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FINE FRACTIONS FROM LANDFILL MINING: POTENTIAL AND MAIN CHALLENGES TO OVERCOME

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Introduction

Several investigations on landfill mining (LFM) and Enhanced landfill Mining (ELFM) have shown that a typical composition of excavated waste from a Municipal Solid Waste (MSW) landfill is – in the order of magnitude – 55 wt% of a mixture of fine materials (“Soil”), 15 wt% of mixed inert materials (“Stones” + “Glass” + “CDW” (construction and demolition waste) + “Inert”), 7 wt% of wood, leather, rubber and textiles (together), 5 wt% of plastics, 5 wt% of paper and cardboard, 5 wt% of organics, 2 wt% of total metals (Fe + non-Fe metals) and 6 wt% of other materials (“Other” + “Non-MSW” (non-municipal solid waste)).[1] The mixture of fine materials (sometimes also referred to as “soil”, “soil-like” or “soil-type” fraction in other studies) is denoted herein as “fine fractions”, since this fraction is also composed of other fractions (*e.g.* plastics, textiles, rubber, leather, wood, glass, metals, *etc.*). The fine fractions (commonly considered as the material with a particle size from < 60 to < 10 mm, depending on the author) have been identified as 40-80 wt% of the total mined material in several investigations.[2]

Due to their quantity, composition and characteristics, the fine fractions are of utmost importance to assess the feasibility of a LFM project. This is the case because, to this day, material and energy recovery in 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 despite their recovery potential.[3,4] A detailed study on the material composition of the fine fractions (< 40 mm) of mined waste from a Municipal Solid Waste (MSW) landfill in Austria[5] reveals the following composition (Figure 1): the largest sub-fraction of the “fine fractions” accounts for the fraction “Sorting residue”, representing 65.6 wt% (wet basis). This fraction corresponds to what in the present paper is referred to as the “soil-like” fraction, due to its resemblance to soil in appearance; nevertheless, the composition and properties of this fraction can differ strongly from those of soil. At the same time, the soil-like fraction is composed to a major extent of an organic sub-fraction and a mineral sub-fraction, similarly to soil.

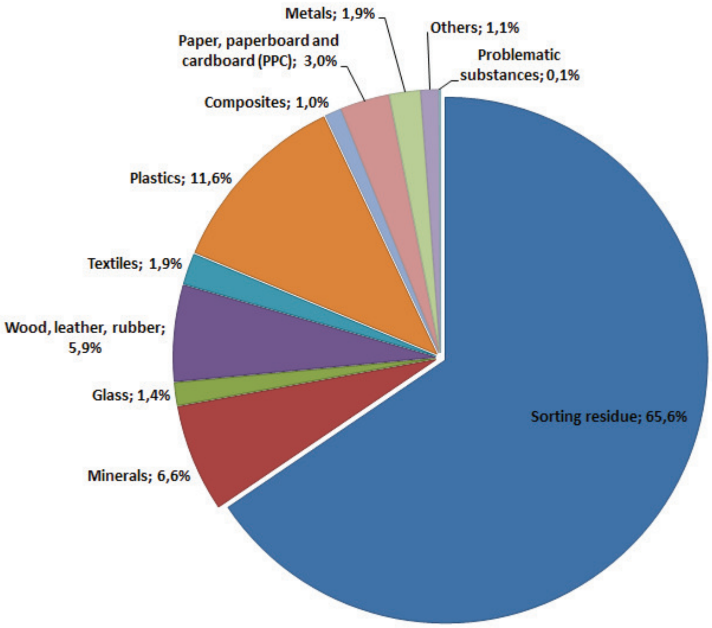

Figure 1: Composition of fraction < 40 mm from mined MSW landfill in Austria (modified)[5]

The three following, most abundant constituents of the fine fractions in that study correspond to the fractions: “Plastics”, “Minerals” and “Wood, leather, rubber”, with amount to 11.6 wt%, 6.6 wt% and 5.9 wt% (wet basis), respectively; while contents 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[6] of 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. 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 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 ($Al_4[(OH)_8|Si_4O_{10}]$), which confirms the presence of SiO_2 and CaO as main components and further suggests that also MgO and Al_2O_3 are present in significant amounts.

It is important to point out that the composition of MSW changes according to geographic region, its development level, culture and many other factors.[7]

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.[8] Moreover, previous research has stressed that the costs and benefits in LFM projects are always case-specific and cannot be generalised.[9] The specific conditions of a given landfill will determine if landfill mining and land reclamation are feasible for the site.[10]

Furthermore, studies have also highlighted the importance of a proper exploration of the landfill as one of the initial phases of a LFM project.[6,11,12] During the exploration phase of a landfill mining project, test excavations or drillings into the landfill are necessary to assess the composition of the landfilled material.[13] The validation and utilisation of non-invasive exploration methods, such as geophysical exploration, will also play a critical role in LFM and ELFM 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 characterisations of the disposed waste are to be performed and several factors are to be taken into account. In order to be able to direct a relevant amount of the fine fractions towards Waste-to-Energy (WtE) and Waste-to-Material (WtM), some technological, legal and economic challenges are to be overcome and a new approach to process the fine fractions is to be implemented. The potential of the fine fractions for material and energy recovery, as well as the main technological challenges that this represents, are the main topics discussed in this paper.

Potential for WtM and WtE

Previous LFM investigations have shown that the fine fractions are mainly composed of a soil-like fraction and an inert fraction, as well as of smaller amounts of plastics, metals, wood, paper and cardboard, textiles, leather, rubber and, in some cases, problematic substances.[2] These fractions could be separated from each other and be directed towards energy or material recovery, according to their properties. For this purpose, liberation of individual particles is required, which might require a thorough material processing (*e.g.* drying, washing). It might be the case that a certain amount of these fractions is not suitable for any of the previously referred pathways; as a result, this residual fraction could be re-stored, perhaps at the same landfill, till new technologies for its exploitation are available. Alternatively, the fine fractions could also be thermally valorised as a whole, but this would likely require additional fuel to compensate for its low calorific value. The potential of each of the fractions that constitute the fine fractions towards energy and material recovery proposed in the present paper is shown in Figure 2.

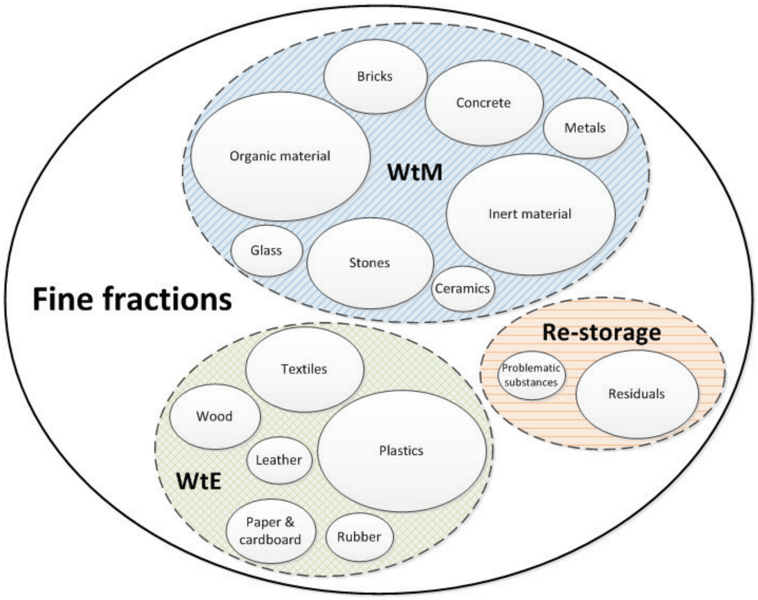

Figure 2: Potential of the fine fractions towards WtE and WtM

In order to minimise the overall impacts and improve the efficiency of the utilisation of resources, 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); where waste management has been given five main priorities. These priorities are shown in Figure 3 from the highest (top) to the lowest priority (bottom). Prevention targets the avoidance of waste, while preparing for re-use, recycling and recovery aim to valorise waste materials. Disposal, as a last resort, targets the elimination 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 ELFM.[6]

Figure 3: Waste management hierarchy[14]

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 used again. In the case of LFM, the quality of the recovered materials might exclude its direct re-use and, as already stated, limit the recyclability of some of them. Nonetheless, previous LFM investigations have revealed that interesting amounts of metals, Fe plus non-Fe metals, could be recovered from the fine fractions for recycling.[2] 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 aggregate) if the heavy metals and organic pollutants contents are low. These fractions are of utmost importance, because combined they account for most of the fine fractions and, therefore, they are presently the materials which are mainly sent back to the landfill for re-disposal; hindering the overall economic and environmental feasibility of a LFM project.

It is known from previous studies[2] 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. The intermediate and daily cover materials usually consist of a 15-30 cm layer of *e.g.* soil, clay or compost,[15] although this can vary depending on local regulations and site-specific, operational procedures. The presence of large amounts of fine fractions in excavated waste can be explained by the use of intermediate or daily covers in landfills, while a low amount of fine fractions could be related to open dumpsites.[16] Furthermore, it is not rare to find landfill sites where a variable amount of C&D waste 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 usage 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.[2] Thus, it can be suggested that the soil-like fraction is mostly composed of an organic sub-fraction and a mineral sub-fraction, which could be sorted out from each other by further processing. As for the inert fraction, which has been identified as mainly composed of C&D waste, stones, minerals, glass and ceramics in previous studies, a relevant amount of organic matter could also be present due to the presence of soil and waste mixtures. The recovery of these organic and inert materials could yield an organic fraction, which could be used, among others, as ground substitute or soil improver, and an inert fraction, which could be suitable for the substitution of mineral aggregates (*e.g.* sand) for construction purposes, provided that they comply with the corresponding quality and characteristics stipulated in the local regulations. Figure 4 conceptually shows the recovery of metals, construction aggregates and a ground substitute from the fine fractions.

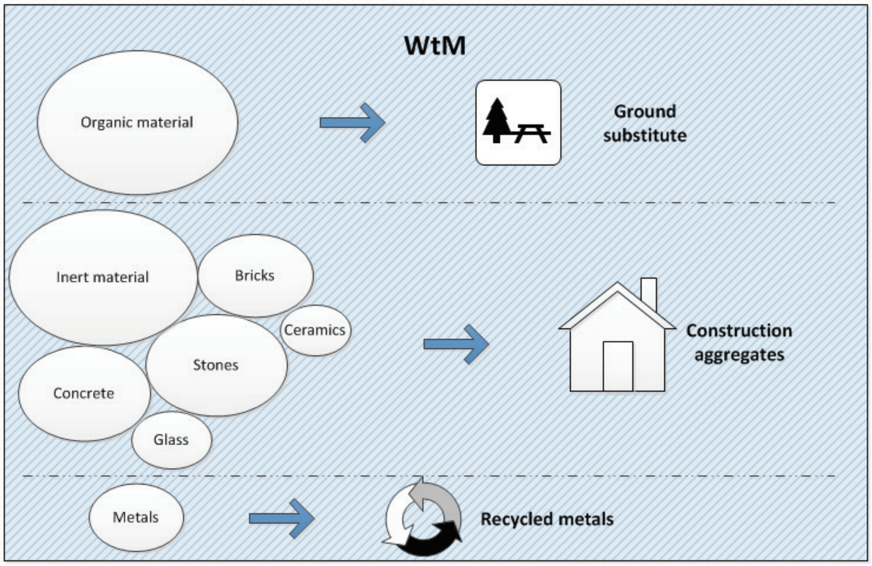

Figure 4: Material recovery from organic and inert fractions of LFM fine fractions

For metals, glass, ceramics, stones and other inert material, waste-to-material might be possible if the materials can be separated adequately.[6] Fine fractions have been also used as cover material in landfill to build a methane degradation layer.[17] When the level of pollutants is low, the fine fractions could be used as future landfill cover.[4] The material can be used as cover material after assessing the geotechnical suitability.[10] The hydraulic conductivity (DIN 18130-1) of a fine fraction from an Austrian landfill investigated in the LAMIS project accounted for 5.3-5.7*10^{-8} m/s.[18] One potential end-use for fines excavated from a landfill could be as clean fill off-site.[12] The fine fractions of most recent landfilled MSW might even be able to be used as soil fertiliser or compost at green areas and gardens,[6,19] provided that the pollutant concentrations meet the corresponding requirements for such use. Landfill mined materials should be characterised for heavy metals of environmental concern before they are applied on land.[20] Amounts of inorganic pollutants, such as Cr, Cu, Pb and Zn, in the calorific fractions (*i.e.* plastics, textiles, rubber, leather, wood and paper and cardboard) of the same order of magnitude as in MSW have been found.[21] 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,[10] 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.[22] Fines from older disposed MSW might exceed pollutant concentrations and would then need further treatment to be used as soil fertiliser or compost.[6]

Moreover, landfills could be transformed into temporary storage sites,[23] which have been defined as structurally and environmentally-safe storage places that would permit *in-situ* material recovery from waste materials, facilitating the access to the potentially future resources later on, when the technology to recover certain materials is available, and allowing the implementation of improvements to these sites, such as reshaping and volume reduction. Temporary storage would bring us a step closer towards a circular economy, creating a connection between the past, present and future regarding resource availability.[6,13,19,24,25]

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.[26] The compaction of re-landfilled MSW results in a considerable volume decrease due to the reductions of pore spaces and voids caused by the degradation of the organic waste fractions.[26] 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.[12] Additional volume reductions can be expected if the fine fractions are reused or recycled.[12]

Some other end uses might arise in the future, depending on available markets, material quality and regulatory framework for reuse.[20] Both the increasing market prices for recuperated materials and the legal framework will set the conditions to justify new waste processing technologies.[27-29]

Waste-to-Energy

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.* methane, refuse derived fuel (RDF) and syngas). RDF is an alternative fuel, produced from diverse kinds of waste materials, which can partially or completely replace the usage of conventional fuels, such as fossil fuels, in various industrial applications (*e.g.* cement and power plants). As already mentioned, relevant amounts of materials such as plastics, paper and cardboard, wood, textiles, leather and rubber, which could be suitable for the production of RDF, can be found in the fine fractions. These materials are very likely to fail meeting the required quality criteria for material re-use and recycling; whilst recovered wood, textile, leather and rubber materials are hardly recycled or re-used. 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 possess, in a dry state, high calorific values. Calorific values of 3,9-9 MJ/kg DM have been determined for the fine fractions (< 20 mm) from two Austrian landfills[5]. Provided these circumstances are there, the recovery of these materials in order to produce RDF, thereby exploiting its WtE potential, can be suggested as an interesting option. Figure 5 displays the usage of the calorific fractions from the fine fractions for the production of energy:

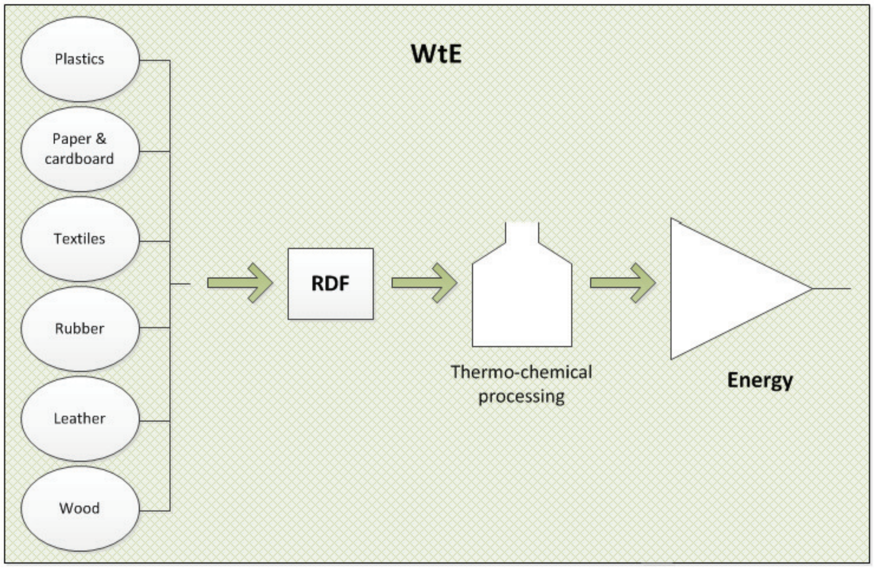

Figure 5: Energy recovery from calorific fractions of LFM fine fractions

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.[30] Concurrently, 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 the last years.[24] Incineration with energy recovery would be possible with the fines fraction (< 18 mm) after the removal of coarse inert material.[9] 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; where the net calorific value (linked to water content) and chlorine and mercury contents are among the most important properties. 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 LFM.[5]

Main challenges to overcome

There are a large number of factors that play a very important role in LFM and ELFM projects (*e.g.* landfill site´s particularities, excavation and material processing procedure and utilised equipment, sampling and laboratory analysis procedures and followed guideline, among many others) and, therefore, very much attention must be paid to the singular characteristics of a site while analysing and comparing information between different projects. The challenges 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.[1,13,31]

Variations in composition and properties

In order to identify the material and energy recovery potentials and 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 characterisation of the fine fractions is an essential first step.[16,32] 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.[6,10,33] Compaction and expansion of solid waste components, as well as the material´s contamination and degradation make excavated material more difficult to sort and characterise than fresh MSW.[12] As it has been reported in previous investigations, 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 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.[34] Some problematic elements that have been found in the fine fractions are, for example, heavy metals, chlorine and sulphur; which can be toxic at certain concentrations and speciation, form harmful compounds when released to the environment and damage the equipment with which this material is 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.[20] To reduce the concentration of metals such as Cr, Cu, Ni and Zn from the fine fractions could be an option to enable the usage of this fraction for other purposes.[6] 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 and < 6,3 mm) fractions.[20]

The first step to identify an adequate processing of the fine fractions from excavated landfills is to determine the leaching properties of the material at laboratory scale.[35] These tests can bring valuable information about the compliance with existing standards and norms. Hence, the further processing of these fractions is to be aimed to remove these problematic fractions (*e.g.* using sensor-based sorting equipment to sort out materials containing chlorine), as far as the available technology allows it, to produce a RDF with the adequate properties for the corresponding thermo-chemical processing technology; as well as to recuperate an organic and an inorganic 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.

Source for surface defilements in coarse fractions

During disposal time, fines adhere as a soil-like layer to the surface of other materials,[36] 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,[5] 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.[37] 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 takes place.[12] This adhered soil-like layer, also known as surface defilements, can lead to efficiency losses of sensor-based sorting.[36] If the surface defilements can be removed, it would be easier to use plastics from LFM as a secondary resource. 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%.[36] 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.[37] 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.[26] In contrast, the assessment of the implementation of a wet processing (*e.g.* washing units), in order to decrease the amount of surface defilements in the coarse fractions, merits further investigation.

Reach of available technologies for processing the fine fractions

The particle size is a very important factor for an optimum separation process; 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.[38] Also, the removal of Fe materials from the fine fractions slows down separation processes and requires a relatively dry material.[4] Therefore, the ability of the technologies for processing the fine fractions, regarding the particle size, needs to be extended in order that smaller particle sizes (< 3 mm) can be handled as well. The planning of a suitable treatment process for recovering waste fractions in a LFM project requires not only knowledge on the composition of the landfilled waste, but also with respect to the treatability of the different fractions.[37] One of the main technological aspects of ELFM is the development of a processing plant that enables maximum resource recovery.[6]

Conclusions

The specific conditions of a given landfill will determine if landfill mining and land reclamation are feasible for the site. The primary recoverable waste fractions from the fine fractions are metals, complementary materials for RDF production, soil-like and inert fractions. The soil-like fraction recovered from the fine fractions could have potential as a ground substitute, such as cover material for operational landfills, material to form embankments, soil for non-edible crops and formation of bio-soils to be used in environmental remediation activities. This fraction could, theoretically, be used as fertiliser at green areas and gardens, provided the material complies with all applicable regulations for such purpose. Particle size and nutrients content are relevant parameters to evaluate the usage possibility of the fine fractions for soil applications. For metals, glass, ceramics, stones and other inert material, WtM might be possible if the materials can be separated adequately. Characteristics such as moisture content, ash content, calorific value and amount of organic carbon, total carbon, hydrogen and nitrogen are needed to assess the efficiency for WtE applications.

When the level of contamination of paper and cardboard, 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. 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 ELFM. Landfills and dumpsites without leachate and biogas collection networks could be attractive candidates for LFM projects, since the economic and environmental assessments for the mitigation of their environment pollution would not include investments in such infrastructure and, thus, would likely raise the feasibility of this kind of project.

The planning of a suitable treatment process for recovering waste fractions in a landfill mining project 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 and 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 characterisation 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. One of the main technological aspects of ELFM is the development of a processing plant that enables maximum resource recovery. 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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