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ANALYSIS OF ARTIFICIALLY CREATED LANDFILL FILTRATE CONTAINING WASTE BATTERIES

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Abstract. Landfill leachate is one of the main sources of heavy metal contamination of soil and surface water. In this study, leachate formation was modeled in laboratory conditions using two experimental systems: a control system (without additional contaminants) and a system with the addition of crushed batteries. The content of copper (Cu), zinc (Zn), manganese (Mn), nickel (Ni), and lead (Pb) was analyzed in eight samples taken between November 2023 and July 2024. Curve equations and nonlinear curve equations of metal content changes over time were constructed to present a visual result. It was found that the addition of batteries significantly increases the concentrations of Mn (average 8.55 mg/L) and Ni (0.55 mg/L). The control system shows high variability of Zn (38.52 mg/L). The results highlight the risk of contamination from hazardous waste and the need to strengthen control over its disposal. The modeling system presented can also be used to study the impact of other various pollutants.

Keywords: landfill leachate, heavy metals, batteries, environmental pollution, household waste, toxic substances.

1. Introduction

The use of solid waste landfills is a common waste management method in many countries, including Ukraine, where more than 10 million tons of solid waste are generated annually (State Statistics Service of Ukraine, 2024; Nahursky et al., 2022). One of the key environmental risks of landfills is the formation of leachate, a liquid that seeps through waste and accumulates toxic substances, including heavy metals (Vaverková, 2019). Heavy metals such as Cu, Zn, Mn, Ni, and Pb are persistent pollutants that do not decompose and accumulate in ecosystems, causing toxic effects on biota and humans (Tchounwou et al., 2012). It is also dangerous that even if a landfill is closed, leachate containing heavy metals can continue to form for 20–50 years if the waste is not isolated by a sealed sarcophagus or cap (Grzegorz, 2025).

Hazardous waste such as used batteries (Xiaodong et al., 2026) and waste electrical and electronic equipment (WEEE), which contain high concentrations of metals (e. g., Zn and Mn in batteries, Pb and Ni in electronics), pose a particular threat. According to EU data, 12 million tons of WEEE are generated annually, of which only 35 % is recycled (EEA, 2022). In addition to chemical contamination of soil and water, such waste poses a direct threat to human health, in particular causing damage to DNA and the thyroid gland (Parvez et al., 2021). At the same time, improper disposal or lack thereof leads to significant economic losses, as metals from electronics remain unused. This waste may contain valuable metals such as gold, silver, and copper. The total value of these metals worldwide in 2022 is estimated at $91 million (Ewastemonitor, 2024).

In Ukraine, the problem is exacerbated by the lack of an effective collection system for such waste, which leads to it ending up in regular landfills. (European Commission, 2024). In terms of two types of

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waste – batteries and electronic and electrical equipment waste − the situation in Ukraine is indeed very different. There are many initiatives to collect batteries from various volunteer companies (about 66 tons were collected in 2025) (Batteries, Act Now!, 2025). The collection of WEEE is in a much worse state. While batteries can be handed in at the nearest supermarket, there are almost no such collection points for electrical equipment, apart from a few isolated initiatives (Waste Management Center, 2026). Only about 5–6 % of electronic waste is officially collected in Ukraine (Ewastemonitor, 2024).



Fig. 1. Photo of model barrels with waste

The aim of the study is to assess the impact of batteries on the content of heavy metals in artificially created landfill leachate. The experiment is based on laboratory modeling, which allows controlling variables and simulating real landfill conditions (Fig. 1).

2. Materials and Methods

The experiment was conducted in plastic barrels with a volume of 200 liters each, filled with simulated solid waste (Table 1). All barrels were filled to approximately 80 %. The barrels were hermetically sealed, with a distilled water irrigation system (rate of 7 liters / week to simulate precipitation) and leachate collection at the bottom. The amount of water for irrigation was calculated according to the natural precipitation in the Vinnytsia region (650 mm/year) in relation to the cross-sectional area of the barrels under study. Each of the barrels was also equipped with an automated temperature recording system. The barrels were insulated with mineral wool to reduce temperature fluctuations. The experimental system was designed to simulate the natural processes that occur in waste at real landfills.

*Barrel 1 (control, on the left in the photo): Only modeled solid waste without additional contaminants.

*Barrel 2 (with batteries, on the right in the photo): Simulated MSW + 0.25 % by weight of discharged and deliberately crushed used alkaline batteries (type AA, AAA, Zn content ~20 %, Mn ~30 %).

Table 1

Morphological composition of waste in barrels

Fraction	Barrel 1, kg	Barrel 2, kg
food	18.83	18.83
paper	0.93	0.93
cardboard	0.36	0.36
wood	0.36	0.36
glass	1.56	1.56
metal	0.60	0.60
PETE	0.50	0.50
lamina	0.33	0.33
plastic packaging	3.96	3.96
other plastic	0.3	0.3
textiles	1.06	1.06
hazardous waste	0.23	0.23
caoutchouc	0.13	0.13
other	2.23	2.23
batteries	0	0.077*
TOTAL	~31.38	~31.457

*Note:**– Barrel 2 contains 0.25 % of the total weight of batteries of various types.

This morphological composition was formed on the basis of components actually available on the territory of Vinnytsia National Technical University. This approach maximizes compliance with real conditions and increases the representativeness of the results obtained.

The experiment began in November 2023 and ended in July 2024. Infiltrate samples were collected monthly.

Concentrations of metals – copper (Cu), zinc (Zn), lead (Pb), manganese (Mn), nickel (Ni) – were determined by atomic absorption spectrometry (AAS) using a Selmi C-115 device. The sensitivity of the C-115 atomic absorption spectrophotometer (and its C-115M1 modification) depends on the element being determined and the atomization mode (flame or electrothermal), and is, for example, ~0.05 mg/L for copper (Cu), 0.6 mg/L for aluminum (Al), and as low as 0.001 mg/L for mercury (Hg) with a mercury hydride attachment. The samples were pre-mineralized with nitric acid (HNO_3, 65 %). Standard metal solutions for calibration (Merck) were used to prepare the samples. Measurements were performed in triplicate; the total error was <5 %.

Statistical processing was performed to determine the mean values and standard deviation (SD) using Python (pandas, numpy).

3. Results and Discussion

The obtained values were compared with the threshold values for drinking water according to DSanPiN 2.2.4-171-10 of Ukraine: Cu ≤1.0, Zn ≤5.0, Mn ≤0.1, Ni ≤0.1, Pb ≤0.03 mg/L. The standards for drinking water are clear with regard to heavy metals; however, it is not entirely clear which type of natural water landfill leachate should be compared to, so it was decided to compare it with drinking water standards.

The main goal is to clearly demonstrate the difference in heavy metal concentrations. Table 2 shows the concentrations of metals in infiltrate samples from used batteries.

Table 2

Concentrations of heavy metals in infiltrate, mg/L

Sample	Date	Cu (B1)	Cu (B2)	Zn (B1)	Zn (B2)	Mn (B1)	Mn (B2)	Ni (B1)	Ni (B2)	Pb (B1)	Pb (B2)
1	17.11.2023	0.0984	0.1572	51.8	16.26	0.88	3.37	0.97	1.09	0.03	0.041
2	25.12.2023	0.2036	0.158	83.07	62.92	1.69	27.41	0.38	0.85	0.036	0.037
3	01.02.2024	0.0772	0.0684	22.12	16.66	0.7	9.91	0.17	0.67	0.06	0.047
4	29.02.2024	0.09	0.074	64.7	31.11	0.6	20.29	0.11	0.72	0.14	0.026
5	19.03.2024	0.0908	0.0844	69.56	13	0.46	3.25	0.07	0.53	0.063	0.048
6	16.04.2024	0.0948	0.1012	15.38	0.32	0.29	2.02	0.049	0.3	0.039	0.036
7	14.05.2024	0.122	0.1204	0.59	0.05	0.13	1.94	0.06	0.18	0.028	0.027
8	12.07.2024	0.0948	0.0964	0.93	0.072	0.13	0.195	0.03	0.098	0.033	0.018

Note: B1 – Barrel 1 (control); B2 – Barrel 2 (with batteries).

The mean values and standard deviations are shown in Table 3. Cu concentrations are stable (~0.1 mg/L) in all systems. Zn shows peaks in early samples. In the barrel without batteries, concentrations are higher than zinc concentrations in the barrel with batteries, which may indicate the influence of other waste components on its content, such as the presence of metals that may be galvanized. Mn and Ni concentrations are higher in the barrel with batteries, which may indicate the gradual leaching of these elements from the battery mass.

Table 3

Average concentrations of heavy metals mg/L, ± SD

Metal	Barrel 1 (control)	Barrel 2 (batteries)
Cu	0.1089 ± 0.0376	0.1075 ± 0.0327
Zn	38.5187 ± 30.5492	17.5490 ± 19.9188
Mn	0.6100 ± 0.4787	8.5481 ± 9.3971
Ni	0.2299 ± 0.2990	0.5548 ± 0.3219
Pb	0.0536 ± 0.0349	0.0350 ± 0.0099

At the same time, more than 5-fold increase in Mn content was recorded compared to the control sample, indicating a direct impact on the leachate. The lead concentration and its leaching rate are very low, so there is almost no observable difference between the barrels. This also requires a separate, more in-depth study.

The results indicate a differentiated impact of pollutants. The high Zn content in the control barrel (average 38.52 mg/L) is explained by its natural content in solid waste (galvanic coatings, paints). Batteries, on the contrary, reduce Zn (17.55 mg/L), but sharply increase Mn (8.55 mg/L, max 27.41) due to the oxidation of MnO_2, and Ni (0.55 mg/L). There is no exact explanation of higher concentration of Zn in 1st barrel comparing to 2nd. It's possible that waste sample in the 1st barrel contained more zinc than in the 2nd one. This affected the results. However, this requires a more in-dept investigation, which is beyond the scope of this experiment.

All systems exceeded the standards for Mn (B2: >0.1 mg/L in 75 % of samples), Ni (B2: >0.1 in 50 %), Cu (B2: >0.1 in 57 %), and Pb (B1: >0.03 in 25 %). Zn in B1 exceeds 5 mg/L in early samples, indicating a risk to aquatic ecosystems, as demonstrated in an experiment with Daphnia (EC50 for Daphnia magna ~0.1–1 mg/L) (USEPA, 2002).

Table 4 shows data on changes in pH and oxidation-reduction potential (ORP).

Table 4

pH and ORP measurement data

No.	Date	pH in B1	pH in B2	ORP in B1, mV	ORP in B2, mV
1	17.11.2023	Not available	5.17	Not available	94.2
2	25.12.2023	5.35	5.35	86.0	85.7
3	01.02.2024	5.59	5.40	74.6	79.4
4	29.02.2024	5.41	5.30	82.4	83.5
5	19.03.2024	5.48	5.46	79.0	90.1
6	16.04.2024	5.67	5.67	70.0	70.0
7	14.05.2024	5.72	5.74	67.5	66.2
8	12.07.2024	6.06	6.40	51.0	33.0

As can be seen from the pH measurement results, there is a gradual increase in pH, which corresponds to the normal state of waste "maturation", which usually gradually changes from acidic to alkaline (Ishchenko, 2018). The redox potential gradually decreases in both experiments, indicating a gradual leaching of electrolytes from the waste, which is also a normal process.

Variability (SD up to 38 %) is associated with the dynamics of metal dissolution, which depends on pH (4.5–6.5) and organic acids in the infiltrate. Compared to field data (Wang & Qiao, 2024), laboratory values are lower, but the trends are similar. In Fig. 2 we can see that in this case, the change in copper concentration over time is insignificant, and its fluctuations are almost indistinguishable from those in the control barrel.

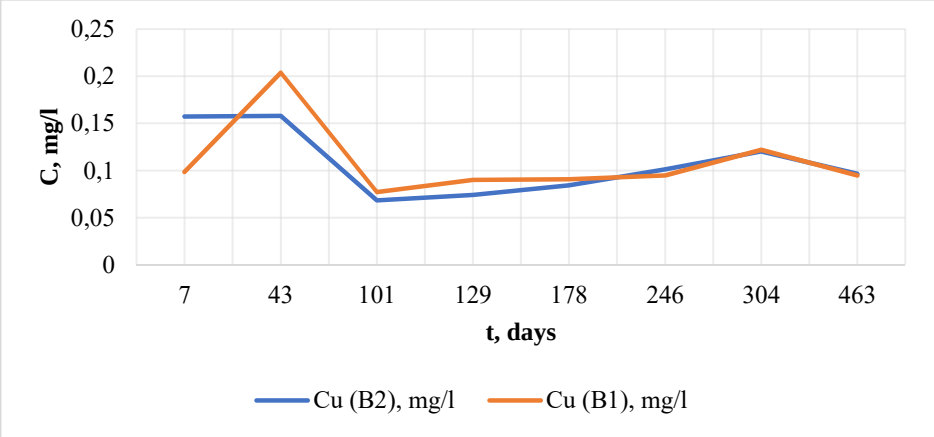

Fig. 2. Change in copper concentrations over time (days) in the infiltrate

Fig. 3 shows that the zinc concentration greatly exceeds the MPC, although the concentration values are lower than in the control barrel.

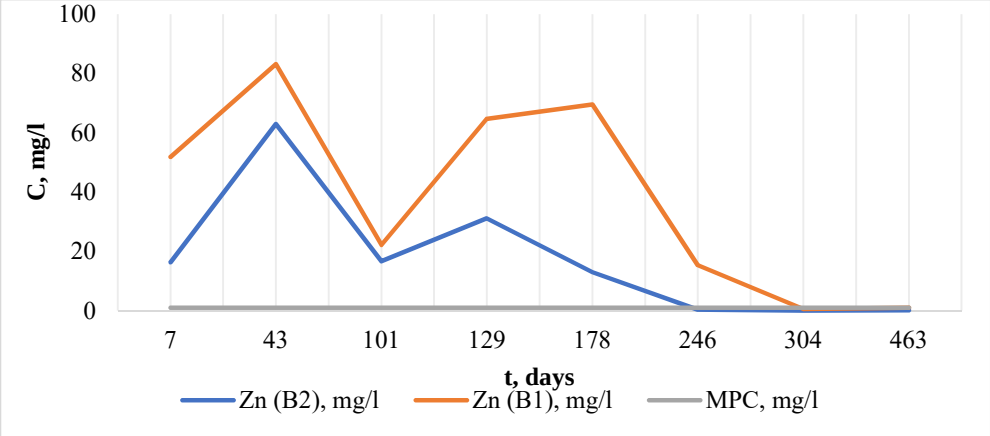

Fig. 3. Change in zinc concentrations over time (days) in the infiltrate

The manganese concentration exceeds the MPC with two peaks in the first half of the experiment, illustrated on Fig. 4. Over time, leaching brings the concentration close to that of the control barrel.

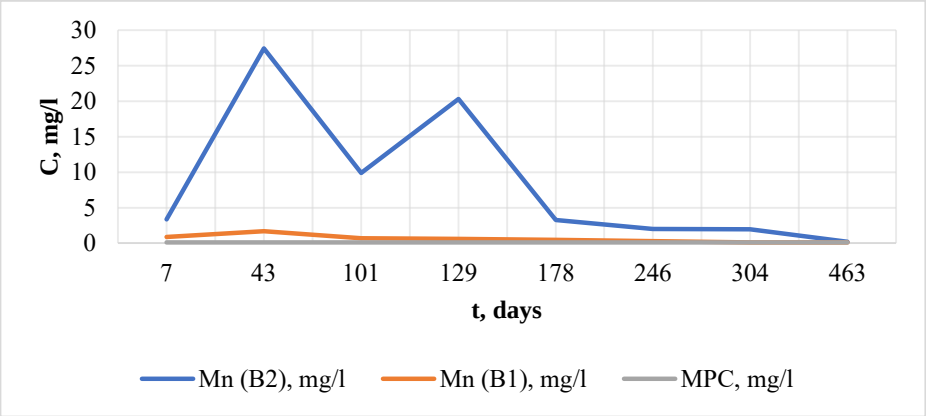

Fig. 4. Change in manganese concentrations over time (days) in the infiltrate

On Fig. 5 we can see that the nickel concentration in both barrels exceeds the MPC. The barrel under investigation has a higher nickel concentration than the control barrel.

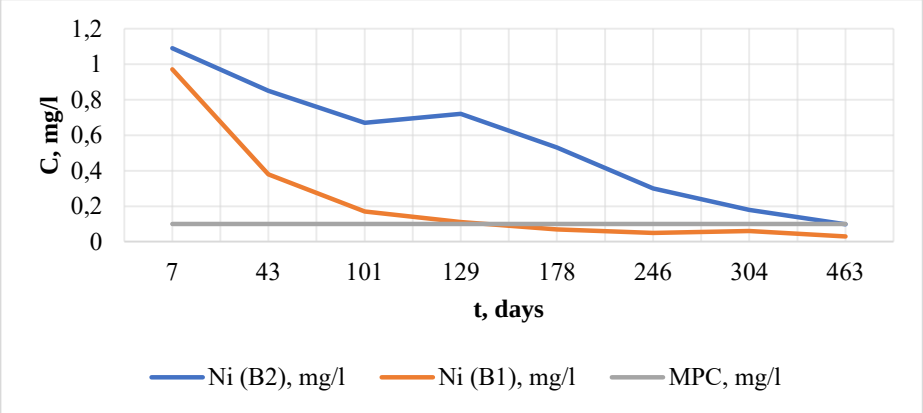

Fig. 5. Change in nickel concentrations over time (days) in the infiltrate

The lead concentration in both barrels is close to the MPC value (Fig. 6).

A significant peak in concentration is observed in the control barrel.

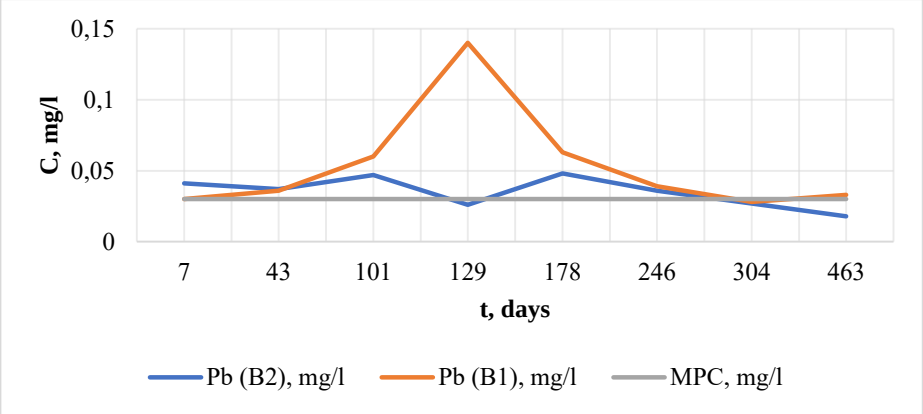

Fig. 6. Change in lead concentrations over time (days) in the infiltrate

The pH values observed are almost identical for both samples (Fig. 7).

This is a natural phenomenon for the landfill maturation process.

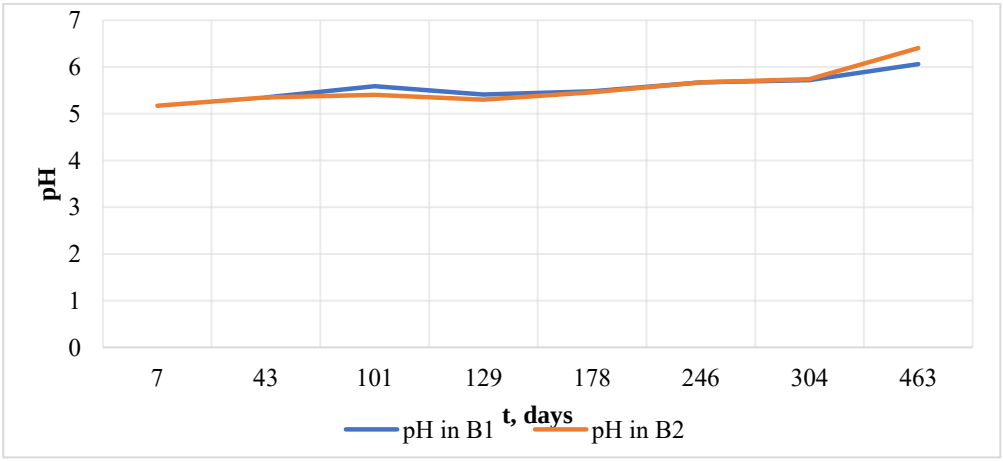

Fig. 7. Change in pH over time (days) in the infiltrate

Also, the change in ORP in the studied barrel is close in value to the control, illustrated on Fig. 8 Limit values for chemical content in water bodies for drinking, domestic, and other needs of the population (MoH in Ukraine, 2022). Background levels are 1000 times lower.

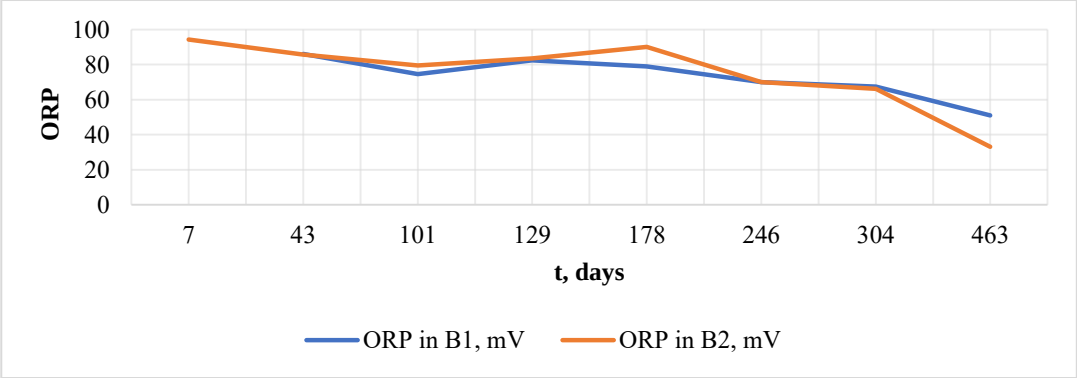

Fig. 8. Change in ORP over time (days) in the infiltrate

Statistical processing. Regression analysis methods were used for mathematical modeling of experimental data dependencies. Data from eight samples were used to calculate the curve equations, where time (x) is expressed in days from the date of the first sample (November 14, 2023, based on Excel serial numbers). Linear regression was used ($y = a{\cdot}x + b$, where y is the metal concentration in mg/L, a is the slope, and b is the intersection with the y-axis). The quality of the fit was assessed by the coefficient of determination R^2 (the closer to 1, the better the linearity). Data days: 0, 36, 94, 122, 171, 239, 297, 456.

The results are presented in Table 5 for each metal separately. The slopes (a) are negative for most, indicating a general trend toward decreasing concentrations over time.

Equations of nonlinear curves describing changes in metal content over time (exponential decay). To model nonlinear dynamics, an exponential decay model was used: $y = a{\times}\exp(-b{\times}x) + c$, where y is the metal concentration, mg/L, x is the time in days from the first sample (November 14, 2023), a is the initial amplitude, b is the decay coefficient, and c is the asymptotic value (equilibrium background). The parameters were calculated using the least squares method (curve_fit from SciPy).

The quality of the fit is estimated by the coefficient of determination R^2 (the closer to 1, the more reliable). Time points: 0, 36, 94, 122, 171, 239, 297, 456 days.

Table 5

Equations of curves (linear regression) of the initial data

Barrel	Equation ($y = a \cdot x + b$)	R^2
Copper (Cu) B1	$y = –0.000070 \times x + 0.121268$	0.067
Copper (Cu) B2	$y = –0.000080 \times x + 0.121707$	0.119
Zinc (Zn) B1	$y = –0.161347 \times x + 67.056947$	0.548
Zinc (Zn) B2	$y = –0.094490 \times x + 34.261947$	0.442
Manganese (Mn) B1	$y = –0.002655 \times x + 1.079564$	0.605
Manganese (Mn) B2	$y = –0.038146 \times x + 15.295226$	0.324
Nickel (Ni) B1	$y = –0.001444 \times x + 0.485227$	0.458
Nickel (Ni) B2	$y = –0.002182 \times x + 0.940652$	0.903
Lead (Pb) B1	$y = –0.000053 \times x + 0.063080$	0.046
Lead (Pb) B2	$y = –0.000048 \times x + 0.043508$	0.462

Note: $R^2 < 0.5$ indicates weak linearity (e. g., for Cu and Pb in B1), which may indicate nonlinear dynamics (e. g., exponential decay). Calculations were performed using Python (scipy stats.linregress).

Table 6

Equations of curves (exponential) of initial data

Barrel	Equation ($y = a \times \exp(–b \times x) + c$) R^2	
Copper (Cu) B1	$y = 0.039646 \times \exp(–0.009549 \times x) + 0.095086$	0.116
Copper (Cu) B2	$y = 0.074201 \times \exp(–0.023188 \times x) + 0.092381$	0.563
Zinc (Zn) B1	$y = 71.060656 \times \exp(–0.004102 \times x) + 0.000000$	0.488
Zinc (Zn) B2	$y = 38.823700 \times \exp(–0.005582 \times x) + 0.000000$	0.428
Manganese (Mn) B1	$y = 1.285546 \times \exp(–0.005532 \times x) + 0.000000$	0.675
Manganese (Mn) B2	$y = 15.972477 \times \exp(–0.004113 \times x) + 0.000000$	0.280
Nickel (Ni) B1	$y = 0.905746 \times \exp(–0.026495 \times x) + 0.057724$	0.995
Nickel (Ni) B2	$y = 1.085388 \times \exp(–0.004855 \times x) + 0.000000$	0.964
Lead (Pb) B1	$y = 0.061586 \times \exp(–0.000808 \times x) + 0.000000$	0.036
Lead (Pb) B2	$y = 0.043572 \times \exp(–0.001322 \times x) + 0.000000$	0.421

Note: For many sets, $c \approx 0$, which indicates complete attenuation to zero.

The results are presented in Table 6 for each metal. Compared to linear regression, the exponential model improves the fit for most data sets, but for Cu and Pb in B1, it remains weak due to high variability.

The best values of the coefficient of determination ($R^2 > 0.95$) were recorded for Ni in all studied barrels compared to the linear model 0.46–0.90. A satisfactory approximation quality was also obtained for Mn for Barrel 1. At the same time, for Barrel 2, the Mn model is characterized by lower reliability due to the presence of pronounced peaks in the data.

4. Conclusions

This experiment clearly demonstrates the impact of batteries on landfill leachate, which, in turn, has negative consequences for the environment. Laboratory modeling confirms that batteries significantly increase the contamination of leachate with heavy metals, in particular Mn and Ni. It was found that the content of the metals studied in leachate samples from a barrel with crushed batteries added significantly exceeded the maximum permissible concentrations. Also, during the experiment, a gradual increase in pH was observed, which is a sign of landfill "maturation." An interesting phenomenon observed during the experiment was a decrease in the content of Zn, but an increase in the content of Mn due to the oxidation of MnO_2 and Ni. It was also found that over time, the content of the metals studied decreases. This is explained by the so-called "leaching" of these elements. For a comprehensive assessment of the dynamics of metal content changes in the studied infiltrate samples, a combination of linear regression methods and an exponential decay model was used. Linear approximation showed that for most metals, their concentration decreases over time. Comparison with the exponential model confirmed the decrease in metal concentrations, but the high variability of the data still shows weak linearity for Cu and Pb in the control barrel. Comparison of metal concentrations in the control and studied (with crushed waste batteries) barrels using linear regression and exponential decay methods allowed us to quantitatively reflect the decrease in concentrations (washout), which makes it possible to potentially predict the achievement of MPC in landfill leachate.

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