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POTENTIAL AND MAIN TECHNOLOGICAL CHALLENGES FOR MATERIAL AND ENERGY RECOVERY FROM FINE FRACTIONS OF LANDFILL MINING: A CRITICAL REVIEW

Juan Carlos Hernández Parrodi *[1,2], Daniel Höllen [1] and Roland Pomberger [1]

[1] *Montanuniversität Leoben, Department of Environmental and Energy Process Engineering, 8700 Leoben, Austria*
[2] *Renewi Belgium SA/NV, NEW-MINE project, 3920 Lommel, Belgium*

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ABSTRACT

Multiple landfill mining investigations of municipal solid waste landfills have been carried out worldwide in the past decades. Some of these studies have led to the conclusion that landfill mining is not feasible and could represent more of a problem than a solution for old landfill sites. This is the case to a certain extent because, to this day, material and energy recovery in landfill mining has been restricted to the coarse fractions (>10 mm to >60 mm) in most projects, while the fine fractions (<10 mm to <60 mm) have been often re-directed to the landfill with poor or no treatment at all despite their recovery potential. The fine fractions account for 40-80 wt.% of the total amount of the landfill-mined material. Its material composition is characterized by about 40-80 wt.% decomposed organic matter or weathered mineral fractions which cannot be hand-sorted, followed by significant amounts of calorific fractions and a small amount of metals. The main chemical compound found in landfill mining fine fractions is SiO_2, mostly present as quartz and minor amounts of sheet silicates, followed by CaO, mostly present in carbonate minerals. MgO, Fe_2O_3 and Al_2O_3 represent minor components. Heavy metals are present in concentrations of few to several hundreds of mg/kg without a clear general trend of enrichment compared to the coarse fractions. In contrast, the net calorific value of the fine fractions (about 3-9 MJ/kg DM) can be several times lower than that of the coarse fractions (about 10-30 MJ/kg DM). These data clearly indicate that both a mineral fraction for waste-to-material and a calorific fraction for waste-to-energy might be recovered if suitable mechanical processing technologies can be employed. The potential of the fine fractions for material and energy recovery, as well as the main technological challenges to unlock it, are the main topics discussed in the present review article. This article has been elaborated within the framework of the EU Training Network for Resource Recovery through Enhanced Landfill Mining – NEW-MINE.

1. INTRODUCTION

Investigations on landfill mining (LFM) and enhanced landfill mining (ELFM) of municipal solid waste (MSW) landfills have shown that landfill-mined material is composed of a mixture of fine fractions (e.g. cover layer material, organic material and small particles of diverse materials) and inert materials (e.g. stones, glass, ceramics and construction & demolition waste (C&D)), as well as of a smaller amount of wood, leather, rubber, textiles, plastics, metals (ferrous and non-ferrous), paper & cardboard (P&C), among others (Hernández Parrodi, Höllen, & Pomberger, 2018).

Table 1 presents the average material composition of the standard landfill calculated by Van Vossen & Prent, 2011, from data of 60 LFM projects. The table shows that the fine fraction (<24 mm) accounts for about 55 wt.% (raw state) of the total mass of landfill-mined material.

However, it is important to highlight that the material composition varies between individual landfills and also within one landfill due to differences in the type of landfilled material, as well as due to the decay of organic and the weathering of inorganic matter, including the corrosion of metals. Nonetheless, the previous material composition presents a good average compared to other LFM studies (Quaghebeur et al., 2013; Wolfsberger et al., 2015).

The mixture of fine fractions is sometimes also referred to as "soil", "soil-like" or "soil-type" fraction in other studies, due to their appearance, organic matter and mineral contents and relatively homogeneous composition compared

* Corresponding author:
Juan Carlos Hernández Parrodi
email: juan.carlos.parrodi@renewi.com

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TABLE 1: Average material composition of landfill-mined material (Van Vossen & Prent, 2011).

Material fraction	Amount
Fine fractions (<24 mm)	54.8%
C&D	9.0%
Inert	5.8%
P&C	5.3%
Organic	5.3%
Plastics	4.7%
Wood	3.5%
Others	2.6%
Stones	2.5%
Total metals	2.0%
Textiles	1.6%
Leather	1.6%
Glass	1.1%
Non-MSW	0.3%

Note: Figures have wt. and raw state basis

to the coarser fractions. However, it is relevant to note that the different genesis of the fine fractions in landfills with respect to that of soils and the lack of separation of the fine fractions from other materials in the landfill, do not allow referring to the fine fractions from landfill-mined material, in a rigorous manner, as soil.

The fine fractions (commonly considered as the material with a particle size from <60 mm to <10 mm, depending on the author and investigation) have been identified as 40-80 wt.% of the total amount of landfill-mined material in several investigations (Hernández Parrodi et al., 2018), which is in agreement with the average amount of about 55 wt.% reported by Van Vossen & Prent, 2011.

Furthermore, the fine fractions tend to contain most of the moisture of the whole excavated material. This is the case because water is retained in a stronger way by the fine fractions than by the coarser fractions, which occurs mainly by physical absorption, chemisorption and capillary forces, together with the fact that the fine fractions present a higher specific surface area than the coarse fractions. A significant variation of the moisture content in the fine fractions has been identified from previous research, ranging from 16 wt.% to 54 wt.% (Hernández Parrodi et al., 2018).

Due to their quantity, composition and characteristics, the fine fractions are of utmost relevance to assess the feasibility of a (E)LFM project. This is partly the case because, to this day, material and energy recovery in (E)LFM has been restricted to the coarse fractions in most of the projects, while the fine fractions have been re-directed to the landfill with poor or no treatment at all beforehand (Bhatnagar et al., 2017; Münnich, Fricke, Wanka, & Zeiner, 2013). Moreover, it is important to add that the revenues to be obtained through land recovery play a crucial role for the economic feasibility of most (E)LFM projects, since without such revenues it is highly unlikely that the OPEX and CAPEX associated with the processing of the fine fractions can be covered (van der Zee, Achterkamp, & Visser, 2004).

A detailed study on the material composition of the fine fractions (<40 mm) of landfill-mined material from a MSW landfill in Austria (Wolfsberger et al., 2015) reveals the composition shown in Figure 1. The largest constituent of the fine fractions in that study accounts for the fraction "Sorting residue", which was in this case 65.6 wt.% (raw state). This fraction is hereafter referred to as "soil-like fraction". The three following, most abundant constituents of the fine fractions correspond to the sub-fractions: "Plastics", "Minerals" and "Wood, leather, rubber", with amounts of 11.6 wt.%, 6.6 wt.% and 5.9 wt.% (raw state), respectively; while amounts of 1.9 wt.% of metals and textiles (each) were reported.

This information suggests that the fine fractions can contain an interesting amount of materials that could be recovered and, therefore, to ignore their potential and keep on directing them to the re-disposal pathway is to be questioned.

Analyses on the chemical composition of the fine fractions (<10 mm) from the Remo landfill, Belgium, report a composition of 45 wt.% SiO_2, 9 wt.% CaO and 5 wt.% Fe_2O_3 (Quaghebeur et al., 2013). Mineralogically, few data on the composition of the fine fractions are available. One of these is the composition of the fine fractions (<40 mm) from an Austrian landfill which was investigated in the LAMIS project and showed amounts of 34 wt.% quartz (SiO_2), 30 wt.% calcite ($CaCO_3$), 16 wt.% dolomite ($CaMg(CO_3)_2$), 15 wt.% muscovite ($KAl_2[(OH,F)_2|AlSi_3O_{10}]$) and 5 wt.% kaolinite ($Al_4[(OH)_8|Si_4O_{10}]$). This confirms the presence of SiO_2 and CaO as main components and further suggests that also MgO and Al_2O_3 can be present in significant amounts.

It is important to reiterate that the composition of MSW changes according to geographic region, its development level, culture and many other factors (UNEP/Grid-Arendal, 2004). Additionally, the internal conditions to which the disposed waste in a landfill is exposed to (e.g. aerobic/anaerobic conditions, moisture, temperature and pressure) can vary significantly from site to site, as well as the operation procedures, local weather conditions and legislation, among many others. Even between landfills that appear to be very similar to each other (in terms of size, volume, region, received type of waste and climatic conditions), the straightforward application of information from one landfill to the other, without sampling, appears unfeasible (Sormunen, Laurila, & Rintala, 2013).

Moreover, previous research has emphasized that the costs and benefits in (E)LFM projects are always case-specific and cannot be generalized (Hogland, Marques, & Nimmermark, 2004; van der Zee et al., 2004). The specific conditions of a given landfill will determine, to a large extent, if landfill mining and land reclamation, which is an essential factor for the implementation of (E)LFM, are feasible for the site (Kurian, Esakku, Palanivelu, & Selvam, 2003; van der Zee et al., 2004). For instance, landfills and dumpsites without leachate and biogas collection systems could be appealing candidates for (E)LFM projects, since the economic and environmental assessments for the mitigation of their environmental pollution would not include investments made in such infrastructure, which might raise the feasibility of this kind of project.

Studies have also highlighted the importance of a prop-

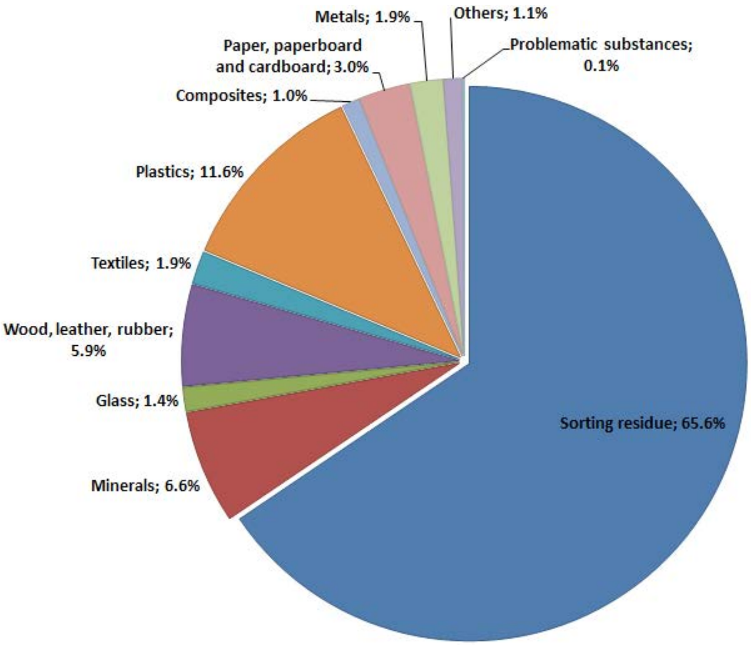

FIGURE 1: Composition of fraction <40 mm of landfill-mined material from a MSW landfill in Austria (modified from Wolfsberger et al., 2015).

er exploration of the landfill as one of the initial phases of a (E)LFM project (Cossu, Salieri, & Bisinella, 2012; Hull, Krogmann, & Strom, 2005; Quaghebeur et al., 2013). During the exploration phase of a (E)LFM project, test excavations or drillings into the landfill are necessary to assess the composition of the landfilled material (Krook, Svensson, & Eklund, 2012). The validation and utilization of non-invasive exploration methods, such as geophysical exploration, will play a critical role in (E)LFM projects.

Thus, in order to evaluate the material and energy recovery potentials of the fine fractions from a specific landfill, adequate and proper quantitative and qualitative characterization of the disposed waste is to be performed and several factors are to be taken into account.

Additionally, technological, legal and economic challenges are to be overcome and a new approach to process the fine fractions is to be implemented, so that a significant amount of the fine fractions can be directed towards material and energy recovery.

The potential of the fine fractions for waste-to-material (WtM) and waste-to-energy (WtE), as well as the main technological challenges to unlock it, are the main topics discussed in this review article.

2. MATERIALS AND METHODS

The present review article comprises the discussion of the potential for material and energy recovery from the fine fractions of landfill-mined material, as well as the main technological challenges that need to be overcome to unlock it. The arguments for the discussion are based on the analysis of several previous (E)LFM investigations found in scientific literature and their reported results. The scope envisages scientific articles published in international peer-reviewed journals, as well as review papers and international conference proceedings, books, guidelines, standards and legislation.

The search for literature was performed using different internet search engines and online scientific databases of peer-reviewed research articles, scientific journals, books and conference proceedings. Relevant references and citations from previous studies were also taken into account.

Keywords such as landfill mining, enhanced landfill mining, resource recovery, material recovery and energy recovery were used as baseline for the search of information; while terms such as fines, fine fractions, soil-like material, soil-type material and soil were employed to filter the search results and obtain more specific information.

The selection of the sources of information for this paper was made based on the relevance of their content regarding the material composition, properties and characteristics of the fine fractions from (E)LFM, as well as to provide a solid foundation for the discussed topics in this article.

3. RESULTS AND DISCUSSIONS

3.1 Potential for WtM and WtE

As already mentioned, previous (E)LFM research reveals that the fine fractions are mainly composed of a soil-like fraction, followed by a smaller amount of a mineral fraction, plastics, metals, textiles, leather, rubber, wood, P&C (Hernández Parrodi et al., 2018). This information suggests that some of these materials could be recovered from the fine fractions via further material processing.

One approach to achieve material recovery, which is the one proposed and discussed in the present article, is to separate the fine fractions (incl. those which cannot be separated by manual sorting) from each other, according to their physico-chemical properties, by mechanical processing. Once the LFM material has been separated into different material fractions, it would be possible to direct these to either material or energy recovery pathways. For this purpose, the segregation of individual particles is required. To accomplish an adequate segregation, a particle size classification of the excavated material is to be performed as an initial step (e.g. particle size fractions: >40 mm, 40-20 mm, 20-10 mm, 10-8 mm, 8-6 mm, 6-4 mm, 4-2 mm, 2-1 mm and <1 mm). This will raise the efficiency and effectiveness of the further mechanical processing regarding the disintegration of agglomerates and subsequent material classification (e.g. plastics, metals and inert material fractions). Some particle size ranges might require a wet processing (e.g. washing) to achieve quality material (e.g. for the recuperation of plastics and inert materials). Additionally, the amount of moisture contained in the different particle size fractions will play a significant role while selecting the most appropriate mechanical processing method.

However, it might be the case that a certain amount of these fractions is not suitable for any of the previously referred pathways. And as a result, this residual fraction could be re-stored, perhaps at the same landfill, till new technologies for its exploitation are available. An alternative approach, which has been already studied in previous (E)LFM projects, would be to thermally valorise the fine fractions as a whole. This would require additional fuel to compensate for its low calorific value, which has been found to be in the range of 0.4-9 MJ/kg in previous studies (Hernández Parrodi et al., 2018). Nevertheless, the calorific value of the fine fractions could be raised by reducing the amount of inert materials and the moisture content. Therefore, to separate the fine fractions into different material and particle size fractions, as proposed in this paper, could be the most adequate pathway to achieve a holistic valorisation.

In order to get a visual understanding of the approach proposed herein regarding the theoretical potential of the fine fractions, Figure 2 presents the material fractions that constitute the fine fractions grouped into three clusters, which are WtM, WtE and Re-storage.

The EU has employed a hierarchical concept for the management of waste (Directive [2008/98/EC] of the European Parliament and of the Council on waste) in order to minimise the overall impacts and improve the efficiency of the utilization of resources, in which waste management has been given five main priorities. These priorities are shown in Figure 3 from highest (top) to lowest priority (bottom).

Prevention targets the avoidance of waste, while preparing for re-use, recycling and recovery aim for the valorisation of waste materials. Disposal, as a last resort, targets the safe permanent storage of waste.

Therefore, according to the European waste management hierarchy, preparing for re-use and recycling are to be preferred, as far as they are feasible and represent a better environmental solution, to energy recovery from waste. In other words, WtM is, in general, to be considered before WtE.

The quality of the retained materials in the landfill and the WtM and WtE technologies available for material valorisation will, among others, determine the feasibility of (E)LFM (Quaghebeur et al., 2013).

3.2 Waste-to-Material

This concept refers to the recovery of materials from waste. These recovered materials are commonly referred to as secondary raw materials. In theory, these materials can be directly reused, recycled or processed in such a way that they can be reincorporated to the material´s life cycle.

In the case of (E)LFM, the quality of the recovered ma-

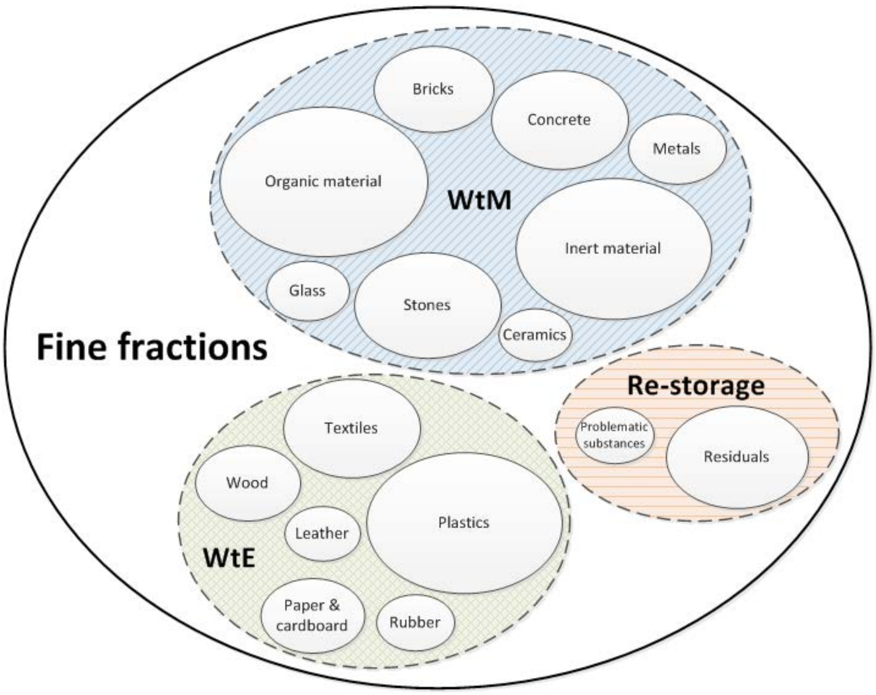

FIGURE 2: Potential of the fine fractions for WtE and WtM.

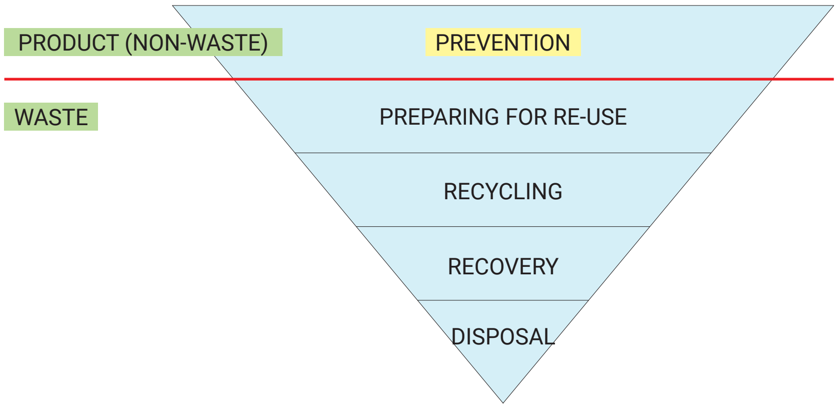

FIGURE 3: Waste management hierarchy (European Commission).

terials might impede its direct re-use and, as already stated, limit the recyclability of some of them. Nonetheless, previous (E)LFM investigations have revealed that interesting amounts of ferrous and non-ferrous metals could be recovered from the fine fractions for recycling (Hernández Parrodi et al., 2018).

Besides metals, two other highly interesting fractions from the fine fractions for material recovery are the soil-like and inert fractions, which could be used in various applications (e.g. soil-like fraction as ground substitute and inert fraction as construction aggregates) if the heavy metals and organic pollutants contents are low. These fractions are of paramount importance because they, together, account for most of the fine fractions and they are, to this day, the materials that are mainly sent back to the landfill for re-disposal, hindering the overall economic and environmental feasibility of (E)LFM projects.

It is known from previous research (Hernández Parrodi et al., 2018) that the soil-like fraction is, in some cases, composed of the material used to cover the waste (daily, intermediate or final cover material) during the operation of the landfill. In many cases, materials with a low permeability (e.g. clay) have been used for this purpose. Therefore, the presence of large amounts of fine fractions in landfill-mined material can be related to landfill sites, while a low amount could be related to open dumpsites (Mönkäre, Palmroth, & Rintala, 2016). The intermediate and daily cover materials usually consist of a 15-30 cm layer of e.g. soil, clay or compost (Tchobanoglous, Theisen, & Vigil, 1993).

Furthermore, it is not rare to find landfill sites where a variable amount of construction and demolition waste (C&D) was mixed with the cover material to give a better load capacity to the platforms for the transit of the trucks on the landfill area, as well as the use of other received materials in combination with the main cover material, such as soil, compost and dry sewage sludge, as daily cover materials.

A significant percentage of the fine fractions can also be formed through the weathering of mineral wastes and through the humification and mineralisation of biowaste (Hernández Parrodi et al., 2018).

Thus, it can be concluded that the soil-like fraction is mostly composed of organic and mineral materials, which could be separated from each other, up to a certain extent, by further mechanical processing.

As for the inert fraction, which has been identified as mainly composed of C&D, stones, minerals, glass and ceramics in previous studies, a relevant amount of organic matter could also be contained in it due to the presence of soil and waste mixtures.

The recovery of these organic and mineral materials could yield an organic material, which might be used, among others, as ground substitute or soil improver, and a mineral material, which might be suitable for the substitution of mineral aggregates for construction purposes (e.g. construction sand). This, provided that they comply with the corresponding quality and characteristics stipulated in the local regulations.

Figure 4 schematizes the recovery of metals, construction aggregates and a ground substitute from the fine fractions.

Using the material composition of the fine fractions reported by Wolfsberger et al., 2015 (Figure 1), as an example and assuming a hypothetical scenario, in which optimal material processing allows quality and proper segregation of the corresponding material fractions with a recovery amount of 60-80 wt.%; an amount of around 3-5 wt.% minerals, 1 wt.% metals and 1 wt.% glass could be recovered from the total amount of the fine fractions. This would represent that about 5-8 wt.% of the whole amount of the fine fractions could be recovered through the WtM pathway.

The previous range represents a small amount of the total excavated material and, thus, might not be very appealing to future (E)LFM projects. However, a very significant amount of about 60-70 wt.% of the total excavated material corresponded to the soil-like fraction (shown as "Sorting residue" in Figure 1), which depends on the implementation of an adequate material processing approach, as well as on the further development of technology and recovery techniques, in order that organic and mineral materials can be recovered from this fraction, as previously proposed.

Therefore, it could be said that, to this day, the main key-factors to divert a large amount of material from re-disposal to material recovery are: the implementation of an adequate material processing approach and the further de-

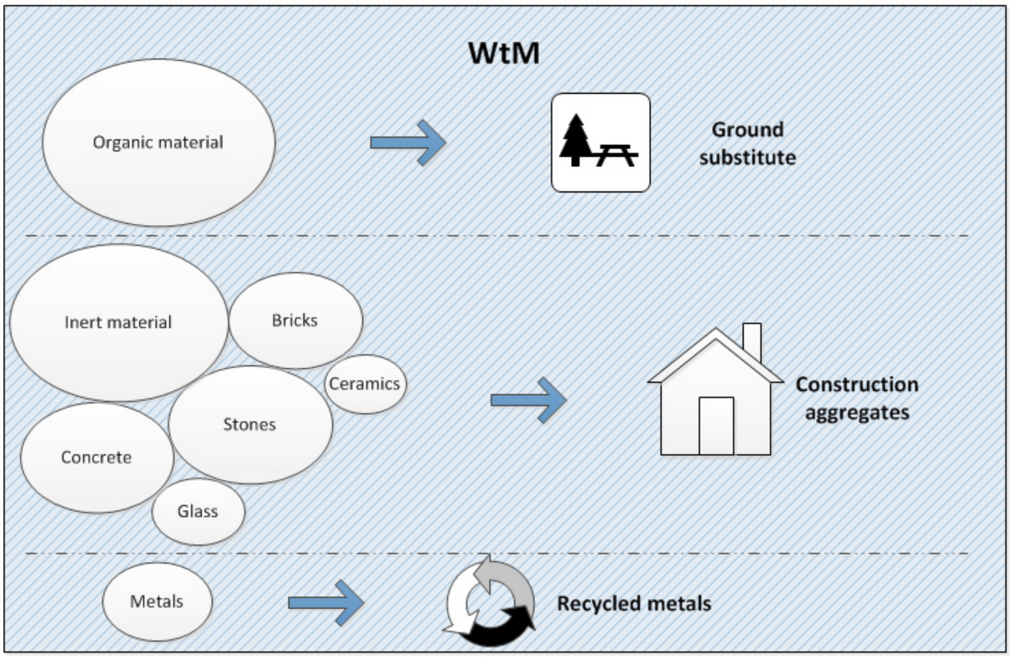

FIGURE 4: Material recovery from organic and inert fractions of LFM fine fractions.

velopment of technology and material recovery techniques. Given the previous key-factors, the amount of material recovery could increase significantly, as well as the economic and environmental feasibility of the whole project.

Moreover, the fine fractions have been also used as cover material in landfill sites to build a methane degradation layer (Kaczala et al., 2017). When the level of pollutants is low, the fine fractions could be used as future landfill cover (Bhatnagar et al., 2017). The material can be used as cover material after assessing the geotechnical suitability (Kurian et al., 2003).

One additional potential end-use for the fines excavated from landfill could be as clean fill off-site (Hull et al., 2005). The fine fractions of most recent landfilled MSW might even be able to be used as soil fertilizer or compost at green areas and gardens (Jones et al., 2013; Quaghebeur et al., 2013), provided that the pollutant concentrations meet the corresponding requirements for such use. Landfill-mined materials should be characterized for heavy metals of environmental concern before they are applied on land use (Jain, Kim, & Townsend, 2005). Amounts of inorganic pollutants, such as Cr, Cu, Pb and Zn, in the calorific fractions (i.e. plastics, textiles, rubber, leather, wood and P&C) of the same order of magnitude as in MSW have been found (Vesanto et al., 2008). However, besides the total contents, also the leachability and the mineralogical bonding of these possible contaminants have to be assessed.

According to a previous study by Kurian et al., 2003, the fine fractions complied, for most parameters of most samples, with the heavy metal limit values from the US EPA standards to be used as compost for non-edible crops. It has been reported that the concentrations of almost all heavy metals (except for Pb, Cd and As in some cases) in waste samples (<10 mm and <4 mm) met the pollutant ceiling concentrations set by the US EPA and the EU limits (Masi, Caniani, Grieco, Lioi, & Mancini, 2014). Fines from older disposed MSW might exceed pollutant concentrations and would then need further treatment to be used as soil fertilizer or compost (Quaghebeur et al., 2013).

Furthermore, landfills could be transformed into temporary storage sites (Jones & Tielemans, 2010) for, if the case, a fraction concentrated in problematic substances, such as heavy metals and asbestos. As conceptualized by Deltares independent institute for applied research, a temporary storage site is a structurally and environmentally safe deposit place that would enable in-situ material recovery from waste materials in the future, facilitating the access to the potential future resources, when the technology to recover certain materials is available. Such concept would also allow the implementation of improvements to the temporary storage sites, such as reshaping and volume reduction. For instance, German landfill mining and site remediation investigations reported reductions of 8-30 vol.% after re-landfilling and re-compacting the excavated MSW without recycle or reuse of the waste fractions (Collins, Brammer, & Harms-Krekeler, 2001). The compaction of re-landfilled MSW results in a considerable volume reduction due to the decrease of pore spaces and voids caused by the degradation of the organic waste fractions (Collins et al., 2001). The extent of the reduction depends on the degree of degradation of the organic fraction and the compaction of the MSW in the landfill before the excavation (Hull et al., 2005). Additional volume reductions can be expected if the fine fractions are reused or recycled (Hull et al., 2005).

Consequently, temporary storage would mean a step further towards circular economy, creating a connection between the past, present and future regarding resource availability (Bosmans, Vanderreydt, Geysen, & Helsen, 2013; Jones et al., 2013; Krook et al., 2012; Krook & Baas, 2013; Quaghebeur et al., 2013).

Some other end-uses might arise in the future, depending on available markets, material quality and regulatory framework for reuse (Jain et al., 2005). Both the increasing market prices for recovered materials and the legal framework will set the conditions to justify new waste processing technologies (Archer, Baddeley, Klein, Schwager, & Whiting, 2005; Forton, Harder, & Moles, 2006; Tachwali, Al-Assaf, & Al-Ali, 2007).

3.3 Waste-to-Energy

In general, energy recovery from waste refers to the generation of electricity and/or heat by processing waste materials, as well as to the production of energy carriers (e.g. refuse derived fuel (RDF) and syngas for the production of hydrogen and methane). RDF is an alternative fuel, produced from diverse kinds of waste materials, which can replace partially or completely the use of fossil fuels in various industrial applications (e.g. cement and power plants).

As already mentioned, relevant amounts of materials such as plastics, P&C, wood, textiles, leather and rubber, which could be suitable for the production of RDF, can be found in the fine fractions. If recovered, it is unlikely that these materials can meet the required quality criteria for material re-use and recycling, whilst recovered wood, textile, leather and rubber materials are hardly re-used or recycled. However, assuming that these materials could be recycled, their value on the recyclables market would most likely be very low with high recycling costs.

Moreover, these materials are composed of carbon to a major extent and they, in a dry state, possess high calorific values. Calorific values of 4.4-9 MJ/kg DM have been determined for the fine fractions (<20 mm) from two Austrian landfills (Wolfsberger et al., 2015), which can be significantly increased by reducing the amount of the inert fraction present in them (e.g. extracting mineral materials like stones, glass and ceramics).

Provided these circumstances, the recovery of calorific materials (i.e. plastics, P&C, textiles, rubber, leather and wood) in order to produce RDF and exploit its WtE potential can be suggested as an interesting option. Additionally, the added value of the calorific materials would be significantly larger in this manner.

Figure 5 displays the usage of the calorific fractions from the fine fractions for the production of energy.

Similarly as in section 3.2, using the material composition from LFM fine fractions reported by Wolfsberger et al., 2015 and assuming a hypothetical scenario to provide with an example of the amount of material that could be directed to WtE with recovery amounts of 60-80 wt.%: a total amount of about 15-20 wt.% of the whole quantity of the fine fractions could be used to produce RDF, from which around 8-10 wt.% would be conformed of plastics, 4-5 wt.% of wood, leather and rubber (all together), 2-3 wt.% of P&C and 1-2 wt.% of textiles.

It is important to note, that the quality requirements and, hence, the composition of the produced RDF will vary according to the thermal valorisation technique to be employed and, therefore, the total amount of RDF to be obtained will depend strongly on these requirements.

Mined waste from landfills may be used to improve combustion through co-incineration at MSW incineration plants; helping to avoid auxiliary fuel consumption and releasing landfill space (Chen, Guan, Liu, Zhou, & Zhu, 2010).

Thermo-chemical based technologies, such as gasification, pyrolysis and incineration, to process the fine fractions from landfill excavated waste materials have been tested to a certain extent in recent years (Bosmans et al., 2013). Incineration with energy recovery would be possible with the fines fraction (<18 mm) after the removal of

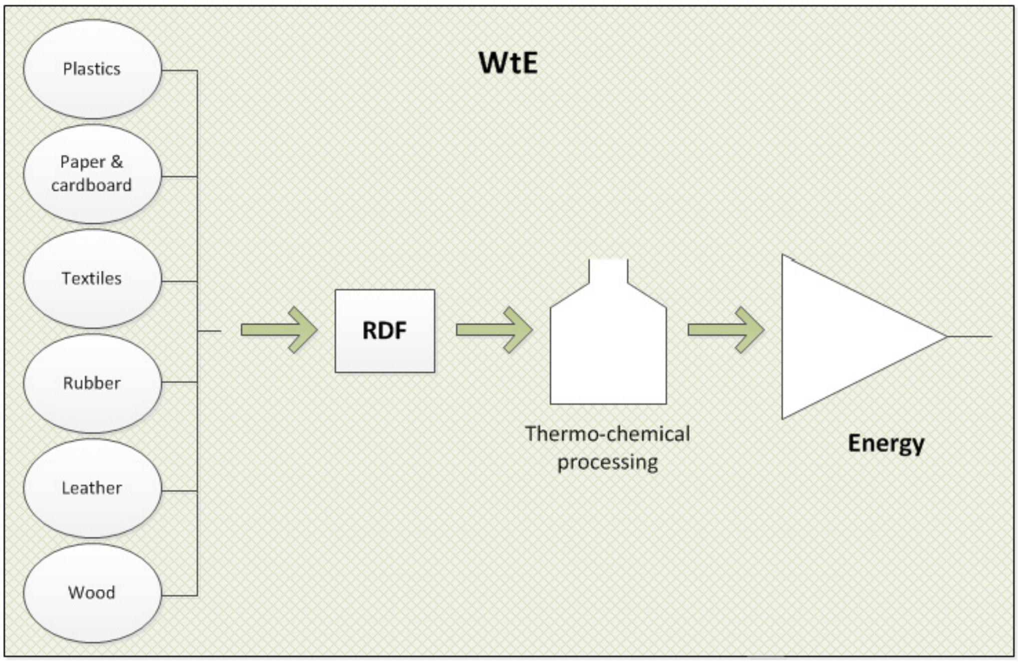

FIGURE 5: Energy recovery from calorific fractions of LFM fine fractions.

coarse inert material (Hogland et al., 2004). Research on plasma gasification and further upcycling of its by-products has been increasing in the last years (Bosmans et al., 2013; Danthurebandara, van Passel, Machiels, & van Acker, 2015; Danthurebandara, van Passel, Vanderreydt, & van Acker, 2015a; Danthurebandara, van Passel, Vanderreydt, & van Acker, 2015b). The outcomes of those studies have shown that, due to the robustness and flexibility of the process, plasma gasification might be used as an adequate WtE route for the calorific fractions from the fine fractions.

The EU standard that states the specifications and classes for solid recovered fuels (SRF), which is a type of RDF, is the BS EN 15359:2011, in which the net calorific value (linked to water content) and chlorine and mercury contents are among the most important parameters. A case study reported that the limit values for SRF usage in cement or power plants, according to the Austrian guideline BMLFUW 2002, were not exceeded by the fines fraction (<40 mm) from one LFM case study, but exceeded them for another one (Wolfsberger et al., 2015).

3.4 Main challenges to overcome

There are a large number of factors that play a very important role in a (E)LFM project (e.g. landfill site´s particularities, excavation and material processing procedure and utilized equipment, sampling and laboratory analysis procedures and followed guideline, among many others) and, therefore, attention must be paid to the singular characteristics of a site while analysing and comparing information between different projects.

The factors discussed below, together with the economic and legislative aspects, represent some of the main challenges in order to start full scale recovery of resources from landfills (Jones, Geysen, Rossy, & Bienge, 2010; Krook et al., 2012; Van Vossen & Prent, 2011).

3.4.1 Variations in composition and properties

In order to identify the material and energy recovery potentials and possible alternative uses of the fine fractions, and be able to design an appropriate material processing and final disposal method during the planning phase, the characterization of the fine fractions is an essential first step (Jani et al., 2016; Mönkäre et al., 2016). Some key aspects to be considered are: the material, chemical and mineralogical composition, size and volume of the site, type of the landfilled waste, location of the site, historic operation procedures of the site, extent of degradation of the disposed waste, types of markets and uses for the recovered materials and environmental and health risks (Frändegård, Krook, Svensson, & Eklund, 2013; Kurian et al., 2003; Quaghebeur et al., 2013). Additionally, the amount of moisture present in the fine fractions is a key parameter for the selection of an appropriate material processing, as the water content plays a decisive role regarding the efficiency and suitability of mechanical separation methods (e.g. sieving and density separation methods and sensor-based sorting).

Compaction and expansion of solid waste components, as well as the material´s contamination and degradation make excavated material more difficult to sort and characterize than fresh MSW (Hull et al., 2005).

As it has been reported in previous research, a variable quantity of problematic substances could be present in the fine fractions. These are substances that, due to their toxic or undesired characteristics, would hinder or limit to a great extent the further usage of the produced or recovered materials from the fine fractions. The presence of trace amounts of hazardous chemicals would most likely limit the quality of the fines fraction for further use (Reinhart & Townsend, 1997).

Some problematic elements that have been found in the fine fractions are, for example, heavy metals, chlorine and sulphur. Such elements can be toxic at certain concentrations and speciation and might form harmful compounds when released to the environment. In addition to that, they can damage the equipment with which the fine fractions are being handled or processed.

The risk due to the elevated pollutant concentrations should be evaluated before such material can be reused outside of a landfill (Jain et al., 2005). To reduce the concentration of metals such as Cr, Cu, Ni and Zn in the fine fractions might be needed to enable the use of this fraction for further purposes (Quaghebeur et al., 2013).

In general, metal concentrations, except those of As, Be and Cd, were found below EU, UK and US regulatory threshold values, for use in unrestricted settings, for the fine (<0.425 mm) and intermediate (>0.425 mm and <6.3 mm) fractions (Jain et al., 2005).

One first step to identify an adequate processing of the fine fractions from landfill-mined material is to determine the leaching properties at laboratory scale (Mahmoudkhani, Wilewska-Bien, Steenari, & Theliander, 2008). These tests can bring valuable information about the compliance with existing standards and norms.

Hence, the mechanical processing of the fine fractions is to be aimed to remove problematic materials (e.g. using sensor-based sorting equipment to sort out materials containing chlorine) to produce a RDF with the adequate properties for the corresponding thermo-chemical processing technology. This together with the recovery of an organic and a mineral fraction, whilst concentrating the undesired elements and compounds in a residual fraction, which might be suitable for further processing for the recovery of certain elements (e.g. heavy metals) in the near future.

3.4.2 Surface defilements and material agglomerates

During disposal time, fines adhere to the surface of other materials (Maul & Pretz, 2016), leading to limitations in the final sorting outputs due to decreased sorting performance of the sensor-based sorting units. This has also been reported in other investigations (Wolfsberger et al., 2015), in which the fines adhered to other waste fractions as impurities, contaminating the rest of the waste fractions and decreasing their quality and value. Results from a previous study show that all manually sorted size categories contained impurities of the other sorted fractions (Kaartinen, Sormunen, & Rintala, 2013). Contamination of all fractions with fines (adherent “soil”) showed an increasing trend with age, which in high levels will likely prove to be an insurmountable obstacle to recycling most of the excavated waste fractions, unless further processing is conducted (Hull et al., 2005).

This adhered layer, also known as surface defilements, can lead to efficiency losses of sensor-based sorting (Maul & Pretz, 2016). If the surface defilements can be removed, it would be easier to use plastics from LFM as a secondary resource (Maul & Pretz, 2016). Further analyses on the sorted plastics show that the mass share of the surface defilements in the final sorted products can be as high as 7.5 wt.% (Maul & Pretz, 2016).

Apart from the above, the presence of moisture in the fine fractions favours the formation of material agglomerates during the mechanical processing, especially in the sieving steps. Material agglomerates are a mixture of water and fine particles (mainly material <1 mm) that stick together to form slumps of fine fractions. These slumps might encapsulate other material fractions contained in the fine fractions as well, such as plastics, P&C, metals, etc. This can hinder the performance of the mechanical processing (in particular the size and density separation methods) and, hence, the material recovery from the fine fractions as well.

The drying of the material might increase the amount of the fines, as in moist conditions some fine particles tend to stay attached to bigger particles (Kaartinen et al., 2013) and avoid the formation of material agglomerates. This could improve the quality of the coarse fractions and raise the overall efficiency of the material processing. Composting (aerobic biodrying) has been suggested to dry the excavated waste prior to thermal valorisation; this would improve the removal of the material contamination due to adhered fines, the efficiency of the sieving steps and reduce the ash generation during the thermal processing (Collins et al., 2001).

In contrast, the implementation of a wet processing (e.g. wet sieving and washing units) in order to decrease the amount of surface defilements and eliminate material agglomerates might also result in a high quality of the recovered calorific fractions and an efficient separation of the different material fractions. Nevertheless, the feasibility of a wet processing is yet to be fully assessed in the context of LFM fine fractions, since it is a complex treatment that might require sophisticated processing, as well as additional energy to reduce the moisture content of the products afterwards.

3.4.3 Application range of available mechanical processing technologies

The particle size is a very important factor for an optimum separation process; though, conventional waste sorting techniques (e.g. metals separation, density classification and sensor-based sorting equipment) cannot be applied below a certain particle size of the material (Spooren, van den Bergh, Nielsen, & Quaghebeur, 2013).

Also, the removal of ferrous materials from the fine fractions slows down separation processes and requires a relatively dry material (Bhatnagar et al., 2017); the latter would mean the addition of a certain amount of energy to the process and could negatively affect the economic feasibility of (E)LFM projects.

Therefore, the application range of the technologies for processing the fine fractions, with respect to particle size, needs to be extended in order that smaller particle sizes (<3 mm to <1 mm) can be reached. This will play an essential role regarding the separation of organic and mineral materials and the recovery of non-ferrous metals from the soil-like fraction of LFM fine fractions, since these materials are mainly found in small particle size ranges.

Concurrently, material processing technologies and techniques are to be developed further in such a way that LFM material can be processed in an efficient way without the need of a drying step.

The planning of a suitable treatment process for recovering waste fractions in (E)LFM projects requires not only knowledge on the composition of the landfilled waste, but on the treatability of the different fractions as well (Kaartinen et al., 2013).

One of the main technological aspects of ELFM is the development of a processing plant that enables maximum resource recovery (Quaghebeur et al., 2013).

4. CONCLUSIONS

The primary recoverable waste fractions from LFM fine fractions are complementary materials for RDF production, soil-like and inert materials and metals. In this respect, the specific conditions of a given landfill will determine if landfill mining and land reclamation are feasible for the site. One critical factor for the implementation of (E)LFM is the recovery of land, since the revenues to be obtained from land reclamation can be the main driver of the project´s business case. The quality of the retained materials in the landfill and the WtM and WtE technologies available for material valorisation will also, among others, determine the feasibility of (E)LFM. Landfills and dumpsites without leachate and biogas collection systems could be appealing candidates for (E)LFM projects, since the economic and environmental assessments for the mitigation of their environmental pollution would not include investments made in such infrastructure, which might raise the feasibility of this kind of project.

The organic fraction recovered from the fine fractions could have potential as ground substitute, such as cover material for operational landfills, soil for non-edible crops and formation of bio-soils to be used in environmental remediation activities. This fraction could, theoretically, be used as fertilizer at green areas and gardens, the latter given that the material complies with all applicable regulations for such purpose. Particle size and nutrients content are relevant parameters to evaluate the use of the fine fractions in soil applications. When the level of contamination of P&C, plastics, textiles and wood (calorific fractions in general) recovered from a landfill is too high or their quality is too low, WtE could be the most suitable valorisation route. Material properties such as moisture and ash contents, calorific value, organic and total carbon amounts and hydrogen and nitrogen contents are needed to assess the efficiency for WtE applications.

For metals, glass, ceramics, stones and other inert materials, WtM might be possible if the materials can be separated adequately from each other and the applicable limit values for pollutant substances can be met.

The planning of a suitable treatment process for recovering material fractions in (E)LFM projects requires not only knowledge on the composition of the landfilled waste, but on the treatability of the different fractions as well. In order to identify the material and energy recovery potentials, possible alternative uses of the fine fractions and to be able to design an appropriate material processing and final disposal method during the planning phase, the characterization of the fine fractions is an essential first step. Some key conditions to be considered are: the composition and type of the landfilled waste, location of the site, historic operation procedures of the site, extent of degradation of the disposed waste, types of markets and uses for the recovered materials and environmental and health risks.

To this day, predominant factors to divert a large amount of material from re-disposal to material recovery, raise the amount of material recovery and, hence, the economic and environmental feasibility of (E)LFM projects, are: the implementation of an adequate material processing approach and the further development of technology and material recovery techniques. These, together with the economical and legislative aspects, represent some of the main challenges in order to start full-scale recovery of resources from landfills.

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