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Impact of Fires at Illegal Waste Storage Sites on Soil Contamination—A Study of Five Cases from Poland

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Abstract: In recent years in Poland, there has been an increasing issue with waste management. Despite waste sorting and fees paid by residents for waste collection, many of these waste materials are illegally disposed of. Such formally unclassified waste poses a significant threat to the surrounding residents and exerts toxic effects on soil and as well as surface- and groundwater and also fauna and flora in the vicinity. Due to the significant number of illegal storage site fires in Poland, the authors of this article assessed the impact of five different fires at illegal waste storage sites in Poland on the soil by analyzing the composition of the ashes remaining after a fire. Based on the chemical evaluation of the ashes, it was found that there are substances present in quantities exceeding permissible concentrations. Therefore, the authors concluded that some of these substances may have a negative impact on human health and degrade the surrounding flora and fauna in the storage areas. Consequently, it is essential to exercise stricter control over waste storage locations, classifying the waste left there to prevent adverse environmental and human impacts in case of a fire. Further research is necessary to assess the influence, for example, of leachate following a fire on the quality of the natural environment.

Keywords: landfill fires; illegal dumping; waste; environmental pollution

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1. Introduction

Illegal waste disposal is a serious societal and environmental issue worldwide [1–3]. In recent years, fires at waste storage sites have become increasingly common, caused by spontaneous ignition processes or deliberate actions [4–7]. In Poland, between 2017 and 2022, there have been 754 fires at waste storage sites [8]. Fires at waste storage sites can have a significant impact on the environment, safety, and human health [9]. Depending on the composition of the deposited waste, various toxic compounds can be emitted during a fire [7,10,11]. Storage site fires can pose a substantial environmental threat through air, groundwater, surface water, soil, and crop pollution [12–14]. A survey conducted by Raudonytė-Svirbutavičienė et al. has shown the presence of high quantities of heavy metals (HMs), trace elements, mutagenic compounds, toxic and carcinogenic substances, such as volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs), as well as solid particles [15]. Due to the diversity of waste deposited at illegal storage sites, the quantity and type of substances and mixtures present there are unknown, making it challenging to conduct a meaningful risk assessment [16]. Numerous studies conducted so far have indicated that smoke from waste incineration can negatively affect the respiratory system, increase the frequency of neurological and musculoskeletal symptoms [17], impact reproduction, carcinogenicity, hormonal systems [10], and raise mortality risk [18].

To date, only a small number of studies have focused on waste storage site fires and their environmental impact. Most of the research has centered on fires at legal municipal waste storage sites, which have become a global phenomenon in recent times [11]. Following municipal waste storage site fires, studies have examined leachate comparisons with values obtained during normal operation [4], analyzed food samples (meat, eggs, dairy products, and vegetables) collected near the storage site [10], investigated the spatial distribution of selected pollutants in soil and vegetation [19], and analyzed air quality [20]. Additionally, potential impacts on human health, including respiratory, neurological, and cardiovascular effects, have been studied [17].

Far fewer studies [21,22] have explored the potential impact of illegal waste storage site fires, which may be attributed to limited access to data. Almost all the studies conducted have focused on fires at illegal tire storage sites, as tires represent one of the most hazardous waste materials found in wild dumps [21]. So far, the effects of illegal tire storage site fires on air and soil quality and human health have been investigated [22], soil samples from uncontrolled tire storage site fires have been analyzed using two-dimensional gas chromatography [23], polluted soils with volatile organic compounds (VOCs) and heavy metals after a fire at a tire recycling facility have been studied [15], and toxic substances produced during a fire at an illegal waste storage site have been analyzed [21].

The problem of fires at illegal waste storage sites is not limited to environmental and human health hazards. The process of extinguishing a fire at such storage sites is also important. It requires specialized solutions that take into account the diversity of stored materials. The type of waste also affects the process of removing the specific pollutants generated during a fire, which is crucial for subsequently restoring the ecological balance of the area [24]. Knowledge of the environmental impact of illegal waste storage site fires and the substances emitted during the fire, therefore, has a huge impact on the effectiveness of environmental cleanup efforts.

Despite numerous waste storage site fires worldwide in recent years, to the best of our knowledge, there are only a few studies available in the scientific literature regarding uncontrolled storage site fires and their potential environmental impact. Therefore, the aim of this article was to conduct an initial assessment of five different fires at illegal waste storage sites in Poland on the soil environment. Additionally, selected properties of the residues from waste incineration (ash and slag) were analyzed to identify potential pollutants that could leach from them.

The aim of the research was to answer the questions:

1. What substances are generated during fires at illegal waste storage sites, which often contain hazardous substances?
2. At what distance from the source of contamination does the content of substances generated during a fire in the soil drop the values permitted by the standards?
3. Whether a correlation be found between the type of waste stored and the pollutants generated?

Two research hypotheses were formulated:

Hypothesis 1: *Immediately after the fire outbreak (within 48 h), in windless weather, dry deposition of pollutants in the soil will be observed at short distances from the waste storage site (up to 150 m).*

Hypothesis 2: *There is a correlation between contaminants detected in soil and the composition of waste stored in landfills.*

The conducted research can be valuable in determining environmental changes following illegal waste storage site fires and identifying pollutants that have accumulated in the soil. Furthermore, the research results can assist in developing strategies for dealing with fires at illegal waste storage sites.

2. Materials and Methods

2.1. Study Area

The research was conducted at five illegal waste storage sites located in Poland where fires occurred. The material for the study was collected in the Lower Silesian, Greater Poland, and Łódź voivodeships. The study site selection depended on the occurrence of the fire—investigations were undertaken each time as soon as information about the fire was received. The level of fire damage during the sample collecting at each waste storage site was comparable (approximately 80–90% of the landfilled waste was incinerated). Table 1 presents basic information regarding the five illegal waste storage sites where the research was conducted. All objects were located in arable fields, consistent with the findings of Bihałowicz (2022), who demonstrated that arable land is the most common location for illegal waste disposal in Poland [12].

Table 1. Basic information on illegal waste storage sites covered by the study.

Waste Storage Site	Estimated Area [ha]	Distance from Buildings [m]	Distance from Roads [m]	Location	Examples of Deposited Waste
Site 1	1	200	100	51°6′43.127″ N 16°21′18.015″ E	asbestos (crushed Eternit), construction debris, barrels with remnants of unknown-origin oil, paint cans, rubber (car tires), electrical cable
Site 2	0.5	500	10	51°43′51.98″ N 16°42′15.15″ E	automotive parts, rims, burnt motor oil, body parts, car upholstery, paint cans, electrical cables
Site 3	0.2	100	300	51°9′23.078″ N 17°11′39.947″ E	car tires, asbestos (crushed Eternit), municipal waste, bags with agglomerated construction materials, colored glass, railway ties
Site 4	0.3	1500	500	51°7′20.96″ N 16°26′35.905″ E	bottles and packaging for plant protection products, PET bottles, roofing felt, agricultural foil
Site 5	0.3	1000	20	51°5′18.814″ N 19°14′18.552″ E	paint cans, tar, glass, PET bottles, debris, black plastic film, lacquered wood.

Figure 1 depicts examples of substances and materials found in two burned areas from which samples were taken for the study. The waste remained uncovered and unsecured throughout the entire period.

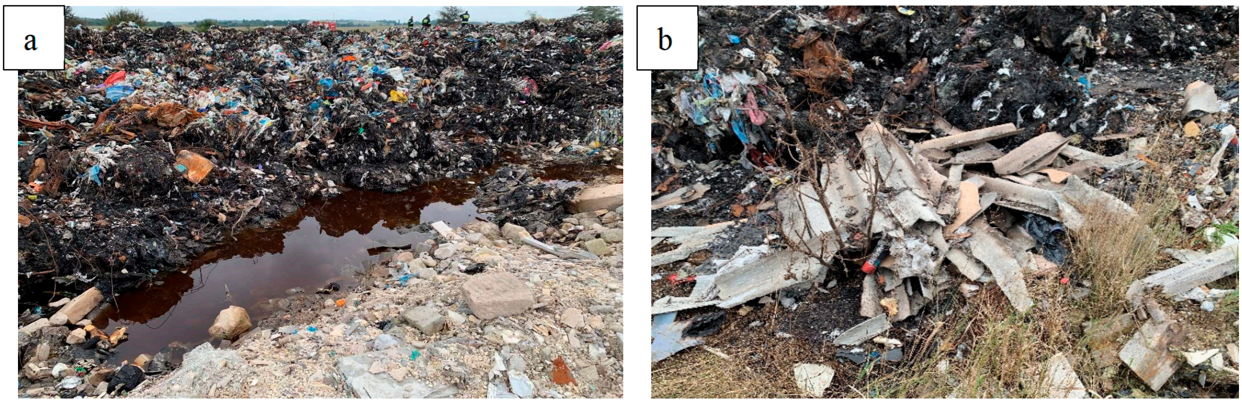

Figure 1. Sample substances and materials collected at two sampling points; (**a**) leachate after a fire; (**b**) waste located at the landfill, including asbestos.

2.2. *Analysis of Samples of Ash from Waste Incineration and Soil in the Vicinity of the Fire Site*

Samples for the study were collected in place of illegal waste storage sites in any case within 48 h of the fire's occurrence. During sample collection, the average air temperature ranged from 20 °C to 22 °C, with air humidity at approximately 70%. Samples of burned waste and soil were collected in sealed containers. The mass of an individual sample was 3 kg. A total of 21 samples of ash and 21 samples of soil were collected from each burned area. The samples were immediately transferred to the laboratory, where further physicochemical analyses were conducted.

Figure 2 illustrates the sampling locations. Soil samples were obtained from the vicinity and at different distances from the site of the fire event, specifically at distances of 25 m, 50 m, 75 m, 100 m, 125 m, and 150 m from the burned area in the direction of wind drift. As the samples were taken immediately after the fire (within 48 h), it was assumed that, given the prevailing low wind velocity, the maximum distance over which dry deposition in the soil would be observed was 150 m. In addition, this was the largest distance, common to all study sites, where soil sampling was possible due to the boundary of a development area or road. Soil samples were collected from the surface layer of soil within the depth range of 0–0.25 m below the surface.

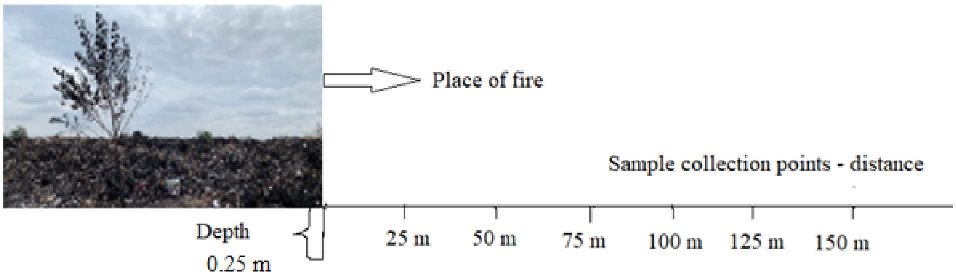

Figure 2. Sampling locations for soil samples for research from illegal waste storage site.

2.3. Physicochemical Analyses of Samples of Waste Incineration Ash and Soil in the Vicinity of Illegal Landfills

The collected samples were immediately transferred to a laboratory that conducted physicochemical analysis. Physicochemical property analyses were performed according to ISO standards (International Organization for Standardization). Laboratory analyses that did not require sample mineralization were conducted within 24 h of sample collection [25]. Mineralization was also carried out, followed by analyses that required it. The following properties of ash from waste incineration and soil in the vicinity of illegal disposal sites were determined: chlorides, fluorides, sulfates, dissolved organic carbon (DOC), total organic carbon (TOC), total dissolved solids (TDS), phenolic index (PI), BTEX (benzene, toluene, ethylbenzene, and xylene), polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs), as well as mineral oil. Additionally, concentrations of trace elements (As, Ba, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, Zn) were examined. Table 2 presents the scope of individual determinations for substances included in the study. Additionally, the legal basis for the applied research methodology and the specified determinability of substances are provided.

Sample analysis was conducted using laboratory equipment. Gas chromatography with electron capture detection (Labindex, Model GC 102 AF, Warsaw, Poland) was employed for PCB analysis, while gas chromatography with mass spectrometry surface analysis (EnviSense, Model GC-MS 6800, Lublin, Poland) was used for BTEX and PAH analysis. Elemental analysis was carried out using atomic spectrometry (RIGOL Beyond Measure, Model DSA815, Rygol, Poland), and chlorides were analyzed using an automatic titrator (Mettler-Toledo, Model HI901C, Warsaw, Poland). Sulfate analysis was conducted using a muffle furnace (Alchem Grupa, Model SNOL 8.2/1100 LSM01, Toruń, Poland), and fluorides were analyzed using an ion meter (Atest, Model CPI-502, Kielce, Poland). All examined ash samples from the five illegal waste disposal sites after a fire, in accordance with the Regulation of the Minister of Climate of 2 January 2020, concerning the waste catalog (Journal of Laws 2020, item 10), were classified as waste with code 19 01 12, meaning they are non-hazardous furnace slag and ashes.

Table 2. Legal foundations for individual determinations made during the research, as well as detection and quantification limits for the analyzed substances.

Detection Limit for the Tested Substance, mg/kg dw.	Research Method Characteristics—Legal Foundations
Arsenic (0.025–50)	
Barium (0.010–1000)	
Cadmium (0.005–5000)	
Chromium (0.030–5000)	
Copper (0.040–10,000)	
Mercury (0.010–10)	
Molybdenum (0.040–1000)	
Nickel (0.040–5000)	
Lead (0.10–5000)	
Antimony (0.025–10)	
Selenium (0.025–10)	PN-EN ISO 11969:1999, PN-EN 12457-4:2006 [26,27]
Zinc (0.050–10,000)	PN-EN ISO 11885:2009, PN-EN 12457-4:2006 [27,28]
Benzene (0.020–15)	
Toluene (0.020–15)	
Ethylbenzene (0.020–15)	
o-Xylene (0.020–15)	
Total Monoaromatic Hydrocarbons (BTEX) (from 0.020)	PN-EN ISO 22155:2016-07 [29]
PCB 101 (0.020–2.0)	PN-ISO 10382:2007 [30]
Mineral Oil (C10–C40 hydrocarbons) (20–20,000)	PN-EN 14039:2008 [31]

2.4. Statistical Analysis

The obtained research results were subjected to statistical analysis using software, namely Origin Pro 2022b (OriginLab Corporation, Northampton, MA, USA), Statistica 13.3 (StatSoft Polska, StatSoft, Inc., Tulsa, OK, USA), Microsoft Office 2013 and 2021 (Microsoft, Richmond, WA, USA). The analysis of selected contaminants was characterized using Principal Component Analysis (PCA), which allowed for an initial assessment of how individual parameters determine the pollution state and the relationships between variables within the extracted components (for $p < 0.05$). Additionally, a Hierarchical Cluster Analysis (HCA) was conducted on the normalized dataset using Ward's method and Euclidean square distances as a measure of similarity. The results were presented on a dendrogram.

3. Results and Discussion

3.1. Analysis of Selected Trace Elements in Ash Samples from Wildfires and Illegal Waste Dumps

Waste composition analysis is considered one of the most valuable resources for those responsible for proper waste management [32]. Identifying the types of waste contained in illegal waste storage sites is particularly challenging, especially after a fire. Studies of incineration ashes play a significant role in identifying potential pollutants that can be leached from them [33]. The European Environment Agency's 2016 report highlighted that special attention should be paid to the emission of metals such as Pb, Cd, Hg, As, Cr, Cu, Ni, Se, and Zn during waste incineration [20], and therefore, the analysis was conducted in this scope. Furthermore, heavy metals are known for their toxicity, bioaccumulation potential, high mobility, and environmental persistence, posing a threat to the environment and human health [34], making their analysis highly important. Figure 3 shows the contents of selected trace metals in ashes sampled from 5 illegal waste storage sites.

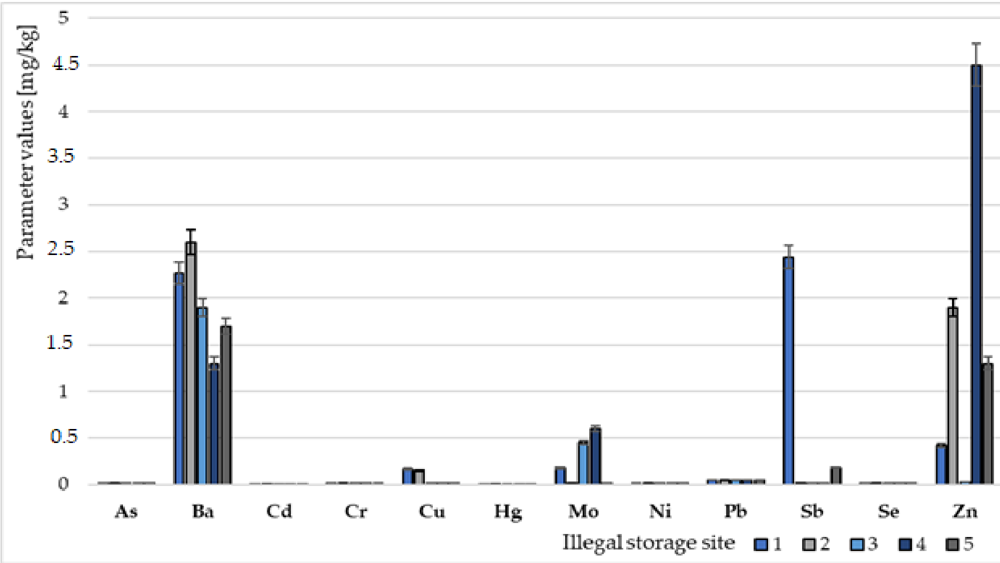

Figure 3. Content of trace metals [mg/kg] in ashes from 5 illegal waste storage sites.

The analyses of waste incineration ashes showed that the content of trace metals is generally low (i.e., <1.0 mg/kg) in most cases. Only in the case of Ba, its values exceeded 1.0 mg/kg in all variants. Higher values were also observed for Zn in ashes from three sites, with values exceeding 1 mg/kg. The highest Zn content was recorded in the ashes from site 4, reaching 4.5 mg/kg. Slightly elevated contents were also noted for Mo but did not exceed 1 mg/kg. As reported in the literature, commonly occurring metals in ashes include Cu, Zn, Cr, Ni, Cd, Hg, and Pb. Among them, Cu, Zn, and Pb usually occur in the highest quantities [35]. In the analyses conducted on five sites, no high contents of Cu and Pb were found; only elevated Zn contents were observed.

Filipponi et al. (2003) also identified Zn as one of the main trace elements in incineration ashes from municipal waste incinerators, a finding confirmed by the present study [36]. Similarly, Rykała et al. (2022), while analyzing ashes from an illegal waste storage sites fire, observed that Zn constituted the largest share of metals, although at significantly higher levels compared to this study, averaging 18.47 mg/kg [21].

3.2. Content of Selected Compounds in Samples of Ash from Wildfires and Illegal Dumps

In the ash samples from five burnt waste storage sites, the contents of other parameters, such as chlorides, sulfates, and mineral oils, were also analyzed and are presented in Figure 4.

The results of physicochemical analyses indicate that the analyzed ash samples were most contaminated with sulfates (sites 3, 4, and 1) and mineral oils (sites 4, 2, and 5), as well as chlorides (sites 1, 3, and 4). High sulfate content (exceeding 1000 mg/kg) was observed in the ashes from three illegal waste storage sites, likely due to a significant proportion of burnt tires, rubber, and foam in these samples [18]. Previous studies on illegal waste storage sites have shown that many of them contain hazardous compounds, such as mineral oil or tire residues [37], which is confirmed by the results obtained for most of the samples. The presence of hazardous waste, including mineral oils, was observed at all the investigated illegal waste storage sites. On one of the storage sites (site 4), the content of mineral oils reached as high as 14,000 mg/kg, while on the other sites, the values ranged from 4900 mg/kg (site 2) to 1200 mg/kg (site 5), 853 mg/kg (site 1), and 380 mg/kg (site 3). Almost all sites recorded significantly higher chloride contents than reported in the literature. According to Tomaškinová et al. (2014), the chloride content in waste at the largest illegal landfill in the Końska Diera chasm in Slovakia was below 40 mg/kg [38]. Rykała et al. (2022) reported an average chloride content of 51.9 mg/kg, with maximum values reaching 320 mg/kg [21]. In the present study, only at site 2 were these values below 40 mg/kg (25 mg/kg), while at the other sites, they were significantly higher and ranged from 187 mg/kg (site 5) to 4907 mg/kg (site 1), which may result in a higher level of risk to the environment and people. Furthermore, in the collected ash samples from wildfires at illegal waste dumpsites, the contents of fluorides (F), BTEX (benzene, toluene, ethylbenzene, and xylene), polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) were analyzed and are presented in Figure 5.

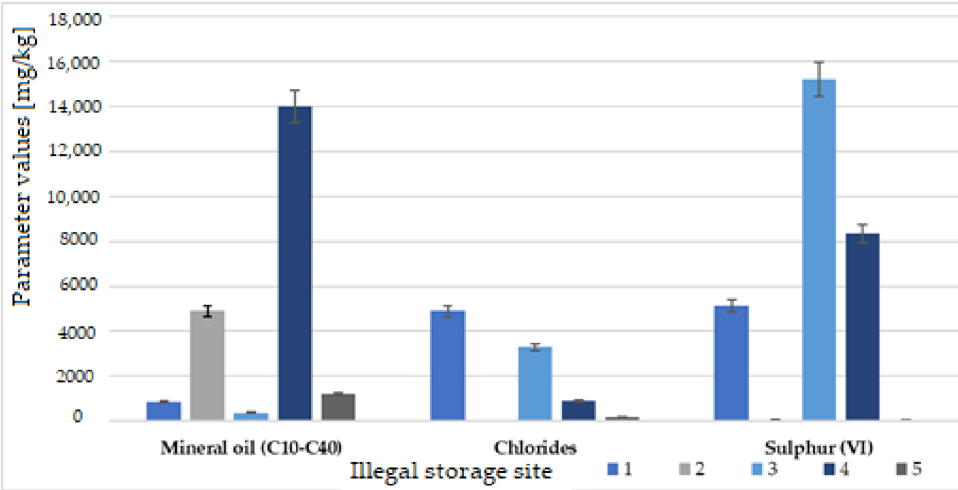

Figure 4. Content of selected compounds [mg/kg] in ashes from 5 illegal waste storage sites.

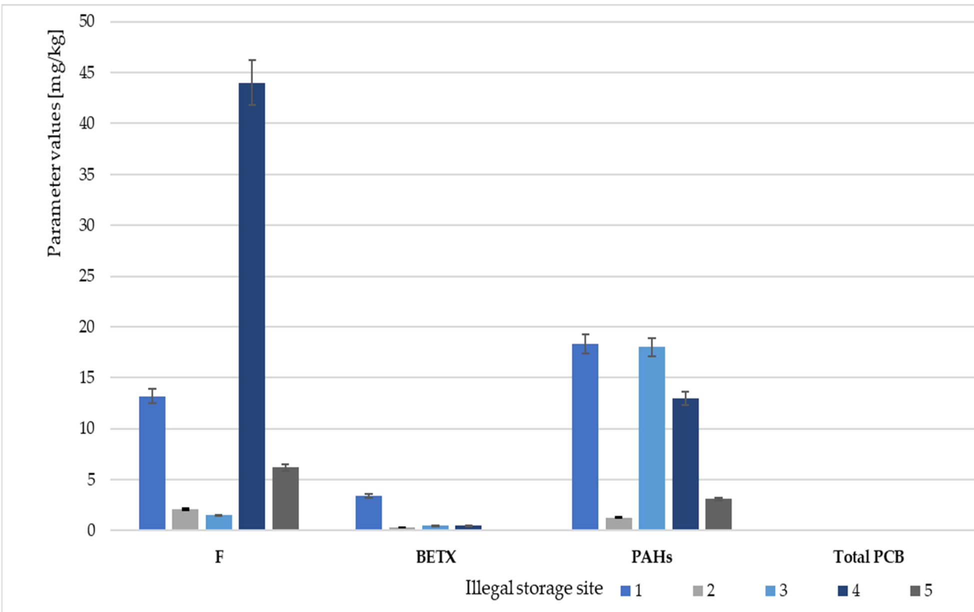

Figure 5. Others compounds [mg/kg] in ashes from 5 illegal waste storage sites.

Residues indicating the presence of paints, pesticides, various solvents, or electronic waste were found at the investigated waste storage sites from which samples were taken after the fires. Since such industrial waste may contain BTEX compounds that can be released directly from waste materials [39], the collected samples were analyzed for their presence. Special attention was paid to this because BTEX compounds are highly toxic and even carcinogenic [40], and they also exhibit high solubility in water compared to other fuel components, contributing to their high mobility in the environment [41]. However, in the ashes from the five illegal waste storage sites, BTEX remained at a low level; only at one illegal storage site, the values were slightly elevated (just below 3.5 mg/kg). Fluorides are considered one of the main pollutants causing environmental degradation, and they have received much attention due to their harmful effects not only on the environment but also on the health of humans and animals [42,43]. Therefore, chemical analyses included the fluoride content in the analyzed samples. In all samples from the five sites, fluoride contents were elevated (>1 mg/kg) and reached up to 44 mg/kg in the ashes from the fourth site.

Tomaškinová et al. (2014), during their analysis of waste composition at the largest illegal waste storage site in the Końska Diera chasm in Slovakia, recorded values of fluorides below 1 mg/kg [38]. Open burning, due to unfavorable combustion conditions, typically leads to the formation of particulate matter (PM), semi-volatile organic compounds including polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds including polychlorinated biphenyls (PCBs). PCBs are persistent pollutants known for their bioaccumulative and toxic properties [14]. As the literature indicates, the most significant source of dioxins in the environment is the intentional or accidental burning of household waste in municipal or illegal landfills [10]. However, PCBs were not detected in the analyzed ash samples from any of the sites.

PAHs are widely distributed harmful organic compounds that raise serious concerns regarding human health and the environment. They typically persist in soil for extended periods due to their relatively low mobility and high resistance to degradation, making them challenging to remove [44–46]. Literature suggests that PAHs belong to the main group of organic pollutants generated in open-burning processes, a claim not confirmed by the conducted research [40]. The levels of PAHs in the ashes from the five illegal waste storage sites ranged from 1.3 mg/kg (site 2) to 18.3 mg/kg (site 1). The highest concentrations of PAHs were recorded in the ashes from sites 1 and 3 at levels of 18 and 18.3 mg/kg, respectively. These higher values in these two cases may be attributed to the large quantities of tires deposited at these storage sites, which can release PAHs into the environment after their combustion [15]. Analyzing pollutants leached from such waste after fires at illegal waste storage sites, it can be observed that heavy metal contamination constitutes a smaller portion compared to organic compounds, as observed by other researchers, such as Rykała et al. [21].

As the obtained results show, ash from incineration can contain elevated levels of trace metals (Zn, Ba) and organic pollutants (PAHs, sulfur, and chlorides), which can be sources of environmental issues. Therefore, the final disposal of incineration ashes should always be preceded by physicochemical analyses and verified with respect to factors specific to the particular location, legal requirements, and possibilities for further utilization or disposal.

3.3. HCA Analysis

The results of the Hierarchical Cluster Analysis (HCA) are presented in the form of a dendrogram, where the distance axis represents the degree of association between groups of variables, i.e., the lower the value on the axis, the more significant the association (Figure 6).

The clustering analysis was performed on data related to the content of trace elements (As, Ba, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, Zn), as well as chlorides, fluorides, sulfates, PI, BETX, PAH, PCB, and mineral oils. This was conducted to detect spatial similarities and differences and group the sampling locations. The obtained dendrogram (Figure 6) allowed for the grouping of the five illegal waste storage sites into two statistically significant clusters (cluster 1 and 2). These clusters were delineated based on differences in the average content of selected pollutants (As, Ba, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, Zn), chlorides, fluorides, sulfates, PI, BETX, PAH, PCB, and mineral oils observed at the analyzed points. The analysis facilitated the identification of four groups, with one group further divided into two subgroups. The strongest association was found between sites 5 and 2, possibly due to the deposition of a similar type of waste at these two illegal waste storage sites. It shows that knowledge of the type of waste accumulated in the waste storage site is crucial when choosing how to extinguish a fire, and allows for predicting what pollutants will be found in the surrounding soils after a fire. Therefore, further research on the pollutants emitted during the incineration of different types of waste is needed.

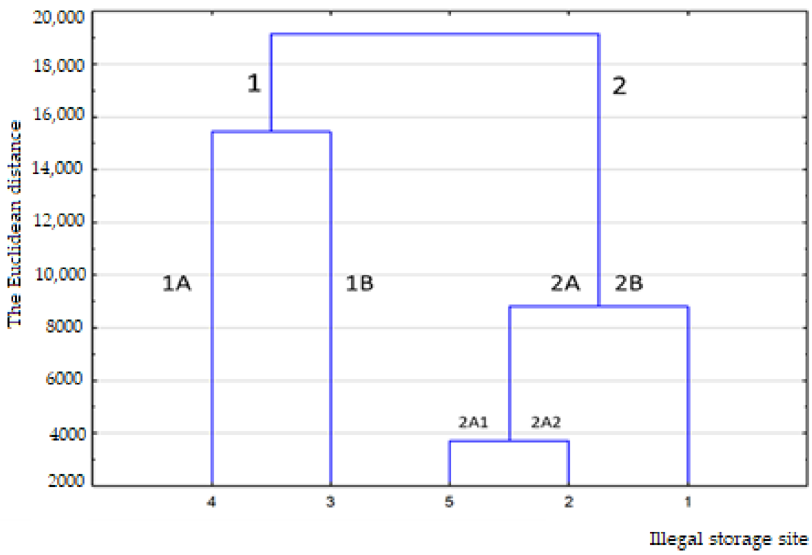

Figure 6. Dendrogram of selected pollutant content in analyzed ash samples based on hierarchical cluster analysis.

3.4. PCA Analysis

Principal Component Analysis (PCA) can be used to assess the correlations between multiple parameters, allowing for the evaluation of correlations among a large number of variables with minimal data loss [47]. It can also be employed to select the parameters that best characterize a given phenomenon by reducing the number of dimensions [48]. In Figure 7, the results of PCA for the chemical composition of ashes from waste fires at five illegal waste storage sites are presented. The analysis revealed that the first four components collectively explained nearly 100% of the variability in the research results.

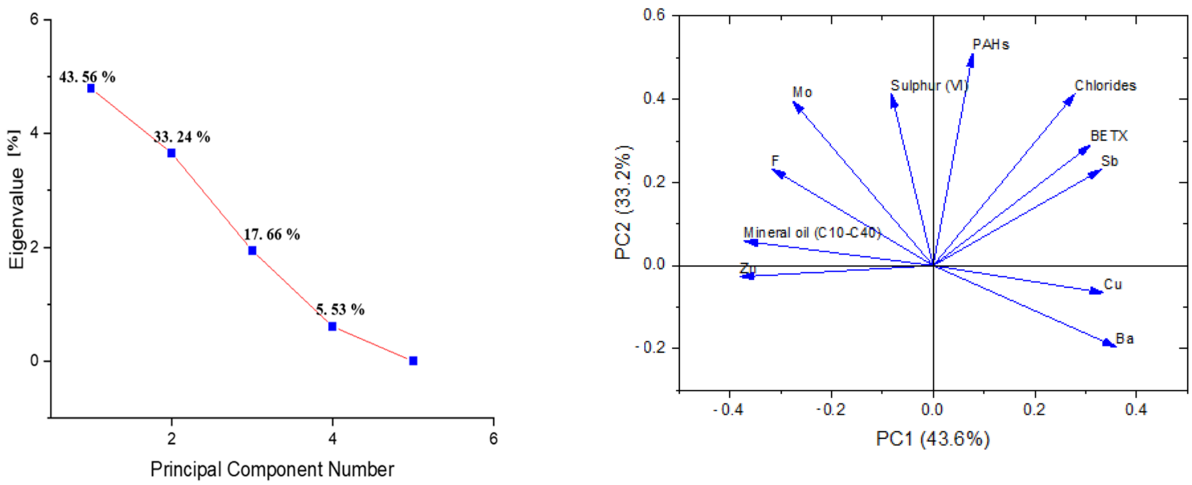

Figure 7. PCA results.

The first principal component (PC 1), explaining 43.56% of the variability in the ashes' research results, had the most significant (positive) influence from the content of copper and barium. Conversely, PC 1 exhibited the strongest negative correlations with zinc content. The second principal component (PC 2), explaining 33.2% of the variability in the research results, showed the most negative correlation with barium content.

The analysis of relationships between variables characterizing the properties of ashes from the five sites demonstrated negative correlations between fluorides (F) and barium (Ba) as well as copper (Cu) and mineral oils. The negative correlation between the two pairs of substances may be due to the specific composition of the accumulated waste in the analyzed waste storage sites.

3.5. Content of Selected Compounds in Soil Samples at Different Distances from Illegal Waste Storage Site

In the first part of the study, it was demonstrated that all obtained substances do not meet the criteria for inert waste. This primarily results from the factors identified, namely chlorides, fluorides, sulfates, DOC, TDS, TOC, PAH, and mineral oil. However, all substances meet the criteria for classification as hazardous material storage. Figure 8 illustrates the relationship of certain elements with respect to the distance from the waste fire site. The presented data clearly show how the content of these substances in the soil changes as one moves away from the fire site. Two elements, barium and zinc, merit special attention. Between distances of 25 m and 125 m from the source, the content of these elements decreases by up to 50%.

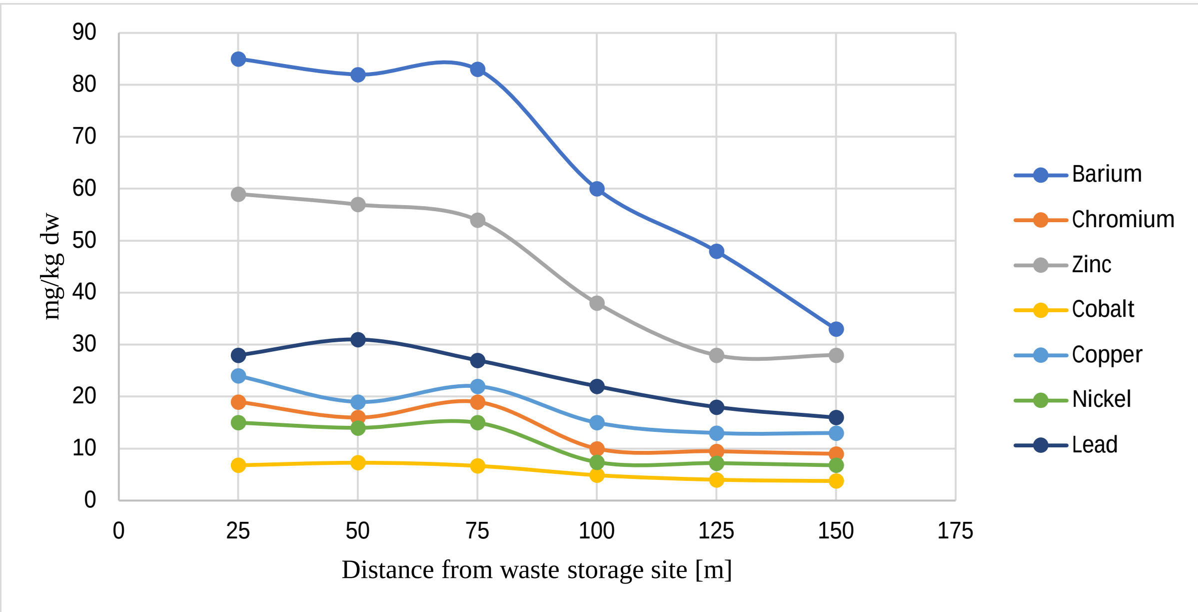

Figure 8. Heavy metals contents present in the vicinity of the studied waste storage sites.

Additionally, the analysis indicates that among the substances generated at the fire site were dioxins and heavy metals. The migration of heavy metals into the environment may also lead to serious threats to human health [49,50]. Figure 9 also presents the results of benzene presence. Within a distance of up to 100 m from the waste storage site, the values of all analyzed substances no longer exceed acceptable standards. The greatest amounts of the benzo(b)fluoranthene and benzo(a)pyrene were located between 50 and 70 m from the waste storage site, 0.65 and 0.45 mg/kg dw, respectively. The lowest values in this range occurred for dibenzo(a,h)anthracene.

Quina et al. (2008) [51] and Lindberg et al. (2015) [52] identified similar elements in their chemical studies after waste fires, such as As, Cr, and Hg, based on the analyzed residues from burned waste. Pereira, P., et al. (2012) identified substances present in ash from burned waste based on their color [53]. Based on these results, it was turned out, that the variables showed a statistically significant difference in results between substances that occurred in illegal waste storage sites after fire depending on distance from these places (25–150 m), the *p*-value was 0.043. The results presented in this article pertain to the post-fire condition and are representative of the moment of sample collection. The primary limitation of these studies is their reliance on a limited number of samples. Due to the complex composition of the present compounds with varying physicochemical properties, spatial variation in the environment can be expected over time. The research was conducted also in response to the concerns of firefighters who are tasked with extinguishing fires at illegal waste storage sites and who are exposed to toxic substances emitted during fires. Therefore, the focus was on conducting analyses at the specific moment when firefighters were present on-site. This topic is also of interest to scientists and addresses the limited information available regarding fires at illegal waste storage sites. This study is also relevant for informing residents about the associated risks.

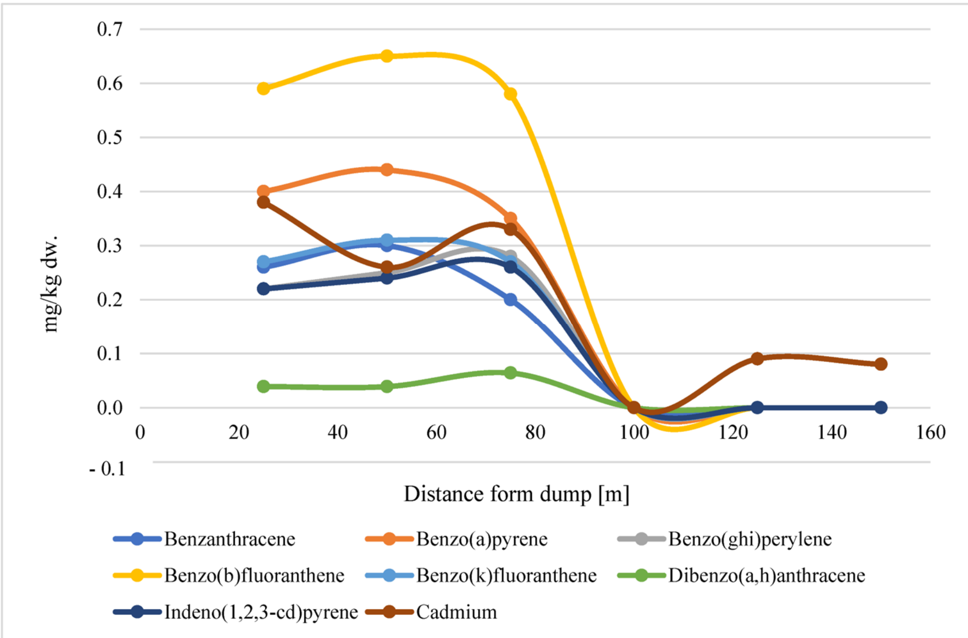

Figure 9. Substances present in the vicinity of the studied waste storage sites.

4. Conclusions

The soil samples around five illegal waste storage sites, where fires occurred (at distances of 25 m, 50 m, 75 m, 100 m, 125 m, and 150 m from the burn area), as well as ashes from burned waste, were analyzed to conduct a preliminary assessment of the impact of five illegal waste storage site fires on the soil environment and identify potential pollutants that could leach from them. The analysis revealed that some of the waste accumulated at the five analyzed illegal waste storage sites exhibited hazardous properties.

1. Analyzing the pollutants leaching from such waste after fires at illegal waste storage sites, it can be observed that heavy metal pollutants constitute a smaller proportion compared to organic compounds. In the analyzed samples, significantly elevated levels of trace metals were not observed, with only slightly increased concentrations of Zn (up to 4.5 mg/kg) and Ba (up to 2.7 mg/kg) noted.

2. However, the presence of mineral oils was detected at most illegal waste storage sites, ranging from 380 mg/kg (site 3) to as high as 14,000 mg/kg (site 4). Significantly higher chloride concentrations than reported in the literature were observed at nearly all sites. In the present study, chloride content ranged from 25 mg/kg (site 2) to 4907 mg/kg (site 1). High sulfate content (exceeding 1000 mg/kg) was identified in the analyzed ash samples from three illegal waste storage sites, likely due to a significant contribution of burnt tires, rubber, and foam.

3. No presence of PCBs was found in the analyzed ash samples from any of the sites. However, elevated fluoride levels (>1 mg/kg) were present in all samples from the five sites, reaching up to 44 mg/kg in ashes from site 4. The content of PAH in the ashes from the five illegal waste storage sites ranged from 1.3 mg/kg (site 2) to 18.3 mg/kg (site 1). Higher concentrations of PAH (18 and 18.3 mg/kg) were recorded at two sites where tires had been deposited.

4. Hierarchical Cluster Analysis (HCA) allowed for the identification of four groups, with one group further subdivided into two subgroups. The strongest association was found between sites 5 and 2, possibly due to similar types of waste being deposited at these two illegal dumping sites.

5. Considering the obtained results, it appears necessary to expand the analysis to assess the influence of local meteorological conditions in the near-surface layer of the atmosphere (wind speed and direction, air temperature, precipitation) and terrain conditions (terrain topography and cover) on the spread of pollutants from waste storage sites fires—development of a universal model.

6. The conducted research indicated that almost all waste samples do not meet the requirements imposed on waste storage in neutral landfills. The main degrading factors were parameters such as chlorides, fluorides, sulfates, PAH, and mineral oil.

7. The research results suggest that exceedances of permissible PAH values in the topsoil occurred at distances ranging from 25 to 75 m downwind (northeast direction) from the burn area.

Both hypotheses were confirmed. Confirmation of the first hypothesis is particularly important from the point of view of inhabitants of nearby villages and firefighters extinguishing the fire. Immediately after the fire, inhabitants are not exposed to dry deposition of toxic substances generated during the combustion process. That is why it is so important to extinguish the fire quickly, which can protect the soil in home gardens from contamination with harmful combustion products. Firefighters are exposed to toxic substances, which is why their use of personal protective equipment is so important.

Confirmation of the second hypothesis is very important in terms of extinguishing the fire and removing its effects (including reclamation). Since the composition of waste collected in illegal waste storage sites is most often unknown, based on the analysis of soil samples in the immediate vicinity of a burning or burned waste storage site, it would be possible to determine what type of waste was stored. On this basis, it would be possible to determine how to extinguish the fire or how to reclaim the area. However, this requires further research on the pollutants emitted during the incineration of different types of waste. Further research mainly will focus on volatile substances that may cause cancer among firefighters. The occupational risk of hazards occurring while staying at the waste storage site will also be calculated.

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