sustainability

Review

Causes, Types and Consequences of Municipal Waste Landfill Fires—Literature Review

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Abstract: The amount of municipal waste produced worldwide has seen a significant increase in recent years. The need to store waste is a significant problem in the context of environmental threats and spatial development. Due to the fact that the easiest way to reduce the amount of waste is to incinerate it, and despite the fact that waste incineration plants have existed since the late 1800s, the amount of illegal waste burning and landfills has also increased. Subsurface landfill fires are particularly dangerous, as they can affect the structure of the landfill. Methane also plays an important role in fires as it is flammable and contributes to the spread of fire. In addition, the leachate from incinerated waste is much more dangerous than the leachate from waste in its natural state. The effluents from incinerated waste include heavy metals and persistent organic pollutants, as well as sulphates, chlorides, and polycyclic aromatic hydrocarbons. Other pollutants also end up in the atmosphere. The aim of this article is to present the problem of landfill fires and their impact on air, soil, and water, based on a review of the selected documented fires as well as indicators of fires in the areas in which the authors of this article conducted their research. The article presents an overview of methods and tests, such as dynamic leaching tests, monitoring tests, and lysimetric tests, all of which can be implemented to prevent fires as well as for research purposes after a fire has occurred, so that this article can be utilitarian not only for researchers, but also for decision makers.

Keywords: landfill; fires; hydrogeology; waste; leaching

Citation: Dabrowska, D.; Rykala, W.; Nourani, V. Causes, Types and Consequences of Municipal Waste Landfill Fires—Literature Review. *Sustainability* **2023**, *15*, 5713. https://doi.org/10.3390/su15075713

Academic Editors: Shifeng Lu, Benyi Cao and Zhengwei Chen

Received: 20 February 2023
Revised: 20 March 2023
Accepted: 23 March 2023
Published: 24 March 2023

1. Introduction

Due to its associated costs, landfill is one of the most common means of disposing of municipal waste [1,2]. Such costs mainly relate to the occurrence of three phases of waste transformation—physical, chemical, and microbial—and to the impact of waste on the environment. However, uncontrolled use of landfills is a major economic and environmental problem. Due to economic development and population growth, waste production continues to increase [3,4]. According to a forecast by the World Bank, by 2025, the global production of solid waste in cities will have increased by over 70%, amounting to as much as 6,100,000 tons per day [5]. The physical and chemical degradation of land is a typical consequence of uncontrolled landfills [6]. For this reason, landfill sites are at least potential (if not yet actual) sources of pollution, causing soil and groundwater contamination [7,8]. In order to reduce the amount of waste, numerous methods of waste disposal have been developed and used, such as incineration [9]. After incineration, the mass of waste may decrease by up to 70% [10]. This fact makes waste incineration the most popular type of disposal. Municipal waste that is incinerated in incineration plants undergoes compliance tests to determine whether it meets the necessary standards to be disposed of in this way. There are two types of incineration plant: refuse-derived fuel, and mass burning [11]. One of the significant advantages of incinerating waste in incineration plants is the possibility of producing energy [12]. Over 250 million tons of waste are burned worldwide annually [13,14]. Asian countries such as China incinerate the most waste, burning about 30% of this total. Data on waste management in the European Union indicate that incineration is one of the most common waste treatment strategies; approximately 70% of waste is dealt with in this way [15].

The situation is completely different when waste is burnt in an uncontrolled manner. The risk of spontaneous fires is not specific to any particular phase of disposal but exists both for fresh waste and for that deposited earlier. In addition to the negative impact on the aquatic environment [16], illegal landfills can also affect human health [17] and destroy natural habitats [18]. In conjunction with the introduction of regulations on waste management which have increased the costs of waste storage, the problem of people deliberately setting fire to landfills has also emerged. The problem of landfill fires is not a local one. For example, in Poland in 2019 there were 4.65×10^{-6} landfill fires per 1 million inhabitants [14], and in the USA there are 2.56×10^{-5} landfill fires per 1 million inhabitants annually [19]. In Serbia, only one district has around 1000 fires per year [20]. Landfill fires can be broadly divided into surface and subsurface fires [21]. The former is less dangerous because firefighters can react to it quickly as long as it does not cover a large area [22]. However, subsurface fires can have much more significant consequences, including those caused by damage to the structure of the landfill [23,24].

Municipal waste often contains various substances such as heavy metals, persistent organic pollutants, sulphates, chlorides, polycyclic aromatic hydrocarbons from batteries, treated wood discards, and discarded electronic devices [25]. Old disused landfills, the structure of which is heterogeneous, also pose a threat as the type of waste contained within them is difficult to determine [26]. Burnt waste contains residuals in the form of ash and slag [27]. Since these residuals are treated as hazardous waste, the leaching of pollutants from them is a threat to groundwater [28]. The leachate from waste incineration poses a much more significant threat to groundwater than the leachate from untreated waste, due to the higher mobility of the components of incinerated waste [29]. Among the most well-known pollutants released into the atmosphere during combustion, attention should be paid to carbon monoxide and dioxide, nitrogen oxides, hydrochloric acid, hydrogen cyanide, volatile organic compounds, persistent organic pollutants, ketones, aldehydes, and PM [30]. The leaching of pollutants into the aquatic environment (as well as emission of pollutants into the atmosphere) can be observed in various types of fires, e.g., tire dump fires [31], landfill fires [32], and long-lasting landfill fires [33]. Below is a photo showing an example of the waste from a dump (Figure 1).

Figure 1. Burnt waste (photo W. Rykala).

The aim of this article is to discuss the problem of landfill fires and their impact on the soil, water, and air, based on a review of the literature and of indications in the areas in which we, the authors of this article, chose to conduct our research. In recent years, many new landfills have been burned down in Poland. We selected three, where research was already being carried out; landfills in Trzebinia [34], Sosnowiec (southern Poland), and a landfill in Sobolew (in the south-western part of Poland). Samples of waste, soil and leachate were simultaneously collected in two series from, which were then subject to GC–MS analyses (performed at the University of Silesia). Physicochemical analyses (measuring electrical conductivity (EC), in addition to Cl^-, $SO_4{}^2$, nitrogen compounds, B, Cr^{6+}, Cu^{2+}, Zn^{2+}, Pb^{2+}, Hg^{2+}, Co^{3+}, and Ni^{2+}) are being performed in an accredited laboratory, but these analyses are currently in progress. This article highlights the problem of the global environmental threat caused by the migration of pollutants from incinerated waste, indicates possible solutions to such fires, and brings it into the realm of current research.

2. Causes and Mechanisms of Landfill Fires

Unfortunately, landfills are increasingly a threat to the natural environment and its inhabitants as a result of fires. Uncontrolled fires in landfills can be caused, inter alia, by sparks from machinery being operated in the landfill, uncontrolled lightning, and self-ignition [24]. A fire in a landfill can spread because the resulting chemical reaction produces heat. This, in turn, leads to a situation where the waste is kept above the temperature needed for decomposition and incineration. High temperatures from an existing fire can heat the surrounding garbage to the point of pyrolysis. The biological and chemical degradation of the constituents of solid municipal waste leads to an increase in temperature within solid municipal waste landfills [35]. Many studies have observed that self-ignited fire is caused by heat generated from aerobic processes after oxygen has been introduced into anaerobic landfills [36]. In addition, it should be mentioned that anaerobic decomposition releases methane, which is explosive when its presence in the air reaches between 5.3 and 13.9% [37]. Methane emissions from landfills also are affected by site-specific factors such as waste composition, available moisture, and landfill size. The lack of a system for collecting gas from landfills increases the possibility of them producing methane, among other such things. This allows the uncontrolled migration of gas, enabling it to pose a fire and explosion hazard [38]. It is necessary to maintain good heat dissipation in landfills so that hot waste is not stored in one place and landfill fires can be avoided [35]. Intentional arson should also be included among the possible situations that may lead to fire in landfills. This is a very common reason for landfill fires around the world. The most common reason for this type of activity is to get rid of residual waste, which is most likely due to its being located in an unauthorized place, or whose contents are illegal and highly toxic. In addition, the widespread use of landfills, difficulties in waste disposal, costs, and improper storage methods all contribute to landfill fires [31].

When assessing the impact of incinerated waste on soil and water, it is important to control the chemical composition of the leachate. The possibility of carrying out a controlled incineration is extremely valuable, thanks to which it is possible to compare the chemical composition of the leachate from a landfill in its natural state with that resulting from incineration. Additionally, residues from waste incineration plants can be tested for leachability. Similar results can be obtained if a landfill with a groundwater monitoring system is burned. The worst situation is the case of uncontrolled waste fires in waste dumps. Almost 80% of all solid residue from the incineration of solid municipal waste is bottom ash [39]. This residue is alkaline and contains dioxins as well as oxides of silicon, iron, calcium, aluminum, sodium, and potassium [40]. Research on bottom ash is extremely important in the context of identifying the pollutants being leached from them.

3. Consequences of Spontaneous Landfill Fires

There are three categories of environmental consequences with landfill fires [32,41–43]. When waste is burned, some of the pollutants inside it are released into the atmosphere, some migrate to groundwater as a result of leaching, and some contaminate the land surrounding the landfill. Another negative effect of spontaneous landfill fires is the threat to human life. One example of such an eventuality occurred in 2005 in Indonesia, where the collapsed waste hit a nearby settlement and killed 147 people [44]. Indeed, it is possible to find a great many articles that focus primarily on determining the impact of fires on human health [45–47].

The easiest way to monitor this is to study changes in air quality, as it is much more time-consuming and costly to test the quality of soils and the soil–water environment [48]. The amount and degree of hazardous substances released into the atmosphere is dependent on the size of the fire, the type of solid waste involved, and the weather anomalies surrounding the event. Homeowners and business owners tend not to support the siting and development of landfills in their neighborhoods due to perceived notions about noxious fumes, health and environmental effects, and adverse influences on property values [49].

The problem of air pollution caused by fires in landfills is an annually recurring problem not only for a specific area in Poland, but on a regional scale, owing to the migration of toxic pollutants into neighboring areas. Consequently, landfill fires can cause adverse air pollution dispersion to the surrounding area [50]. Through open burning, we are exposed to the immediate impact of the problem as well as its subsequent consequences. Open burning of waste is a form of low temperature combustion with high contaminant emissions, particularly of black carbon (BC), which contributes significantly to air pollution and has both a health and an environmental impact [51]. Based on studies by the Environmental Protection Agency (EPA), one of the main end results is the emission of carbon monoxide and dioxide (CO and CO_2), nitrogen oxides (NOx), hydrochloric acid (HCl), hydrogen cyanide (HCN), volatile organic compounds (VOCs), persistent organic pollutants (POP), ketones, aldehydes, and PM. Moreover, the 2016 report by the European Environmental Agency [52] highlights the emission of metals, such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), copper (Cu), nickel (Ni), selenium (Se), and zinc (Zn) during waste burning [33].

Higher temperature fires can cause the breakdown of volatile compounds which emit dense black smoke (New Zealand Ministry of Environment); one of the biggest threats to humans associated with this is the negative impact of PM10 [53–55].

However, there are fires in which the temperature reaches very high values. An example of such a fire was observed in the Dallas landfill. Shale deposits excavated from a calcareous bituminous marine shale formation spontaneously combusted in 2000. The temperature then exceeded 500 °C [56].

Some of the most common waste materials that are prone to fires are used tires. When ignited, tires burn with a higher per-pound heat output than most forms of coal, and they also produce large amounts of oil and smoke, which can cause serious air and water contamination [57]. Tire fires release a dark, thick smoke that contains carbon monoxide, sulfur dioxide, and the additional products of butadiene and styrene [58]. The emissions from the combustion of tires reflect their chemical composition, comprising 50% natural or synthetic rubber by weight, 25% black carbon, 10% metal (mostly in the steel belt), 1% sulfur, and 1% zinc oxide, in addition to containing trace quantities of other materials [59].

Another important issue is the threat to health resulting from the emission of hazardous substances into the air, which we then consequently breathe. As with all fires, those in landfills produce toxic smoke and gases which can result in headache, nausea, and fatigue (due to a lack of proper sleep) in exposed residents [38]. The associated danger and level of toxicity of these gases depend on both the duration of exposure one has to them and on the type of material that is burning (United States Fire Administration (USFA)). Suspended particulate matter from waste incineration is a major hazard. Particulates affect the environment as they contribute to greenhouse gases. Likewise, they can affect human health because they can easily reach the deepest recesses of the lungs, leading to respiratory ailments, according to the US Environmental Protection Agency [51]. Many pollutants emitted from tire burning are toxic, carcinogenic, and/or mutagenic. An accumulation of

Ni in the human body through inhalation, ingestion, or skin absorption may result in cancer of the lungs, larynx, or prostate [60]. Other effects include dermatitis, bronchial asthma, myocardial infarction, respiratory failure, and birth defects [61,62]. In addition, there is a strong link between exposure to BC and potentially severe health effects, such as cardiovascular disease, chronic respiratory illness, and premature mortality. The problem of air pollution caused by fire in landfills has been documented in several publications [30,31,33].

Analysis of the risks of leaching from waste into groundwater requires knowledge of the chemical and physical properties of the waste, its age, and the local geological and climatic conditions of the waste disposal site. The extent of these risks could be defined by determining the phase and chemical compositions, and by comparing various leaching methods. The use of many commonly used leaching methods has been described by Arain et al. [63], Delay et al. [64], Hesbach et al. [65], Hassett et al. [66], Kalembkiewicz and Sitarz-Palczak [67], Kim and Hesbach [68], Kosson et al. [69], and Menghini et al. [70].

The results from the above research [27] indicate that the amount of heavy metal present in waste ash is several times higher than in natural municipal landfill waste. Combustion of municipal waste in incineration plants is controlled in terms of the possibility of pollutants getting into the atmosphere or soil, but such control is not possible in the case of waste fires. The residues from waste incineration contain metals that are released either as a result of chemical reactions or as a result of infiltrating precipitation [71]. Such research covered the assessment of factors influencing the amount pollutants leaching from waste. Much attention has been paid to determining the ideal leaching pH [29,72].

One of the methods used to assess leaching is the Extraction Procedure Toxicity Test [73]. If the sample grains are larger than 9.5 mm, the sample of the waste is comminuted. It is then placed in an extractor, to which a volume of water is added corresponding to 16 times the weight of the sample. The pH of the solution is then reduced to 5.0 with the slow addition of acetic acid. A control of the pH is performed at 15, 30 and 60 min. If the pH rises above 5.2, some acetic acid is added until the pH drops to 5.0 ± 0.2; the pH control procedure is carried out for 6 h. The added volume of acetic acid may not exceed 4 mL per gram of sample. The sample is then subjected to leaching for 24 h. After this time, the pH should be greater than 5.2, and if it is not (despite the use of an acceptable volume of acetic acid), then extraction should be continued for the next 4 h with a pH adjustment every hour. After completion of the extraction, water is added to the solution in a volume corresponding to four times the weight of solids, minus the weight of CH_3COOH added. Then, the solution is filtered and subjected to chemical analysis. The chemical composition of the solution is then compared to the limit concentration values. If they are exceeded, it is assumed that the investigated waste is toxic.

In the case of incinerated waste, the bulk properties and geochemical characteristics of the ash will also affect the leaching of pollutants. Metal speciation in the ash also depends on the flue gas composition, such as the proportion of chlorine, moisture, sulfur, and inorganic particulates [74,75]. The typical components leaching from the ash are Ca, Cl, K, and, to a lesser extent, Si, Zn, Al, S, Ti, and Fe [76].

To prevent the leaching of pollutants from the ash, appropriate treatment is required. There are a few methods which are used for this, such as physical immobilization, solidification, or chemical (reagent) treatment. Some of the promoted methods are chelating treatment [77,78] and bioleaching [79,80].

There are several papers devoted to research on the possibility of using ash from municipal waste to seal landfills or recover metals [81,82]. Some studies have focused on the mineralogical composition of the ash. Such works include the Siddique studies from 2008 and 2010 [83,84]. This research also described the chemical composition of leachates and the influence of ash on the chloride shrinkage of concrete. Due to the fact that the incinerated waste is treated as a hazardous material and is also sometimes used in construction work or as a neutralizing agent for acid waste, it should undergo various tests in order to avoid negative impacts on the environment or human health [85,86].

4. Case Studies of Illegal Burning

In the literature, it is possible to find a number of examples of descriptions of landfill fires, such as fires in Spain [87], Greece [88], Brazil [89] or the USA [90].

One important example of such a landfill fire is an event that took place in Greece. An uncontrolled ignition took place on 15 July 2006 at the municipal waste storage site known as "Tagarades", situated 20 km from the city of Thessaloniki. The main waste materials in the landfill were household rubbish, with the addition of hospital and commercial waste and sewage sludge. The fire engulfed about 50,000 tons of garbage. The cause of the fire was most likely methane coming out of the storage area (methane in this area was not monitored), and a thick streak of smoke could be seen emitting from the smoldering waste for the next week [24].

The studies performed by Øygard et al. [24] on the site included a collection of soil and plant samples, both from inside and outside of the landfill site. They were collected 15 days after the fire was finally extinguished. In total, 10 soil samples (including one from the landfill) and nine plant samples (from outside the landfill area) were taken. When analyzing the samples, the researchers focused on detecting potential contaminants associated with polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCBs), organochlorophenols (OCP) including hexachlorocyclohexanes (HCH) and DDT, as well as trace elements. The results of these studies showed that the level of PCB and trace elements inside the landfill were significantly higher than those reported in the remaining soil samples. The level of HCH was high inside the landfill, but also in places where the smoke plume may have reached. At agricultural sites, the DDT content of the soil exceeded that of the landfill. However, no exceedance of the relevant intervention values for soil reclamation were recorded. Only Cr exceeded the intervention value for soil reclamation, due to local geological occurrences. As far as the plant samples are concerned, no high concentrations were observed. In addition, the heavy metal content was similar to that recorded for vegetation species in other locations in Greece, meaning that the metals had not affected the vegetation as a result of the fire. The results of this study alone did not conclusively determine whether the landfill fire had an impact on the surrounding terrestrial environment.

A second example is an uncontrolled fire at an illegal tire storage site in Spain, on the border between Castilla–La Mancha and Madrid. The site had been a wild landfill since 2002 and was then declared illegal by the authorities in 2015. The fire broke out on 14 May 2016, and was finally extinguished on 2 June. At that time, it is estimated that between 70,000 and 90,000 tons of tires were present at the scene (https://www.dailymail.co.uk/news/article-3589238/Giant-toxic-cloud-swamps-town-20-000-Spain-blaze-tyre-dump-expected-DAYS.html, accessed on 19 January 2023). The studies performed by Nadal [89] involved the collection of soil and ash samples in the area surrounding the landfill at two different intervals. The first occurred three days after the fire broke out at three distances (500, 1000, and 1500 m, for a total of three soil samples), while the second was carried out one month after the fire (3 soil samples, one ash sample). PAHs with 3–5 rings were the most common accumulations of PAH in the samples. However, in these studies, PWA levels did not appear to correlate with the distance from the tire storage site. The researchers suggested other potential sources of PWA near the samples taken, namely industrial activity, which occurred in a large proportion of the area. A comparison of the relative PMA calculated for the soils harvested during the second round indicates an overall decrease in EPA PVA levels as the distance from the fire increases. In addition, 16 non-primary PWAs and 29 alkylated PWAs were detected and identified in the analyzed samples. A number of heterocyclic PCs were also detected in the results of the studies. Among them, PAHs were the largest class, followed by O-PAH and PAH containing N heterocyclic compounds. Additionally, 20 PASHs were initially identified. The PASH levels in the samples showed a similar trend to that observed for previously discussed PAH derivatives. Elevated O-PAH concentrations were detected in the samples that were affected by the tire fire. Relatively low concentrations of PBDEs and DPs were found in the collected soil samples. This result was confirmed with an ash analysis, in which these compounds were not detected in significant quantities.

Another example of such a disaster is a fire that occurred at a landfill site in Norway [91]. The landfill was established in 1993 to collect solid municipal waste and some forms of industrial and construction waste. By 2003, a total of 230,000 m^3 of landfill leachates had been dumped there. The first fire in the area was observed on 10 March 2003. During the firefighting operations, the landfill reached a depth of up to 12 m, but by digging a deep ditch around them that reached the bottom of the landfill, the burning areas were isolated. The extent of the landfill where the fire was fought was about 8000 m^2 (10% of the total area of the landfill).

However, after the outbreak of this fire, liquid samples were tested daily for up to a week after the fire had ceased. Additional information was also collected on the macroscopic changes resulting from the event itself. The leachates after the fire had a fairly strong, unpleasant smell. In addition, it was black in color and contained relatively high levels of molecules. After the outbreak of the fire, the pH level and conductivity of the samples increased above the norm. The metal levels were also elevated in the cases of Cd, Cu, Cr, and Pb within the liquid samples. However, no PAH compounds were detected during the disaster. It is stated that a landfill fire extinguished with excavations can cause large increases in the concentration of certain substances, but only as a short-term effect if the fire is quickly extinguished.

Another example of a fire at a landfill is an incident that occurred in one of the largest landfills in Europe, located in Toledo (Spain). At this landfill, approximately 80,000 tons of tires had been illegally accumulated over 15 years [89]. The fire lasted 20 days. As part of the research, soil, crop, and air samples were collected. The research mainly focused on the level of PAHs, PCDD/Fs, PCBs, and toxic metals. Among PAHs, the contents of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo (a) anthracene, chrysene, benzo (b) fluoranthene, benzo (k) fluoranthene, benzo (a) pyrene, dibenzo (a, h) anthracene, benzo (g, h, i) perylene, and indeno (1,2,3-cd) pyrene were assessed. The mean levels of the analyzed PAHs in the soils ranged from 8.8 to 33.2 ng/g. The concentration of all PAHs in the air was determined to be 134 ng/m^3, with chrysene being the dominant compound. The concentrations of PCDD/Fs and dl-PCBs in the soils achieved 1.66 ng WHO–TEQ/kg. In the case of the air samples, the concentrations of these components did not differ from the air samples taken in this area before the fire (from prior monitoring tests). The highest concentrations of PCDD/Fs + dl-PCBs, and ndl-PCBs (0.33 ng, WHO–TEQ/kg, and 0.52 ng/g, respectively) were observed in lettuce.

It is worth mentioning that health risks were also assessed. Calculations indicate that the cancer risk due to exposure to environmental pollutants for the population living near the landfill was between three and five times higher than that estimated for the inhabitants of nearby towns.

In terms of controlled combustion, attention should be paid to, among other things, research in Denmark, wherein two examples of residues (bottom ash and air-pollution-control (APC) residues from municipal waste) have been tested for pollutant leaching [92,93]. Five different samples of individual residue types were taken into account in the research. Moreover, laboratory tests were performed in parallel for dried and non-dried samples of treated APC-residues. Bottom ash is a slag-like residue with a homogeneous composition collected from the combustion chamber. APC residues are carried away from the combustion chamber with the flue-gas. Three test methods were used to assess the leaching of pollutants: batch experiments with continuous pH control, up-flow percolation experiments, and static experiments without pH-control [94]. The leaching of Cd, Fe, Mg, Hg, Mn, Ni, Co, Sn, Ti, and P from both bottom ash and from APC was generally below the detection limits for those particular compounds. The highest leaching of pollutants was found for chloride, sodium, and potassium.

This type of waste can also be used as a landfill seal. An experiment was conducted in China on the use of incinerated waste as a sealant [95]. In this research, three simulated landfills were used: R1—typical landfill; R2—landfill with a mass proportion of the bottom ash layer to the municipal solid waste layer of 1:9; and R3—landfill with a mass proportion of the bottom ash layer to the municipal solid waste layer of 2:8. Each reactor was 287 mm in diameter and 1000 mm in height and had a volume of 65 L. Each reactor was equipped with five ports: one for exporting gas, three for the sampling of the bottom ash and waste, and the last one for leachate drainage and sampling. The leachate samples were analyzed for pH, dissolved organic carbon, and for Cu and Zn levels, while the waste samples were analyzed for Cu and Zn concentrations alone. The tested ash showed a high pH = 11.17. This is a consequence of the levels of $CaCO_3$, Al_2O_3, and Fe_2O_3. It was calculated that there were 6464.4 mg of Cu and 57,467.5 mg of Zn in R1, 7390.9 mg of Cu and 61,330.7 mg of Zn in R2, and 8317.5 mg of Cu and 65,193.0 mg of Zn in R3. The average concentration of DOC of the leachates from these three reactors was 28,481.5 mg/L.

The problem of landfill fires is still being investigated in Poland, in terms of the impact of the pollutants from precipitation on groundwater. One of the research areas on which we, the authors of this article, began our work is the landfill in Trzebinia (in southern Poland) [34], where a fire took place in 2018. The landfill contained, among other things, tires, black rubber, plastic packaging, and textiles. The landfill had not been used since 2013. As part of our preliminary studies, samples of soil and waste were collected and subjected to leaching tests, as well as PAHs and MPI analysis. The research showed that fluoranthene and pyrene were detected in all of the samples. Phenanthrene and anthracene were also detected in most of the samples. Among the inorganic pollutants, increased concentrations of sulphates and chlorides were observed. The obtained results have been systematized and analyzed. There are lots of challenges and different solutions connected with landfill fires. The most important aspects of these are presented in Table 1.

Table 1. Landfill fires problems and possible solutions.

Environmental Challenges Related to Landfill Fires	Proposal Solutions to Specific Problems of Landfill Fires
Pollution cloud created from infiltration of burnt waste in landfill [96]	Monitoring of the site by means of lysimeters installed in the region of the landfill site [16]
Damage to the top layer of the landfill [97]	Use of non-combustible materials covering the landfill
Mobile spread of the fire from the landfill to nearby areas [98]	Safer isolation of the site, inter alia, by means of sand shafts or excavations
Ignition of accumulated methane in landfill [99]	Accurate monitoring and discharge of collected methane from residual waste [21]
Production of toxic fumes into the atmosphere by the burning of waste [31]	Monitoring and investigation of the effects of air pollution [33]
Collection of flammable materials in a single landfill	Better segregation and ungrouping of flammable solid waste
The formation of wetlands in landfills	Use of terrain scanning to detect temperature rise [20]
Exposure of the health and life of landfill workers [50]	The right equipment and clothing for safe field work [100]
Containment of hazardous waste emitting permanent pollution over time [4]	Improving the technology for disposing of potential waste [101]

5. Conclusions

Fires in municipal landfills constitute a significant environmental problem in the context of air, soil, and groundwater pollution. Studies on the leaching of pollutants from incinerated waste indicate that such leachates are more toxic than for waste deposited directly into the landfill. Burnt waste not only contains Cu, Zn, Cd, Ni, and Mn, but due to its heavy metal content, ash and slag are also considered to be hazardous waste. The possibility of reusing such waste could be beneficial for the environment, providing that it is not possible for pollutants to migrate from this waste.

Due to the fact that a significant amount of waste is incinerated in wild or unsealed landfills, research on the leaching of pollutants (as well as the processes for the migration of these pollutants from various waste materials) should constantly be conducted. It is also important to identify as many factors as possible that may affect the size and type of the leached contaminants. Performing controlled incineration, reducing emissions from incineration plants, and, finally, securing waste against spontaneous combustion or arson are just a few examples of treatments that would reduce the development of fire-related problems. It is necessary to determine the type of pollution in relation to the type of waste incinerated, as well as the amount of pollution, the rate of migration, and the ability to clean the aquifer over time. It is worth remembering that it is possible to compare the leaching of pollutants from waste in the natural state with waste after incineration, e.g., with static or dynamic leaching tests.

Considering the numerous burnings of landfills, which occur due to increased fees for landfilling, it is necessary to consider whether these activities are expedient and to introduce new rates for landfilling and disposal. The issues discussed in this article can be used to prepare a report on the negative environmental effects of landfill fires. Additionally, they can also serve as a basis for conducting further research on burnt landfills.

Future research on the influence of leachates from burnt waste on groundwater should address the gaps in our current understanding of the differences between the toxicity of natural and burnt waste, between different waste and landfill processes, and fire prevention measures. These should be analyzed with new examples in different storage conditions.

The results of such research should be communicated to our political decision makers, in order to increase fines for those who intentionally burn landfills.

Author Contributions: Conceptualization, D.D., W.R. and V.N.; methodology, D.D.; investigation, W.R.; resources, D.D.; writing—original draft preparation, D.D., W.R. and V.N.; writing—review and editing, D.D. and W.R.; V.N.; supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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