has become a significant environmental challenge worldwide, especially in developing countries. In the B&H region, wild solid waste dumpsites are common, leading to potential ecological threats due to the presence of toxic metals. These metals, originating from discarded industrial and household waste, can persist in the soil for extended periods and pose considerable risks to ecosystems and human health.

Wild solid waste dumpsites are illegal and unregulated disposal areas often situated in remote or marginalized regions. The absence of proper waste management infrastructure in these areas results in haphazard dumping practices, leading to the accumulation of various hazardous materials, including toxic metals. The lack of waste segregation and treatment facilities exacerbates this problem, suggesting that these dumpsites are potential hotspots for metal contamination.

The present study explored the concentrations of toxic metals in soil samples from wild solid waste dumpsites (Ni, Cr, Mn, Zn, Cu, Pb, Cd, Fe and Al) originating from human activities. The impact of waste on the environment is manifested, first, in the pollution of soil and then in surface and underground waters. The results based on the soil samples indicate that severe pollution can be detected, but constant monitoring is necessary. It is also necessary to urgently remove wild dumps from these sites.

Addressing the challenges posed by wild dumpsites and metal pollution requires a multidimensional approach. Sustainable waste management practices, including waste segregation, recycling, and composting, can significantly reduce the volume of waste generated at wild dumpsites. Enforcing stringent environmental regulations and raising public awareness about the hazards of wild dumpsites and metal pollution are vital steps to foster responsible waste disposal practices and community participation in waste management initiatives.

Developing countries face unique challenges concerning waste management, with inadequate financial resources and infrastructure available to handle growing waste volumes. As a result, wild solid waste dumpsites are more prevalent in these regions than in other regions, posing a significant threat to environmental sustainability. The presence of toxic metals in the soil near these dumpsites could affect agriculture, water quality, and human populations in the vicinity, necessitating urgent attention to this problem.

Significant positive correlations are observed between Zn and Cu, between Cd and Pb and between Ni and Cr.

The ERIs for Mn are extremely high; for Ni and Pb, they are high; for Zn, Cu and Cr, they are appreciable; and for Cd, they are moderate. The visualized results of ecological risk assessments for heavy metals in the soil underscore the critical importance of continuous monitoring and effective management of heavy metals at illegal dumpsites to preserve and protect surrounding ecosystems. Furthermore, this spatial representation provides valuable insights for policymakers and environmental authorities in making informed decisions regarding the remediation and conservation of these areas.

These findings emphasize the critical importance of continuous monitoring and effective management of heavy metals at illegal dumpsites to preserve and protect surrounding ecosystems. Further research should be directed toward obtaining a deeper understanding of the mechanisms of metal dispersion and their specific environmental impacts to develop tailored strategies for remediation and environmental conservation.

This study sheds light on the severity of metal contamination in soil samples collected from wild solid waste dumpsites in the B&H. The presence of toxic metals poses potential ecological risks, threatening the delicate balance of local ecosystems and endangering human health. Implementing effective waste management practices, establishing proper waste disposal facilities, and promoting recycling and reuse initiatives are crucial steps toward mitigating the impact of wild solid waste dumpsites on the environment.

The use of Surfer 12 software and the kriging method has proven to be an invaluable tool for exploring the spatial distribution of toxic metals in the study area. This pioneering analysis has laid the groundwork for future research and environmental monitoring efforts and has provided a basis for understanding the potential risks posed to both the ecosystem and human health by the presence of these metals in the environment.

Disposal at wild dumpsites and associated metal pollution present complex and pressing challenges for environmental sustainability and public health. Effective solutions require a multifaceted approach involving robust waste management practices, scientific-based regulations, and public awareness campaigns. Governments, local authorities, nongovernmental organizations, and citizens must collaborate synergistically to address this issue. Implementing sustainable waste management practices, promoting recycling and proper disposal methods, and encouraging innovation in waste treatment technologies are essential steps for mitigating the adverse impacts of wild dumpsites and metal pollution on our environment and ensuring a healthier future for all people.

The findings shed light on the urgency of developing sustainable waste management strategies and stringent environmental regulations to mitigate the adverse impacts of wild dumpsites and metal pollution on our environment and ensure a healthier future for all people. By addressing the issue of wild dumpsites, we can pave the way toward a cleaner, healthier, and more sustainable future for our planet and its inhabitants.

SUPPLEMENTARY INFORMATION

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Statement when using Artificial Intelligence tools in writing this article: In preparing this paper, the authors used ChatGPT in order to translate the text into English. After using this tool/service, the authors have reviewed and edited the content as necessary and take full responsibility for the content of the publication.

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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