DEVELOPING THE CASE FOR ENHANCED LANDFILL MINING IN THE UK

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ABSTRACT

Across the UK there are around 22,000 landfills sites, suggesting a significant opportunity for recovering value from previously discarded materials. Enhanced landfill mining (ELFM) has been identified as a concept to recover value from landfills through optimized valorization of the resources extracted. This approach, including waste-to-energy (WtE), waste-to-material (WtM) and waste-to-land (WtL) options can also assist in addressing critical and secondary raw material demands and scarcity. However, to date, there is still limited evidence on this potential. In this paper, the results of 9 UK landfill sites characterization and feasibility studies for ELFM are presented. Waste characterisation from 9 landfill sites located in the UK was carried out. Overall 36 core drills and 118 unique waste samples were analysed. High volumes of fines (soil-like) organic material were observed across all samples and significant levels of valuable metals were observed in this fraction. Previous work had determined significant aluminium and copper are contained in the soil-like fines fraction, which does not include the separate metals fraction (i.e. aluminium cans, copper wires etc). At one site the combustible fraction was assessed as a potential refuse-derived fuel [RDF]. Typically, 10-40% by weight of the samples at this site were 'combustible', with an average gross calorific value of 12.9 MJ/kg. Plastics extracted from the sites are contaminated and degraded, therefore further work is required to understand the extent of degradation and to assess available options upcycle these materials.

1. INTRODUCTION

Steady raw materials supply is essential for the UK and EU economy and increasingly under pressure to sustain the businesses and industries demand (Rockström et al., 2009). The supply of raw materials is not only a matter of availability of primary but also secondary raw materials (SRM) (Dino et al., 2016; European Commission, 2017). As such, we need to consider both the scarcity and raising prices of raw materials and the waste management policies aiming at reducing the environmental and health impacts of waste. Recent research has demonstrated that landfill sites can offer a high potential of primary and secondary raw materials [SRM] (Dino et al., 2016) rather than just representing contaminated land that needs remediation (Ortner et al., 2014). Across Europe there are around 500,000 landfill sites (EURELCO, 2016) and around 22,000 historic landfill sites in the UK, of which 90% have been closed before 1996 (EA, 2015).

Mining landfill solely for SRM or critical raw materials [CRM] is not expected to be financially viable given the extent of the recovery operations involved (Gutiérrez-Gutiérrez et al., 2015). However, concepts such as 'enhanced landfill mining' (Jones et al., 2013) which provides an integrated valorization of landfilled waste streams as materials (Waste-to-Material) and energy (Waste-to-Energy), using innovative transformation technologies and respecting the most stringent social and ecological criteria has the potential to minimize costs through the recovery of multiple commodities and allowing the recovery of valuable land.

While traditional landfill mining has a long history, enhanced landfill mining (ELFM) has come into focus only recently (Jones et al., 2013). ELFM aims at providing optimized valorization of different types of materials extracted from landfill sites and increased energy recovery from waste, aiming to reduce the amount of re-buried waste to almost zero. Furthermore, ELFM projects aim to mitigate greenhouse emissions from landfill sites and landfill mining activities to the atmosphere. To achieve this, various technologies are developed to make waste streams usable for different valorization techniques.

Different options exist for recovery including Waste-to-Material (WtM), Waste-to-Energy (WtE) and Waste-to-Land (WtL) (Jones et al., 2013; OVAM, 2013; Van Passel et al., 2013). Besides WtM and WtE, (Van Passel et al., 2013) also considers WtL, the creation of space at the

location of the landfill site, as well as allocation of new land use to the remediated landfill site. Furthermore, in ELFM concept, resource management which is defined as "the temporary storage of waste with a view to a later valorization and use of this waste" is taken into account (OVAM, 2013). In most cases of traditional landfill mining, recycling and recovery of materials are only of secondary importance as the main drivers being landfill capacity increase or land clearance for urban development (Ford et al., 2013). This has resulted in a standstill development of specialized mining technologies for ELFM (Ford et al., 2013).

It has been previously reported that recovered materials from landfill sites could provide high economic revenues – the value will depend on the amount and quality of the recovered fractions and the market (Jones et al., 2013; Van Passel et al., 2013). However, the amount of waste that could potentially be recovered depends mainly on the physical and chemical conditions of the landfill site and the efficiency of equipment and technology used (Rosendal, 2009). According to the World Resource Foundation (Strange, 1998), purity of the excavated waste fractions can vary between 70% and 90%. In this context, purity refers to the level of contamination and the level of target material (i.e. non-target material would make up 10-30% of a specific recovered stream). A high amount of plastics can be found in landfills. Joseph et al. (2007) concluded that it is not viable to recycle plastics due to highly diminished quality. Quaghebeur et al. (2013) reaches the same conclusion. The authors state that excavated plastic, textile, paper/cardboard and wood do not have the required quality for recycling and reintegration in the production market. Therefore, the best valorization route for these types of waste is widely considered to be WtE in the absence of other viable means of recovering value from these materials.

As the concept of ELFM gains traction, it is critical to further our understanding of the wastes contained within the landfills across Europe in order to develop robust plans for undertaking large-scale operations and to identify the technology, and technology development, needs.

This paper compiles the data from 9 landfill sites sampled across the UK, investigating the physical composition of each site, determining metal content and the potential of using landfill-derived materials as refuse-derived fuels [RDF].

2. MATERIALS AND METHODS

2.1 Sample collection

Samples were taken from landfill sites across the UK, predominantly handling municipal waste and general waste from commercial premises. 36 core samples were extracted from 9 landfill sites located across the United Kingdom, which were then divided into 118 samples based on the depths, for example the 22 samples from Site 8 is 1x core drill divided into 1 metre increments (up to 22 metres). The core samples were taken from drilling activities using a 450 mm diameter auger (drill barrel). The samples used in this work are summarized in Table 1; the age and status of the sites is shown, however the specific age of each core and sample is not possible to specify accurately. Two separate test sites were investigated at Site 4 which were wet and dry areas of the site and are referred to as 4a and 4b, respectively. The depths of the samples typically ranged from 0-22 metres, with many samples being in the range of 6-18 metres.

2.2 Composition analysis and characterisation

The samples were collected from the landfill sites, sealed in double-layered bags and stored at 4°C until analysis. The samples were hand-sorted Waste was screened and separated by hand into plastics, paper and fines as defined by Quaghebeur et al. (2013) (degraded garden and food materials), textiles, glass and metal. Waste composition was reported as a percentage contribution of total weight. Dry matter (DM) or Total solids (TS) and Volatile Solids (VS) of the paper and fines were determined in triplicate following the procedure British Standard methods (British Standards Institute, 2011a, 2011b, 2011c).

In addition to the DM, TS and VS content, the calorific values of the combustible fractions were determined in accordance with the standard method (British Standards Institute, 2011d) using a Parr 6400 Isoperibol bomb calorimeter.

The composition was determined for all sites. The calorific values were measured for all samples (combustibles

TABLE 1: Overview of sites and samples used.

Site n°.	Site status	Age of site (as of 2018)	Total sample count	No. cores	Maximum sample depth (m)
1	Closed	38	6	1	10
2	Open	26	6	2	26 30
3	Closed	24	10	6	20
4a	Closed	22	13	2	19
4b	Closed	22	10	5	25
5	Open	10	27	5	13
6	Closed	38	10	5	19
7	Closed	20	10	7	19
8	Open	20	22	1	22
9	Closed	28	4	2	20

only) extracted from site 8. The combustible fractions were separated, dried overnight and ground to <10 mm using a Retsch SM 2000 shredder.

2.3 Metal content of waste fractions

The metal content was determined as described by Gutiérrez-Gutiérrez et al. (2015). To achieve the highest quantity of the extracted metals, samples were submitted to nitric acid digestion followed by a digestion with aqua regia (HNO_3 + HCl in a ratio of 1:3), as it was not technically possible to use HF to digest the samples. Briefly, for the nitric acid digestion, 0.5 g of sample was mixed with 8 ml of HNO_3 (70%, 1.42 density, Fisher Scientific) in Teflon tubes and left overnight. The samples were placed in a microwave digester (Multiwave 3000, Anton Paar) for 45 minutes at 800 W. The mixtures were then filtered (150 mm, hardened low ash paper, Fisher Scientific) and the remaining liquid was diluted to 100 ml with distilled water and retained for analysis. The filter paper and residue was then dried for 2 hours at 105°C and placed into a digestion tube with 6 ml of HCl (37%, 1.18 density, Fisher Scientific) and 2 ml of HNO_3. The mixture was subjected to microwave irradiation at 800 W for 45 minutes. The solution was filtered and the liquid diluted to 100 ml and retained for analysis.

The retained solutions were analysed for metal content using inductively coupled plasma mass spectrometry (ICP-MS) (Elan 9000 Perkin-Elmer SCIEX) using several certified standard solutions for calibration.

The organic/fines fraction from sites 1-4 was analysed for rare earth elements and critical/valuable metals (Gutiérrez-Gutiérrez et al., 2015). To further investigate the distribution of metals, along with heavy metal elements, all fractions of waste extracted from site 9 were analysed.

3. RESULTS AND DISCUSSION

The results of the compositional analysis, as an average for each site, is illustrated in Figure 1. The soil-like organic material (fines) ranges between 30-74% (w/w), which is expected due to the relatively high proportion of food waste in household and general commercial wastes, along with the common practice of applying a daily soil cover to landfills during operation. The soil-like fraction had a similar consistency to soil, however is a mixture of the soil cover and humic material formed from the biodegradation of organic wastes. This finding is in agreement with previous studies on the characterisation of excavated waste samples (Garcia et al., 2016; Mor et al., 2006; Quaghebeur et al., 2013) where the composition of fine materials increases with depth (Frank et al., 2017).

Plastics were prominent in many samples, in particular across sites 2, 5, 6 and 7, with the plastic content ranging from 8.5% in site 9 to 44% in site 5. Quaghebeur et al (2013) observed a plastic content of up to 25%, so the waste extracted from sites 2, 5, 6 and 7 are higher than expected. This could be due to the age of the material and extent of degradation (i.e. reduction of the biodegradable proportion), or could be due to the waste types deposited; the sites predominantly accepted MSW, however some commercial and industrial wastes were disposed of, which is typically lower in organic content at the time of disposal.

The presence of such a significant organic/fines fraction suggests that for any enhanced landfill mining operation to be viable, this material would need to be separated and managed. Soil and complex organic matter are able to bind to metals, such as those mobilised in leachate material. This phenomenon was explored (Gutiérrez-Gutiérrez et al., 2015), with the results of this analysis from sites 1-4 presented in Figure 2 (rare earth elements and selected critical metals) and Table 2 (Cu, Ag, Au and Al).

The quantities of rare earth elements (REE) and other critical materials in relatively low concentrations suggest that mining for these materials alone would not be economically viable (Gutiérrez-Gutiérrez et al., 2015). However, when recovered as part of a large enhanced landfill
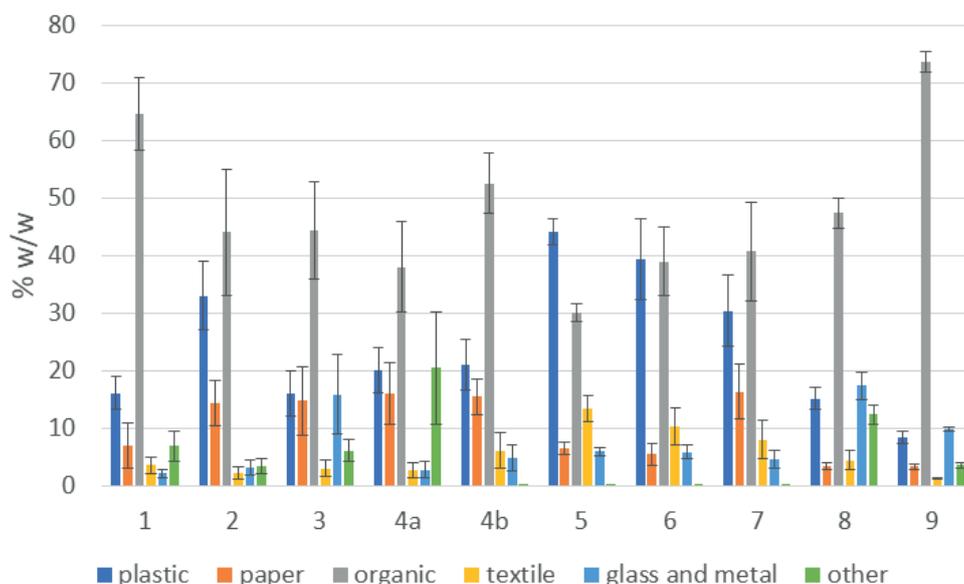

FIGURE 1: Average waste composition of sites 1-9 (error bars shown as standard error of the mean).
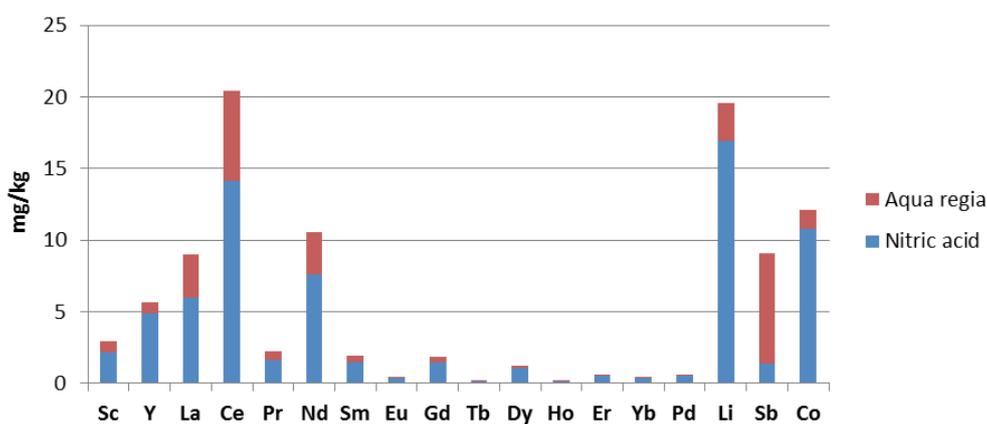
FIGURE 2: Rare earth elements and selected critical metal content of the fines (soil-like organic) fraction from sites 1-4.

mining undertaking then the recovery could be viable. This study focuses on the total metals present, however further work would be required to understand the recoverability of each metal. The Cu and Al concentrations measured are significant, and across the 4x sites analysed this represents a potentially viable resource of these metals. The combined value of aluminium and copper from within the fines fraction across the four sites is around $400 million (Gutiérrez-Gutiérrez et al., 2015), which is assuming complete recovery.Complete recovery wouldn't be expected in any recovery operation, therefore these values provide perspective of the scale of the metals. Due to the varied composition of waste within landfills, excavation solely for the purpose of these metals would be a significant technical challenge, in addition to the commercial viability previously mentioned.

To expand the work described by Gutiérrez-Gutiérrez et al. (2015) a further site was characterised in detail. Each fraction from site 9 was analysed for the REE and critical metals, the results of which are shown in Table 3a-c.

The REE observed in the fines fraction are closely aligned to the values in sites 1-4, however the Cu and Al values are lower, with the reasons for this requiring further research. Of the heavy metals Cr, Pb and Zn are most abundant, with the Cr content being significantly higher than values reported for non-landfilled wastes and MSW incinerator residues (Jung et al., 2004; Øygard et al., 2004). Chromium is, therefore, likely to chemically mobile in landfills through leachate movement arising from hazardous materials such as paints, batteries and chemical/industrial residues. However the values observed in wood materials suggests that the wood fraction separated in this study was treated with copper chromium arsenate [CCA], previous a widely-used

wood preservative. The presence of such high Cr levels does suggest that any enhanced landfill mining operation would need to take into consideration environmental and human health risks posed by Cr, and other hazardous elements present.

For the samples from Site 8, the average gross calorific value [GCV] of the combustible fraction measured with the calorimeter is 18.2 ± 5.7 MJ/kg (GCV, dry). Figure 3 illustrates the net calorific value [NCV] on dry basis for each sample in comparison with the composition of combustible materials. On an as-received basis, the GCV and NCV for the combustible fraction were 12.9 MJ/kg and 11.0 MJ/kg respectively.

The samples analysed here provide an indication of the contents of such landfill sites, however are not absolute values due to the volume of the landfill sites in comparison with the number of samples analysed. Obtaining representative samples from a whole landfill site presents a significant challenge, and further work is required to consider the statistically valid number of samples required. Further work could also involve innovative whole-site characterisation techniques, including electromagnetic measurements (Bobe et al., 2018).

Research groups have investigated the use of excavated landfill material for use as RDF, or solid recovered fuel [SRF], with challenges mostly arising due to the need to separate significant volumes of fines. Wolfsberger and Hollen (2014) concluded that the separation process was not efficient due to the 42% moisture and 69% fines contents in the waste material (Wolfsberger and Hollen, 2014). Results for the current project show a lower moisture content (26,3%) and a reduced percentage of fines (47.4%). Thus, the process' efficiency could be expected to be higher, al-

TABLE 2: Content of Cu, Ag, Au and Al (in mg/kg) for sites 1-4.

Metal	Average content (mg/kg)			
	Site 1	Site 2	Site 3	Site 4
Cu	1,076	1,027	2,595	1,830
Ag	2.26	2.77	3.63	5.02
Au	0.18	0.13	0.16	0.05
Al	17,274	12,357	12,594	12,079

TABLE 3: Critical metals (a), light REE (b) and heavy metal (c) content of waste fractions from site 9. All numbers presented as mg/kg.

Critical metals (a)					
	Cu	**Ag**	**Li**	**Sb**	**Co**	**Al**
Paper	134.38	0.85	5.85	7.08	10.53	10.707
Wood	166.40	2.21	3.49	8.59	24.73	5.045
Fines	254.22	16.66	8.91	58.32	8.49	12.806
Film plastics	148.43	1.71	4.30	182.64	12.21	6.269
Dense plastics	588.75	2.61	8.37	16.49	17.43	8.238
Textiles	377.86	2.91	11.94	13.88	19.11	14.182
LREES (b)					
	La	**Ce**	**Pr**	**Nd**	**Sm**
Paper	4.17	8.84	1.00	3.67	0.69
Wood	3.97	9.00	0.99	3.76	0.71
Fines	10.07	21.25	2.40	9.22	1.79
Film plastics	4.09	9.08	1.00	4.07	0.72
Dense plastics	7.15	15.92	1.78	6.75	1.24
Textiles	8.78	20.52	2.26	8.64	1.69
Heavy metals (c)					
	Cd	**Cr**	**Pb**	**Zn**	**Sn**	**As**
Paper	0.51	1.056	94.10	215.55	18.44	2.97
Wood	0.77	2.435	175.91	325.32	18.88	6.59
Fines	1.11	834	303.73	565.66	30.83	4.81
Film plastics	1.27	1.187	293.97	519.89	18.98	3.00
Dense plastics	1.48	59.14	529.09	1.652	104.96	5.13
Textiles	1.69	1.866	567.91	650.75	35.47	6.23

though an industrial scale testing would have to be undertaken.

On the other hand, the process described by Jones et al. (2013) could be viable for RDF recovery from the present landfill, though it would also need to be evaluated in large scale. The fines fraction, in this case, was lower (39%) than in the work presented here. In short, RDF production is strongly influenced by the amount of fines present in the waste. Extensive sieving and separation of the fines are vital in order to obtain high quality RDF.

The relatively high proportion of plastics in landfill contributes to the CV, which is comparable to SRF produced from fresh MSW (Velis et al., 2012; Wagland et al., 2011). As the plastics are likely to be degraded and/or contami-
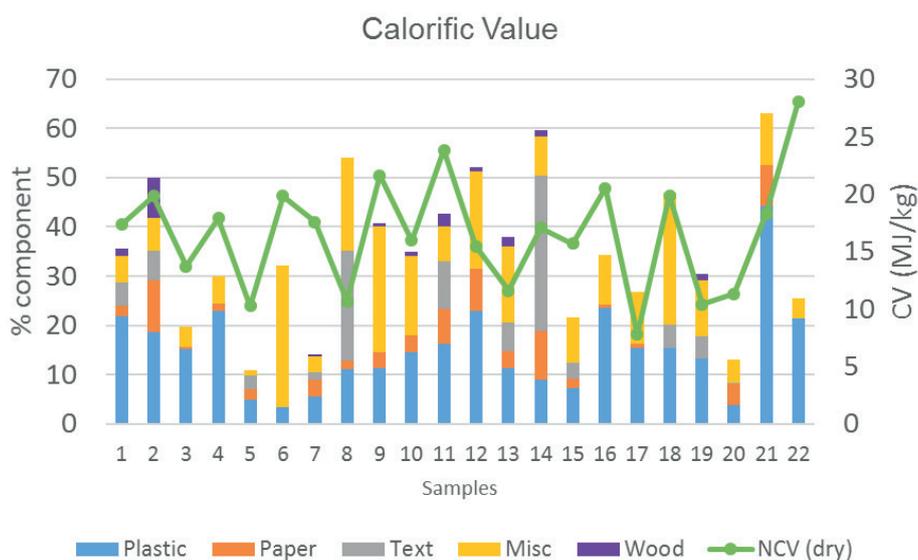
FIGURE 3: Combustible fraction and composition of site 8 with the NCV (dry), MJ/kg, for each sample.

nated through long-term exposure to leachate and landfill gas, it is not likely that all plastics recovered from landfill can be recycled conventionally (Joseph et al., 2007). Therefore, advanced options such as pyrolysis and gasification of plastics could upcycle these materials into chemicals and liquid fuels; this is a topic which has not been fully explored and so further work is required.

In summary, RDF production from enhanced landfill mining operations is one potential outlet, however successful valorisation of landfilled material is likely to comprise a flexible approach utilising options such as the recovery of recyclable materials (metals, for example), upcycling of plastics, refining of the fines material and the production of RDF.

4. CONCLUSIONS

The findings have highlighted that the waste composition varied across sites and between samples, however the percentage of fines (soil-like organics) is consistently high in comparison to other materials. This volume of fines presents a challenge in managing materials excavated from ex-situ landfill mining operations however the results presented here, and in previous studies, suggests that this material also contains valuable secondary raw materials.

Direct recycling of remaining plastics/paper/textiles might not be economically viable due to contamination and degradation. However options for managing these resources include the use of the combustible fraction as RDF or as a feedstock for advanced thermal conversion, potentially to produce valuable chemicals and/or liquid fuels.

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