RUDN Journal of Ecology and Life Safety
Вестник РУДН. Серия: Экология и безопасность жизнедеятельности

ISSN 2313-2310 (Print); ISSN 2408-8919 (Online)
2025 Vol. 33 No. 4 467–476
http://journals.rudn.ru/ecology

GEOECOLOGY

ГЕОЭКОЛОГИЯ

DOI: 10.22363/2313-2310-2025-33-4-467-476
EDN: ILJLFQ
UDC 504.054

Research article / Научная статья

Electronic waste as a source of heavy metal contamination of soils: leaching dynamics under simulated landfill conditions

Daniil A. Ostanniy[1] ✉, Mikhail A. Shakhramanyan[1,2]

[1] *Russian State Social University, Department of Complex Security and Fundamentals of Military Training, Moscow, Russian Federation*
[2] *Financial University under the Government of the Russian Federation, Moscow, Russian Federation*
✉daostanny@ya.ru

Abstract. Electronic waste poses a serious environmental threat due to the content of heavy metals. The aim of the work is to evaluate the leaching of heavy metals (Cu, Pb, Zn, Cd, Cr, Ni) from printed circuit boards and cables under simulated urban landfill conditions (SPLP method, 8 cycles). E-waste was found to be a significant source of contamination. Printed circuit boards showed a gradual increase in the concentrations of Cu (up to 2.33 mg/L), Pb (up to 0.666 mg/L) and Zn (up to 1.385 mg/L) in the leachate. The cables were characterized by high initial Cu removal (3.50 mg/L) followed by a decrease. A heuristic risk assessment model was developed.

Keywords: electronic waste, heavy metals, leaching, soil contamination, environmental risk, printed circuit boards, cables, leachate, municipal landfill, modeling

Authors' contribution. *D.A. Ostanniy* — conceptualization, methodology, investigation, data curation, visualization, writing — original draft. *M.A. Shahramanyan* — conceptualization, supervision, formal analysis, writing — review and editing, validation. All authors have read and approved the final version of the manuscript.

Article history: received 06.08.2025; revised 22.08.2025; accepted 02.09.2025.

Conflicts of interest. The authors declare no conflicts of interest.

For citation: Ostanniy DA, Shakhramanyan MA. Electronic waste as a source of heavy metal contamination of soils: leaching dynamics under simulated landfill conditions. *RUDN Journal of Ecology and Life Safety.* 2025;33(4):467–476. http://doi.org/10.22363/2313-2310-2025-33-4-467-476

Электронные отходы как источник загрязнения почв тяжелыми металлами: динамика выщелачивания в условиях имитации полигона отходов

Д.А. Останний[1] ✉, **М.А. Шахраманьян**[1,2]

[1]*Российский государственный социальный университет, факультет комплексной безопасности и основ военной подготовки, Москва, Российская Федерация*
[2]*Финансовый университет при Правительстве РФ, Москва, Российская Федерация*
✉ daostanny@ya.ru

Аннотация. Электронные отходы представляют серьезную экологическую угрозу из-за содержания тяжелых металлов. Цель исследования — оценка выщелачивания тяжелых металлов (Cu, Pb, Zn, Cd, Cr, Ni) из печатных плат и кабелей в условиях имитации городской свалки (метод SPLP, 8 циклов). Установлено, что электронные отходы являются значимым источником загрязнения. Печатные платы демонстрировали постепенный рост концентраций Cu (до 2,33 мг/л), Pb (до 0,666 мг/л) и Zn (до 1,385 мг/л) в фильтрате. Для кабелей был характерен высокий начальный вынос Cu (3,50 мг/л) с последующим снижением. Разработана эвристическая модель оценки риска.

Ключевые слова: электронные отходы, тяжелые металлы, выщелачивание, загрязнение почв, экологический риск, печатные платы, кабели, фильтрат, городская свалка, моделирование

Вклад авторов. *Останний Д.А.* — концептуализация, методология, проведение исследования, администрирование данных, визуализация, создание черновика рукописи. *Шахраманьян М.А.* — концептуализация, руководство исследованием, формальный анализ, создание рукописи и ее редактирование, верификация данных. Все авторы ознакомлены с окончательной версией статьи и одобрили ее.

История статьи: поступила в редакцию 06.08.2025; доработана после рецензирования 22.08.2025; принята к публикации 02.09.2025.

Заявление о конфликте интересов. Авторы заявляют об отсутствии конфликта интересов.

Для цитирования: *Останний Д.А., Шахраманьян М.А.* Электронные отходы как источник загрязнения почв тяжелыми металлами: динамика выщелачивания в условиях имитации полигона отходов // Вестник Российского университета дружбы народов. Серия: Экология и безопасность жизнедеятельности. 2025. Т. 33. № 4. С. 467–476. http://doi.org/10.22363/2313-2310-2025-33-4-467-476

Introduction

Electronic waste is one of the fastest growing solid waste streams in the world. WHO estimates that around 62 million tons of electronic waste was generated globally in 2022, with only 22% of it being formally collected and recycled. The rest of the electronic waste often ends up in landfills or is processed informally, which leads to the release into the environment of many toxic substances, including heavy metals (lead, cadmium, etc.).[1] The problem of disposal of electronic waste is also relevant for Russia: every year, about 1.6 million tons of waste electrical and electronic equipment are produced in the country, while only about 6% is recycled. Electronic devices contain dangerous components, such as lead, cadmium, mercury and other toxic elements that pose a threat to the environment if such waste is disposed of in conventional landfills. The primary environmental hazard of e-waste is related to the leaching of heavy metals and other toxicants into soil and groundwater when buried. In countries with insufficient electronic waste management systems (e.g., landfills in Africa and Asia) significant heavy metal soil contamination is recorded at the sites of electronic waste collection [1]. Metals from electronic engineering components (Cu, Pb, Zn, Cd, Ni etc.) can migrate into the soil environment, accumulate in the upper layers of the soil and pose risks to ecosystems and public health [2].

The aim of this work is to assess the leaching of heavy metals from various types of electronic waste under conditions simulating an urban landfill and to calculate the environmental risk of such pollution. The research tasks included laboratory modelling of leaching processes of heavy metals under the influence of acid sediments, measurement of concentrations of basic metals (Cu, Pb, Zn, Cd, Cr, Ni) in filters, the analysis of the result and the development of an heuristic model allows it to be used as a basic tool for the primary assessment of potential pollution [3; 4].

Research hypothesis. It is assumed that the leaching of heavy metals from electronic waste at a landfill site is subject to patterns depending on pH, electrical conductivity, type of waste and time of contact with sediment. Their identification will allow for a more accurate assessment of pollutant concentrations and the classification of wastes by hazard level, which will provide the basis for the development of environmental standards and mitigation strategies.

Materials and methods

The experiment was conducted under conditions simulating the soil layer of an urban landfill with sediment infiltration. The substrate used was blackness (pH 6.8), loaded per 500 g into containers with a volume of 1 l. On the surface 50 g of waste were added: (1) fragments of printed circuit boards, (2) sections of

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[1] *World Health Organization. Electronic waste (e-waste)*. Geneva: World Health Organization; 2024. Available from: https://www.who.int/news-room/fact-sheets/detail/electronic-waste-(e-waste) (accessed: 13.05.2025).

copper cables with partially removed insulation, (3) control — only soil. Each option was executed in three repetitions.

Acid deposition simulation. For accelerated leaching of toxic elements used solution simulating acid rain. The standardized conditions of the Synthetic Precipitation Leaching Procedure (SPLP) were used — a mixture of sulfuric and nitric acid in a ratio of 60:40 with a final pH of 5.5 [5]. Within 24 hours of placing the samples, the surface of each vessel was moistened with 100 ml of acid solution (corresponding to heavy rain). The solution was evenly applied to the surface of the soil, after which the filtrate was collected through a drainage system after 24 hours. The procedure was repeated daily, just 8 cycles, which simulated multiple rainfall.

Measurable indicators. After each cycle, the leachate was collected and the following measurements were made: pH, electrical conductivity (EC, characterizes the total mineralization of the solution) and concentrations of heavy metals (in the work Cu, Pb, Zn, Cd, Cr, Ni — basic metals present in electronic engineering were controlled) [3]. Values of pH were measured using a laboratory pH meter (pre-calibrated with buffer solutions at pH 4.0 and 7.0). Electrical conductivity was measured by conductometry at 25°C using a portable conductometer. Filtration samples for metal analysis were taken in plastic vials pre-washed with acid. Samples acidified HNO to pH<2 and stored at +4°C before analysis. The metal concentrations (Cu, Pb, Zn, Cd, Cr, Ni) were measured by atomic absorption spectrometry (AAS) on a graphite furnace spectrometer. Calibration of the instruments was carried out using government standard samples of metal solutions. Detection limits of the methods were: 0.001 mg/l for Cd; 0.005 mg/l for Pb; 0.01 mg/l for Cu, Zn, Ni; 0.02 mg/l for Cr.

Results

Changes in pH. In the simulation of multiple precipitations, there were noticeable changes in pH of the filters and their mineralization compared to the original solution (Table 1). The initial pH value of acid rain was 5.5; when passing through the soil column in the control (soil only), the leachate was neutralized already in the first cycle to pH 7.0 due to the alkaline reserve of blackness. Neutralization was less pronounced in the electronic waste versions: for example, the pH of filtrate after 1 day in the printed plate samples was about 6.2 and in the cables about 6.5.

Starting from the 2nd-3rd day, in samples with electronic waste there was a tendency to increase acidity: minimum values of pH (~5.8) were recorded for 3–4 days in experiments with printed plates. There was a gradual recovery of pH to 6.0-6.3 by day 8, which may be due to depletion of acidifying substances and stabilization of the soil buffer. The pH of the filtrate remained stable at 6.8–7.1 throughout the experiment.

Table 1. **Dynamics of pH of the filtrate depending on the type of electronic waste and the time of contact with acidic deposits**

Sample type	**24h**	**48h**	**72h**	**96h**	**120h**	**144h**	**168h**	**192h**
Printed circuit board	~6.2	~6.0	~5.8	~5.8	~5.9–6.0	~6.0–6.2	~6.1–6.3	~6.2–6.4
Cables	~6.5	~6.4–6.5	~6.2–.3	~6.2 –6.3	~6.3–6.4	~6.4–6.5	~6.5	~6.5
Control (soil only)	~7.0	~7.0	~6.9–.0	~6.9–7.0	~6.9–7.1	~7.0–7.1	~7.0–7.1	~7.0–7.1

Source: compiled by D.A. Ostanniy, M.A. Shakhramanyan.

The electrical conductivity of the filters with electronic waste was significantly above control throughout the experiment (Table 2). After the first cycle it reached 2.1 mSm/cm for boards and ~1.5 mSm/cm for cables, whereas in the control it did not exceed 0.4 mSm/cm. This indicates an intensive extraction of salts and metals in the initial period. From 2 days, there was a decrease to ~1.3–1.6 mSm/cm by 3–4 cycles, and from 5 to 8 days the values stabilized at 1.2–1.4 mSm/cm, reflecting a more inertial phase. The control value was 0.5 mSm/cm, which is 3–4 times lower than with waste.

Table 2. **Dynamics of electrical conductivity (EC, mS/cm) of filtrate depending on the type of electronic waste and contact time**

Sample type	**24 h**	**48 h**	**72 h**	**96 h**	**120 h**	**144 h**	**168 h**	**192 h**
Printed circuit board	2.1	~1.6	~1.5	~1.4	1.3–1.4	1.2–1.3	1.2–1.3	1.2–1.3
Cables	~1.5	~1.4	~1.3	~1.3	1.2–1.3	~1.2	~1.2	~1.2
Control (soil only)	≤0.4	≤0.4	≤0.4	≤0.4	≤0.5	≤0.5	≤0.5	≤0.5

Source: compiled by D.A. Ostanniy, M.A. Shakhramanyan.

Concentrations of heavy metals in leachate. The concentrations of controlled heavy metals were found to be significantly higher in all the filters obtained from the columns with electronic waste than in the control soil. Data on leaching dynamics are given in three tables. In the control filters, all metals remained consistently low: copper and lead — not higher than 0.02 mg/L, cadmium and chromium — at trace level, which reflects background levels of leaching from uncontaminated black soil (Table. 3). The concentrations of controlled heavy metals were found to be significantly higher in all the leachates obtained from the columns with electronic waste than in the control soil. Data on leaching dynamics are given in three tables. In the control filters, all metals remained consistently low: copper and lead — not higher than 0.02 mg/L, cadmium and chromium — at trace level, which reflects background levels of leaching from uncontaminated black soil (Table 3).

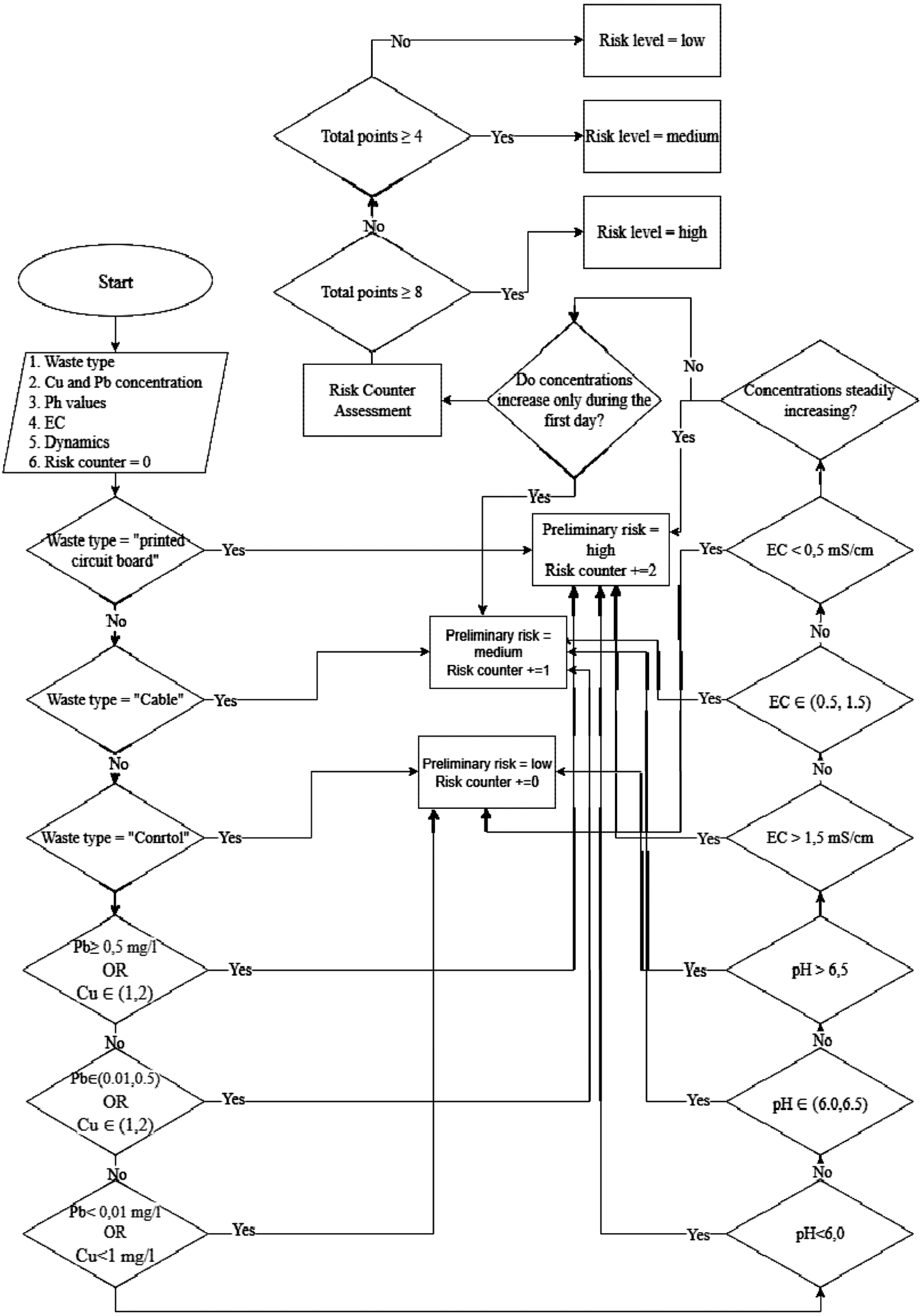
Copper, lead and zinc were the most active leaching agents. In experiments with printing plates, the copper concentration gradually increased from 1.20 to 2.33 mg/L and lead from 0.35 to 0.67 mg/L, reaching maximum values at cycle 8. A gradual increase in zinc concentration to 1.39 mg/L was also observed. Cadmium, nickel and chromium in this version of the experiment were stable but lower: up to 0.03 mg/L for cadmium, 0.37 mg/L for nickel and 0.055 mg/L for chromium. In the version with cables, copper predominated, and already in the first 24 hours its concentration reached 3.5 mg/L, then decreased to less than 1.0 mg/L.

Table 3. **Concentrations of heavy metals in filtrates (mg/L) depending on the sample type (ranges for 8 experimental cycles)**

Metal	Printed circuit boards	Cables	Control (soil)
Cd	0.012–0.023 (increase)	<0.005 (not detected)	<0.002 (not detected)
Cr	0.032–0.055 (increase → decrease)	<0.01 (not detected)	0.003–0.005 (background)
Cu	1.21–2.33 (steady increase)	3.50 → 0.97 (sharp decrease)	0.012–0.020 (background)
Ni	0.182–0.371 (increase)	0.082 → 0.026 (decrease)	0.006–0.010 (background)
Pb	0.359–0.666 (increase)	0.032 → <0.01(decrease to below detection)	0.003–0.005 (background)
Zn	0.832–1.385 (increase)	0.15 → 0.05 (decrease)	0.022–0.030 (background)

Source: compiled by D.A. Ostanniy, M.A. Shakhramanyan.

Samples with printed plates showed a steady increase in the total metal concentration in the filtration from ~3 mg/L in the first 24 hours to more than 5 mg/L by 192 hours (8 days), with no sign of sedimentation. This dynamic indicates a gradual breakdown of the insulation and varnish layers, opening up new sections of conductive paths, as well as the gradual involvement of less accessible metal fractions in leaching processes. In the cabled version, by contrast, the maximum metal removal (~3.5 mg/L) was recorded as early as 1 day, after which the total concentration in the filter gradually decreased to less than 1 mg/L at the end of the observation. This indicates the rapid leaching of available copper from the surface of the core and the subsequent retardation of corrosion processes due to passivation and lack of other significant sources of metals. The concentration of heavy metals in the control column remained within 0.1 mg/L throughout the experiment, which corresponds to the background level of soluble components of blackness under acid wetting (Figure).



Block diagram of the heuristic model for assessing environmental risk based on leachate parameters and e-waste type

Source: compiled by D.A. Ostanniy.

The results show that electronic waste in contact with acid filtration can release significant amounts of heavy metals into the environment.

In the experiments with cables copper peak was fixed already in the first cycle, then its concentration decreased. This is due to the washing of the surface fraction and subsequent passivation of the cores by oxide films, as well as the absorption of Cu_2 ions from the soil. At pH above 5, the copper is additionally precipitated as hydroxides, which limits its mobility.

When leaching copper from the printed circuit boards, its concentration gradually increased. At first the acid penetrated only partially, then the destruction of the protective coatings exposed new parts of the metal, increasing the contact area and the intensity of dissolution. Unlike cables, where the process is short-term, boards provide slow but steady copper discharge even at late stages.

It is important to note that organic materials of printed circuit boards and cable insulation (epoxy resins, textured, PVC) were not analyzed in the study. However, according to the literature, they can secrete toxic compounds (bisphenol-A, formaldehyde, brominated flame retardants, lead and cadmium stabilizers, phthalates, dioxins, etc.), which are highly persistent and able to bioaccumulate[2].

Thus, the present study focusing on inorganic pollutants should be seen as an important first step in assessing the integrated effects of e-waste.

Heuristic model

In order to describe the leaching patterns of heavy metals, a heuristic model has been developed that fixes the dependence of pollutant concentrations on waste type and environmental parameters. It uses a ball system: high risk — 2 points, moderate risk — 1, low risk — 0. The total result for five criteria gives the final risk category: 8–10 points — high, 4–7 points — moderate risk, less than 4 points — low. The logic diagram of the model is shown in Figure.

Conclusion

During the study, a laboratory simulation of leaching heavy metals from electronic waste under conditions similar to the effect of acid rain on an urban landfill was carried out. Based on the results, the following conclusions can be drawn:

- *Electronic waste is a significant source of heavy metal pollution.* Under the simulated conditions (acid deposition) both boards and cables released

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[2] *World Health Organization. Electronic waste (e-waste).* Geneva: World Health Organization; 2024. Available from: https://www.who.int/news-room/fact-sheets/detail/electronic-waste-(e-waste) (accessed: 13.05.2025).

copper, lead, zinc, cadmium, nickel and chromium into the filter. Already after the first cycle, copper and lead concentrations were ten times higher than the background, indicating an intensive metal removal in the initial period.
- *Leaching dynamics depend on the nature of the waste.* Printed circuit board fragments are characterized by a gradual increase in metal concentrations in the filter and a relatively long-term retention of their high level, whereas from copper cables the bulk of the soluble copper is washed out at the first moisture supply.
- *Heuristic risk assessment model has been developed,* it can classify pollution level by waste type, Cu and Pb concentrations, pH and electrical conductivity. The block diagram model with a scoring system integrates these factors into the final risk category and can be used for primary pollution assessment in monitoring and disposal planning.

Recommendations. Results confirm the need for separate collection and recycling of electronic waste, especially lead and cadmium. Their burial with household waste is not acceptable, as they become a source of long-term pollution. To reduce the risk, systems for the disposal and recovery of hazardous components should be developed, and the data obtained should be considered in the development of regulations and measures for environmental protection.

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Bio notes:

Daniil A. Ostanniy, Postgraduate student, Russian State Social University, Faculty of Comprehensive Security and Military Training. 4 V. Pika St, Moscow, 129226, Russian Federation. ORCID: 0009-0009-1107-4922; eLIBRARY SPIN-code: 2500-8186. E-mail: daostanny@ya.ru

Mikhail A. Shakhramanyan, Honored Scientist of the Russian Federation, Doctor of Technical Sciences, Professor, Financial University under the Government of the Russian Federation, Academician of the Russian Academy of Natural Sciences (RAEN). 49 Leningradsky Avenue, Moscow, 125993, Russian Federation. ORCID: 0000-0003-4943-8946; eLIBRARY SPIN-code: 6603-6401. E-mail: shahramanianma@corp-univer.ru