Abstract

Reclamation of landfills and dumpsites requires detailed technical and economic evaluation of actual and potential pollution at the site, including detection of the main contaminants, their concentration, chemical stability and mobility in the environment. Contamination with metallic elements and metalloids is among the most important problems that limits recultivation of landfills and dumpsites and reuse of landfilled materials. This study was implemented at the Kudjape Municipal Landfill, located on Saaremaa Island in Estonia. The Kudjape Landfill is a partly closed landfill recultivated by covering it with a layer of a fine fraction of landfill material after the landfill mining operations. The fine fraction was derived at the site by sorting the landfill material (i.e., disposed waste) using mechanical screening, manual sorting and sieving. Obtained relatively homogeneous material, consisting of particles smaller than 10 mm, was defined as a fine fraction of waste. Samples from the fine fraction at different depth were collected and analyzed. Metal mobility was assessed after the sequential extraction. Results revealed that such elements as Zn, Mn, Mg are found in various fractions; Fe, Cd, Cr—mainly in residual fraction; Cu, Pb, Ni, Ba, Co and Rb mostly in fractions of residuals and reduced compounds, but they are presented in larger proportion of acid and water soluble fractions. Slight interconnection of detected parameters and sampling depth was revealed. Sequential extraction of elements in the fine fraction suggested the valorization of waste and confirmed that such landfill material can be successfully used as a landfill-covering layer under the specific engineering circumstances.

Keywords

Landfill mining · Waste sorting · Metal mobility · Fine fraction of waste · Waste valorization · Estonia

Introduction

Municipal landfills and dumpsites, as well as former landfills are assessed as possibly contaminated areas and they are listed among the most important sources of air, soil, surface water and groundwater pollution that cause environmental problems worldwide [1–3]. In the member countries of European Union, aftercare and closure of dumpsites and former landfills must be performed according to the Landfill Directive [4] and the Waste Directive [5]. These legislation documents establish major principles of waste disposal and reuse including the obligation to handle waste in a way that does not cause negative impacts to the environment and human health. Closure and reclamation of landfills and dumpsites requires detailed technical and economic evaluation with the aim to identify existing and possible future risks of pollution. Thus, determination of the main contaminants, their concentration, chemical stability and mobility or ability to be transported within and into different environmental media.

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should be among the basic steps of evaluation. Former dumpsites can be mentioned as a specific source of pollution among the various types of landfills due to the diversity of waste that consists of construction materials, industrial, municipal, hazardous and mixed waste [6–10]. In many cases, the history of incoming waste type at the landfill has not been well documented. Therefore it is complicated to predict levels and behavior of pollution at the site without specific analysis. Regarding the biochemical processes organic part of waste can eventually decompose while stable contaminants such as toxic and potentially toxic metals and metalloids remain at the site unless they are leached out [9, 11].

Major elements such as Ca, Mg, K, Na and trace elements, e.g., Cu, Fe, Mn and Zn, are essential for living organisms in certain concentration. Accumulation of range of elements (e.g., Al, As, Cd, Cr, Cu, Ni, Pb, Zn) in dumpsites and landfills may result in environmental contamination and elevated toxicity that may affect development of plants, animals and humans [12–14]. Many contaminants, including metals and metalloids, can be taken up from soil by plants and spread through the food chain further to the primary consumers such as herbivorous, following secondary consumers as carnivorous [1], thus, emphasizing the importance of soil, water and air quality assessment. It is proved by many studies that the landfill areas very often need to be remediated, because they are remaining as a point source of metals and metalloids for decades contaminating soil, groundwater flows and surface waters [6, 7, 15]. Recommendations for the reuse of slightly contaminated up to highly degraded areas usually include more detailed environmental pre-assessment in order to understand the severity of the problem and potential contamination level in the environment [6, 9, 16]. Therefore investigation of polluted areas nearby dumpsites, landfills and other contaminated sites is important concerning protection of environment and human health safety especially if the territories are used as domestic or public space after the recultivation.

Reuse and recycling of materials disposed at the landfills also is an important issue. So far, landfill mining (LFM) activities have not been carried out with focus on resource recovery. Very limited research effort for the enhancement of the recycling potential of excavated waste has led to weak results. Thus, need for the development of innovative technologies for valorization of the excavated waste and for a standardized framework for the assessment of the economic potential of LFM is among the topical questions within the scientific community [2, 3, 17]. Currently, a new vision is opening encouraging scenarios for the full exploitation of LFM opportunities. According to the study done by Jones et al. [3], LFM should be embedded in a broad resource management perspective, where a significant role is played by recovery of resources from the disposed waste including energy production from biogas before excavation. This is one of the key issues of the Enhanced Landfill Mining (ELFM) concept, where existing and closed landfills are considered as a temporary storage place of waste awaiting its future valorization [18]. In practice it means that after the waste excavation and treatment, non-recyclable fractions are deposited in certain landfill sectors to be stored until the proper technologies are available for waste treatment and recycling. Thus, further LFM procedure becomes profitable. Temporary storage of waste with a possibility of valorization in future is currently an issue of prospecting in numerous European countries [19, 20].

Historically, the first case of LFM for waste material valorization was implemented in Israel in 1953 [21, 22], later also in Europe and the USA [23–25]. Additional pilot studies of LFM were performed in such countries as England, Italy, Sweden and Germany [26–28]. Landfill mining is defined as one of the possible remediation procedures that is performed to clean up, mitigate, correct, abate, minimize, eliminate, control and contain or prevent release of a contaminant into the environment in order to protect human health and the environment, including actions to study or assess any actual or suspected release [29]; but it is also dealing with potential valorization of waste material in order to return it valuably to the economic cycle. Global release of pollutants into environment may be correlated with the world mineral and energy consumption [30] and the best-known metals pollutants that are leaching from landfills and industrial areas (e.g., Pb, As, Cd, Cr, Cu, Zn, Hg and Ni) induce serious environmental problems. Toxic ions are non-biodegradable and tend to accumulate in tissues of living organisms, causing severe disorders and diseases. Speciation or chemical form of an element is important as the oxidation state for range of elements (e.g., Fe, Mn, Cr) and it is dependent on pH and redox potential. Such elements as As, Hg, Pb or Sn can form complexes with organic compounds that are highly toxic to environment and humans [30–32].

Importance of choosing the fine fraction of waste for analysis is supported by the practical need to gain the specific information and characteristics of the landfill mass itself as the large portion (in some cases 40–50 % of all mass of the landfill waste) is composed of fine material that is supposed to be used valuably, e.g., as a covering material. Especially it is crucial in cases where there are limited options to use another capping material to close the landfill appropriately, for example, in islands, nature parks, hardly accessible and urban areas. The aim of this study was to assess the mobility of metals in samples landfill waste after yield of waste fine fraction consisting of particles smaller than 10 mm, which could be reused as new material.
Materials and Methods

Study Site

The Kudjape Municipal Landfill (58°16′06″N; 22°32′23″E), situated 2 km south-east from Kuressaare town on Saaremaa Island in Estonia (Fig. 1), was chosen as a study site for the practical investigation of landfill components, waste processing and utilization of fine fraction of waste. The total area of the landfill covers 5.6 ha, but waste disposal area occupies 4.2 ha. Location of the landfill on the island is 1.6 km from the coastline of the Baltic Sea. Estimated volume of waste in the Kudjape Landfill is about 193,000 m³. The landfill was in operation from the 1970s until 2009 and it was used mainly for disposal of municipal solid waste. The waste was dumped on a flat area, 4 m above the sea level, but at the closure the landfill reached a height of about 12 m. The waste was compacted by a compactor during the last years of operation and it had very little intermediate cover layers. Before the remediation, the Kudjape Municipal Landfill was unlined and not covered. No leachate, nor gas collection or treatment system existed at the landfill. However, the landfill had several sampling and monitoring wells for groundwater, as well as two gas wells. The Kudjape Landfill is divided in two sectors: the old sector (1.2 ha, built before 2000, containing 35,000 m³ of waste) and the new sector (2.7 ha, containing 158,000 m³ of waste). During the last decade when the landfill was in operation, about 65,000 t of waste was disposed at the site. The Kudjape Landfill was identified as one of the last few non-compliant landfills being in operation in Estonia [6].

A recycling station for sorting and separation of waste was built up at the Kudjape Landfill before its closure. The recycling station still operates also as a transfer station for unsorted municipal waste. Nowadays it is the only site where sorted waste from whole Saaremaa Island is taken and separated for valorization. The material recycling facility consists of 40 mm wide rotary screen (diameter 180 cm, length 3600 mm), conveyor belts, and 15 m long double-sided sorting belt. The equipment of the recycling station is applicable to shred the energy-rich material into fluffy refuse derived fuel. All the unsorted waste is collected in large containers and taken to the terrestrial Estonia, where new built landfills with appropriate cells have been built.

Sampling Procedure

After the removal of the cover layer of the landfill, four test pits were randomly selected and excavated to 5 m with an excavator dividing the excavated material according to the corresponding depth: D1: 0–1.25 m, D2: 1.25–2.5 m, D3: 2.5–3.75 m, D4: 3.75–5 m. In total, 12 t of waste were excavated and it consisted of 54 % fine-medium material (<40 mm) and 46 % coarse material. With the increase of the depth, the proportion of the fine fraction of waste slightly increased (i.e., D1 56 %; D2 54 %; D3 57 %; D4 58 %). Four samples, one for each depth, were taken from the pits and sieved in the trommel screen. Obtained coarse fraction was characterized according to the recommendations of Swedish Waste Management Association [33] for handpicking analysis of household waste, but medium to fine material (<40 mm) was scanned with an Olympus DELTA DS-2000 Handheld XRF Analyzer equipped with 4 W X-ray tube and optimized beam settings for screening purposes. The finest fraction of waste (<10 mm) was sieved out; besides, visually larger pieces of material were handpicked out in order to keep for further analysis only rather homogeneous by size fine fraction of waste. Larger pieces were handpicked during the homogenization procedure to get rid of visually detectable pieces of such materials as plastic, glass, stone etc. Obtained samples of fine fraction of waste were homogenized, diminished by size using quartering method, and analyzed to detect the total content as well as mobility tendencies of metallic elements.
Laboratory Investigations

Collected samples (n = 48) of fine fraction of waste derived at different depth (D1: 0–1.25 m, D2: 1.25–2.5 m, D3: 2.5–3.75 m, D4: 3.75–5 m) were investigated to detect physical and chemical parameters such as electrical conductivity, pH, dry matter content and organic matter content. Organic matter content was measured as a mass loss of ignition at 550 °C in muffle furnace. Electrical conductivity and pH was measured in water extracts 1:5 (v/w) after shaking for 1 h at 140 rpm. Basic analysis was performed taking into account standard methodology of soil analysis [34] as there are no specific methods for fine waste material geochemical analysis.

The total content of metallic elements in fine fraction of waste was determined by a wet digestion method that involves mineralization of samples using concentrated nitric acid (65 % w/v, ISO, Scharlau) and concentrated hydrogen peroxide (30 % w/v, ISO, Merck) for 24 h at room temperature (23 °C), following by heating at 160 °C until the full sample mineralization [35]. Each sample was analyzed in triplicate, as well as blank samples were prepared for every batch of samples to gain reliable and statistically comparable results.

Speciation analysis done by sequential extraction is a way for detection of prevailing chemical forms of elements to assess the mobility manner and bioavailability of metallic elements and metalloids. The oxidation state of various elements (e.g., Cr, Fe, Mn) is dependent on pH and redox potential. Some other elements such as As, Hg, Pb, Sn can form metallic-organic complexes [14, 36, 37]. Speciation of metals and metalloids often is ignored when total or total element analysis has been performed. Consequently, decisions of pollution amounts and recultivation possibilities of mining fields, landfills and contaminated sites are based only on narrow amount of data that does not reflect the real situation at the site. But it has to be taken into account that the total or total concentration of elements is not the only one reason affecting the toxicity of chemicals [1, 36, 37].

Various methodologies of element speciation analysis for soil and sediments are tested under the by Tessier et al. [38], Lake et al. [36], Ure and Davidson [37] and other scientists. Fractions derived after the speciation analysis of samples may vary due to the applied analysis and used reagents. Fractions can be expressed, for example, as a fraction of water soluble compounds, ion exchangeable compounds, carbonate bound species, easily reducible substrates, easily extractable organic compounds, moderately reducible oxides, oxidizable oxides and sulfides, crystalline iron oxides and residual minerals [7, 36–38].

In this study a sequential extraction was performed to estimate the mobility manner of metals in fine fraction of waste. Considering specific properties of the samples (e.g., origin, particle size) and the aim of the study, the five-step extraction procedure developed by Tessier et al. [38] was reduced to the three steps as proposed by Ure and Davidson [37]. The Tessier method was chosen as the basis of sequential extraction due to its wide application in environmental engineering projects and similar studies performed in Norway where it was applied for dried sediments of landfill leachate [39]. The extraction procedure was performed step by step as follows:

**Step 1** Fraction of water soluble components: 3 g of a dry sample were dissolved in 50 mL of warm (40 °C) deionized water, following by extraction on a mechanical shaker (Biosan) for 2 h at room temperature (23 °C). Extracts were filtered through paper filters and 0.45 μm membrane filters (Simplepure) into polypropylene tubes, and acidified with 0.2 mL of HNO3.

**Step 2** Fraction of acid soluble components: residues left after the Step 1 extraction were carefully collected, poured into 100 mL glass beakers and 40 mL of 0.11 M CH3COOH was added. Extraction was done on a mechanical shaker for 16 h at room temperature (23 °C). Extracts were filtered through paper filters and 0.45 μm membrane filters into polypropylene tubes, and acidified with 0.1 mL of HNO3.

**Step 3** Fraction of reduced components: residues left after the Step 2 extraction were carefully collected, poured into 100 mL glass beakers and 40 mL of 0.5 M NH2OH-HCl was added. Extraction was done on a mechanical shaker for 16 h at room temperature (23 °C). Extracts were filtered through paper filters and 0.45 μm membrane filters into polypropylene tubes, and acidified with 0.2 mL of HNO3.

Fraction of residual components was evaluated by the difference between the total concentration of every detected element and the sum of concentration of an element in three above described fractions.

Sequential extraction procedure was performed in triplicate for each sample, as well as blank samples were prepared for every batch of samples.

Analytical Procedure

Concentrations of metals and metalloids were detected by inductively coupled plasma mass spectrometry (ICP-MS)—As, Cu, Ba, Ni, Cd, Pb, Co, Rb, Cr, Sr)—using ELAN DRC-e (PerkinElmer) apparatus and atomic absorption mass spectrometry (AAS)—Fe, Mg, Mn, Zn—using AAnalyst 200 (PerkinElmer) technique. Concentration measurements were performed at the Department of Environmental Science in the University of Latvia.
Statistical Analysis

Statistical analysis of data was performed using MS Excel software (Microsoft Office 2013) equipped with an extension QI Macros. The measurements were expressed in terms of means with standard deviation and all the figures are represented with the mean values.

Results and Discussion

Characterization of Fine Fraction of Waste

Detected physical and chemical parameters (pH, dry matter content, organic matter content, electrical conductivity) for samples of fine fraction of waste at different depth are summarized in Table 1.

Taking into account values of pH, waste samples are tended to be of slightly alkaline reaction. There were no significant differences indicated among the samples derived at different depth. However, slight trend of acidity increase can be associated with the change of the depth, i.e., acidity increased from pH 7.63 for samples derived at 0–1.25 m to pH 7.96 for samples derived at 3.75–5 m.

Content of organic matter varied from 18.14 % at the depth 1.25–2.5 m to 19.06 % at the depth 3.75–5 m. No significant relevance was detected between the content of dry matter and the depth of landfill. However, results showed that electrical conductivity of samples increased stepwise simultaneously with the change of the depth (from 2.00 mS/cm at 0–1.25 m to 3.28 mS/cm at 3.75–5 m).

Among the various factors, change of electrical conductivity due to the depth of samples could be associated with the amount of inorganic soluble salts that increases with depth.

By now, there is no information available of similar investigation of fine fraction of waste, thus, it cannot be compared with situation at the other landfills. However, values of parameters are expected to be very variable due to the low homogeneity of waste material as well as taking into account the predominant waste, age of landfill, local climatic conditions and other related factors.

Detected total content of 14 metallic elements are summarized in Table 2. Concentrations of elements in samples of fine fraction of waste varied widely. The highest average concentration from four different layers of four holes of sampling was detected for such metals as Fe (36.4 g/kg), Zn (1.6 g/kg) and Mg (9.8 g/kg). No significant trends were observed between the total content of elements and the depth of sampling, only for Fe higher concentration was detected for deeper samples. Derived data indicates high amount of several metals in fine fraction of waste, for example, average concentration of Fe is above 10,000 mg/kg, Mg and Zn—above 1000 mg/kg, but concentrations of Mn, Ba, Cu, Pb and Sr are above 100 mg/kg (Fig. 2). Thus, valorization of fine fraction of waste can be attributed mainly due possible extraction of these metals, moreover, it has to be taken into account if fine fraction is used as a material for certain purposes, e.g., for covering of a landfill. Nevertheless total content of metals as an indicator for environmental impact of pollutants, but it does not reveal a lot about ecological and human health risks [40].

Within the context of risk assessment, mobile and available concentrations of metals are much more relevant values to be used in the investigation of waste safety after its excavation as well as for further valorization.

Speciation of Metals in Fine Fraction of Waste

Results from sequential extraction of metallic trace and major elements in fine fraction of waste are presented in Figs. 3 and 4. Data revealed that all metals, except Sr, were mostly bound in residual fraction at any depth of waste sampling, only Sr was mostly bound in reduced fraction. Noticeable part of Cu, Rb, Mg and Pb was bound in water soluble fraction, thus, indicating that these elements can be leached out of waste more easily in great extent due to the change of redox potential. Detected values of metal concentration in water soluble fraction varied widely—from <0.01 mg/kg for Cd up to more than 22 mg/kg for Sr. Variations among the depth were observed, slight tendency for some elements indicated that in bottom layer of waste element occurrence in water soluble fraction became lower, e.g., concentration of Pb in the water soluble fraction of upper layer (D1, 0–1.25 m) of waste was 4.03 mg/kg, while in the bottom layer (D4, 3.75–5 m) it was only 1.04 mg/kg. However, for other elements also the opposite tendency was observed, e.g., Rb concentration in water

Table 1 Characterization of fine fraction of waste derived at the Kudjape Landfill

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sample/depth (m)</th>
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<tbody>
<tr>
<td></td>
<td>D1/0–1.25</td>
</tr>
<tr>
<td>Acidity (pH H2O)</td>
<td>7.63 ± 0.10</td>
</tr>
<tr>
<td>Content of dry matter</td>
<td>66.63 ± 0.63</td>
</tr>
<tr>
<td>Content of organic matter</td>
<td>19.06 ± 1.84</td>
</tr>
<tr>
<td>Electroconductivity (mS/cm)</td>
<td>2.00 ± 0.20</td>
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</table>
soluble fraction raised from 0.60 mg/kg at the sampling depth 0–1.25 m to 0.91 mg/kg at the depth 3.75–5 m. In acid soluble fraction noticeable amount of Ba, Co, Cr, Mg, Mn, Ni, Rb, Sr and Zn was bound among the overall element distribution by fractions. In acid soluble fraction metals are bound in carbonates [38]. It may imply that several metallic elements such as Zn, Ni and Co may become more mobile in environment and thus bioavailable to plants or other living organisms if pH changes to more acidic medium. Although mobility and bioavailability of elements is dependent on a range of conditions, in current study pH values detected for fine fraction of waste varied from 7.63 to 7.96, representing a neutral to alkaline medium. Thus, possible use of this fine fraction of waste as a landfill covering material can be considered at low risk but in addition pH buffering capacity has to be measured.

Despite the high total concentration of such major elements as Fe and Mg (average values 36.5 and 9.8 g/kg, respectively), mobility and bioavailability of these metals are considered to be at low level due to their low concentration in water soluble or acid soluble fractions. Since the water soluble and acid soluble fractions forms also comparably small part of total content of trace elements, the mobility and availability of metals from fine fraction of waste can be considered as low also for Cu, Pb, Cr and Cd.

It is stated that in reduced fraction elements are mostly bound to Fe or Mn oxides [38], but in a framework of soil and sediment analysis, it is important for such elements as Mg, Zn, Mn, Sr, Rb, As, Cd and Ba—these elements can become more mobile and available due to the change of redox conditions. In a study done by Øygard et al. [39], where sequential extraction was also applied, it was detected that in more bioavailable fractions 20–30 % of Cd, Zn and Ni were extracted, but other metals in lower extent. Majority of metallic elements were bound to Fe oxides thus having low solubility and relatively low bioavailability [39].

Figure 4 represents that Zn, Mn, Mg are found in all of the studied speciation fractions; however, element amounts in water and acid extractable fractions are much lower than in reduced and residual fractions. Waste (as well as soil itself) contains abundant amount of Fe, and it can be found in all fractions, but dominantly in residual fraction. Important finding is that very toxic elements such as Cr and Cd are found in negligible amounts in easy extractable fractions. Cu, Pb, Ni, Ba, Co and Rb are found

<table>
<thead>
<tr>
<th>Element</th>
<th>Sample/depth (m)</th>
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<tr>
<td></td>
<td>D1/0–1.25</td>
</tr>
<tr>
<td>As (mg/kg)</td>
<td>4.0 ± 0.4</td>
</tr>
<tr>
<td>Ba (mg/kg)</td>
<td>286 ± 93</td>
</tr>
<tr>
<td>Cd (mg/kg)</td>
<td>1.12 ± 0.33</td>
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<tr>
<td>Co (mg/kg)</td>
<td>5.7 ± 0.9</td>
</tr>
<tr>
<td>Cr (mg/kg)</td>
<td>64 ± 39</td>
</tr>
<tr>
<td>Cu (mg/kg)</td>
<td>191 ± 129</td>
</tr>
<tr>
<td>Fe (g/kg)</td>
<td>31.4 ± 6.8</td>
</tr>
<tr>
<td>Mg (g/kg)</td>
<td>10.2 ± 0.4</td>
</tr>
<tr>
<td>Mn (mg/kg)</td>
<td>317 ± 68</td>
</tr>
<tr>
<td>Ni (mg/kg)</td>
<td>32 ± 6.1</td>
</tr>
<tr>
<td>Pb (mg/kg)</td>
<td>477 ± 397</td>
</tr>
<tr>
<td>Rb (mg/kg)</td>
<td>7.0 ± 0.5</td>
</tr>
<tr>
<td>Sr (mg/kg)</td>
<td>146 ± 26</td>
</tr>
<tr>
<td>Zn (g/kg)</td>
<td>1.8 ± 0.9</td>
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Fig. 3 Distribution of trace elements by sequential extraction fractions in samples of fine fraction of waste from the Kudjape Landfill at different depth (D1: 0–1.25 m, D2: 1.25–2.5 m, D3: 2.5–3.75 m, D4: 3.75–5 m); \textit{concentration}_1 refers to fractions of water soluble, acid soluble and reduced compounds; \textit{concentration}_2 refers to residual fraction.
dominantly in fractions of residuals as well as reduced compounds, nevertheless they are present also in acid and water soluble fractions. After LFM operations and production of the fine fraction for covering layer of rest of the dump, the thickness of this covering layer was planned 1.5 m instead of 0.5 m as it is applied in traditional landfill closure operations. Further this covering layer was planned to be wrapped over by a layer of organic (humic) soil and plant cover additionally.

Significant proportions of trace and major elements such as Zn (47 %), Mn (48 %), Mg (54 %) and Fe (94 %) are bound in fraction of reduced compounds, if assumed that analysis of the total content of elements shows 100 %. Also other metals are tended to be bind in fraction of reduced compounds, i.e., 97 % of Pb, 98 % of Cr and 99 % of Cu. This fraction is characterized by low extractability thus indicating low ability of metal leaching from waste and therefore negligible environmental concern.

Sequential extraction of elements in the fine fraction suggested the potential possibility for valorization of waste and confirmed that such landfill material can be successfully used as a landfill-covering layer under the specific engineering circumstances.

Speciation of elements is important for two main purposes: to assess mobility and bioavailability of elements and at the same time to distinguish potential threat of elements to the environment what can be caused by change of environmental conditions. Additionally it is possible to find promising technological solutions to recover resources, e.g., water soluble and acid soluble fractions are easy to be extracted while other are characterized by low extractability. Observations from this study raise awareness of other important questions which should be considered regarding landfill excavation, sorting and proper choice of analyses as well as accurate management of possible waste valorization. In this study it was important to gain data on easily extractable, soluble fractions of metals as the fine fraction is the product from the waste mass and, if used as cover material, can pose threats to the environment and public health, hence the total amount of studied elements is not fully representative. Current LFM project in full scale was performed for the first time in the country; therefore, local municipality demanded additional information as no specific legislation on LFM exists in Estonia.

Slight interconnection of detected parameters and sampling depth was revealed. Sequential extraction of elements in the fine fraction suggested the potential possibility for valorization of waste and confirmed that such landfill material can be successfully used as a landfill-covering layer under the specific engineering circumstances.

Until now, several examples of scientific studies in the field of element speciation have been addressed to speciation analysis of polluted soils [39, 41], sediments [42, 43], fly ashes [44] and sludge [36], but no studies on speciation of metals in excavated waste from landfills have been done before. It points to a gap in a knowledge regarding potential impacts and environmental risks related to landfill recultivation projects, including planning and implementing of waste excavation, sorting and proper choice of analyses as well as accurate management of possible waste valorization. In this study it was important to gain data on
Valorization of Fine Fraction of Waste

In many regions of the world, waste disposal at landfills and dumpsites still is the most common waste utilization method and landfills are assessed as a final way to store waste at minimum cost and additional resources needed [2, 45]. Landfilling of waste is often implemented even in countries with developed systems of waste treatment and recycling. Nowadays a lack of space for opening of new landfills has become a problem especially in densely inhabited areas and due to the expansion of big cities, therefore in some countries the mining of landfills has become a merely good solution. It is also considered as a future of recycling and a challenge for innovative strategies to get rid of waste deposits with some benefits [46, 47]. Valorization of waste material during LFM projects can be subdivided as follows: (a) production of a fine covering material which fits for use as methane-oxidation layer; (b) recovery of ferrous metals; (c) production of a refuse-derived fuel; and (d) removal of hazardous wastes deposits. In general, LFM mostly is performed as an integral phase of landfill closure procedure, as every single irremediable landfill in Europe has to be closed for disposal according to the EU legislation. According to Krook et al. [2], LFM could be described as a process for extracting minerals or other solid natural resources from waste materials that previously have been disposed by burying them in the ground. According to Hogland [9], the purposes of LFM are stated: (1) conservation of landfill space; (2) reduction in landfill area; (3) elimination of a potential source of contamination; (4) mitigation of an existing contamination source; (5) energy recovery; (6) recycling of recovered materials; (7) reduction in management system costs; (8) site redevelopment.

Waste valorization after LFM recovers valuable recyclable materials, e.g., metals, currently attracting good market prices, plastics that although possibly heavily contaminated could still be utilized for energy recovery and landfill space [47, 48]. However, additional research is needed to test the opportunity of using the fine fraction of waste in building and construction industry and road repairing. Legislation gaps, doubtful feasibility, threats of leaching and complicated geotechnical properties are questions to be solved in future.

Conclusions

Results obtained in current study on speciation of metallic elements in fine fraction of waste derived from the Kudjape Landfill comprehensively indicated that majority of potential toxic elements in studied waste samples are bound into fractions (residual fraction and fraction of reduced compounds) of low extractability and thus have low mobility. It confirms that the fine fraction of material mined at municipal landfill can be used as the covering layer of the same landfill during the site remediation after careful environmental analysis. Expected environmental concern is negligible as leaching of potentially toxic metals is supposed very low. Taking into account already implemented full-scale LFM activities current study is the first investigation dealing with possible valorization of landfill material, especially regarding the use of fine fraction of waste. Thus, current results give valuable information about the use of fine fraction for landfill covering material. Besides, the information will contribute to future research in LFM areas with various physical and environmental conditions such as age of waste at the landfill, waste composition, landfill location etc.

Acknowledgments

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